Thin film heterostructures for spintronics investigated by grazing incidence small angle scattering

JUNE 22 2021 I E. KENTZINGER

JÜLICH CENTRE FOR NEUTRON SCIENCE & PETER GRÜNBERG INSTITUT

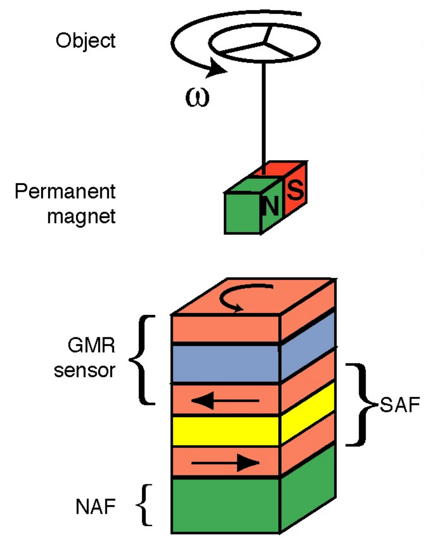
PLAN

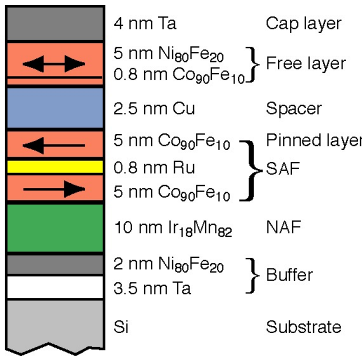
- **Introduction: Spintronics**
- Method: Reflectivity, off-specular scattering, GISAS and neutron polarization analysis
- Simulation of specular reflectivity
- Simulation of polarized neutron reflectivity
- Simulation of GISAS intensities within the Distorted Wave Born Approximation
- Structural ordering in assemblies of magnetic nanoparticles
- Magnetic domain structure in FePd with perpendicular-to-plane anisotropy
- Take-Home Message

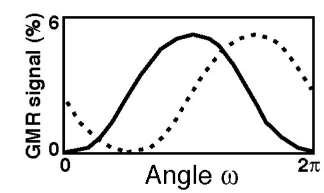
Magnetic thin films

- Ultra thin films
- Anisotropies at surfaces and interfaces
- Exchange bias
- Interlayer exchange coupling
- Giant magnetoresistance
- Tunnel magnetoresistance…

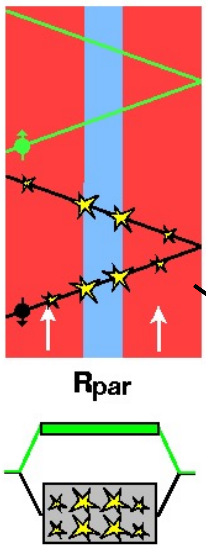
Sensor:

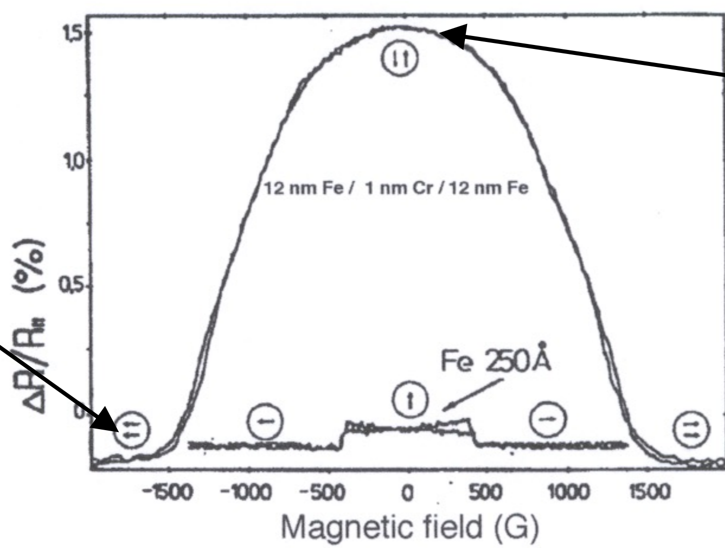


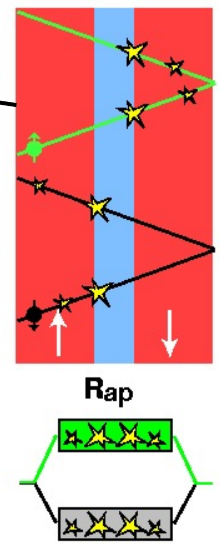




The Giant Magneto-Resistance effect:





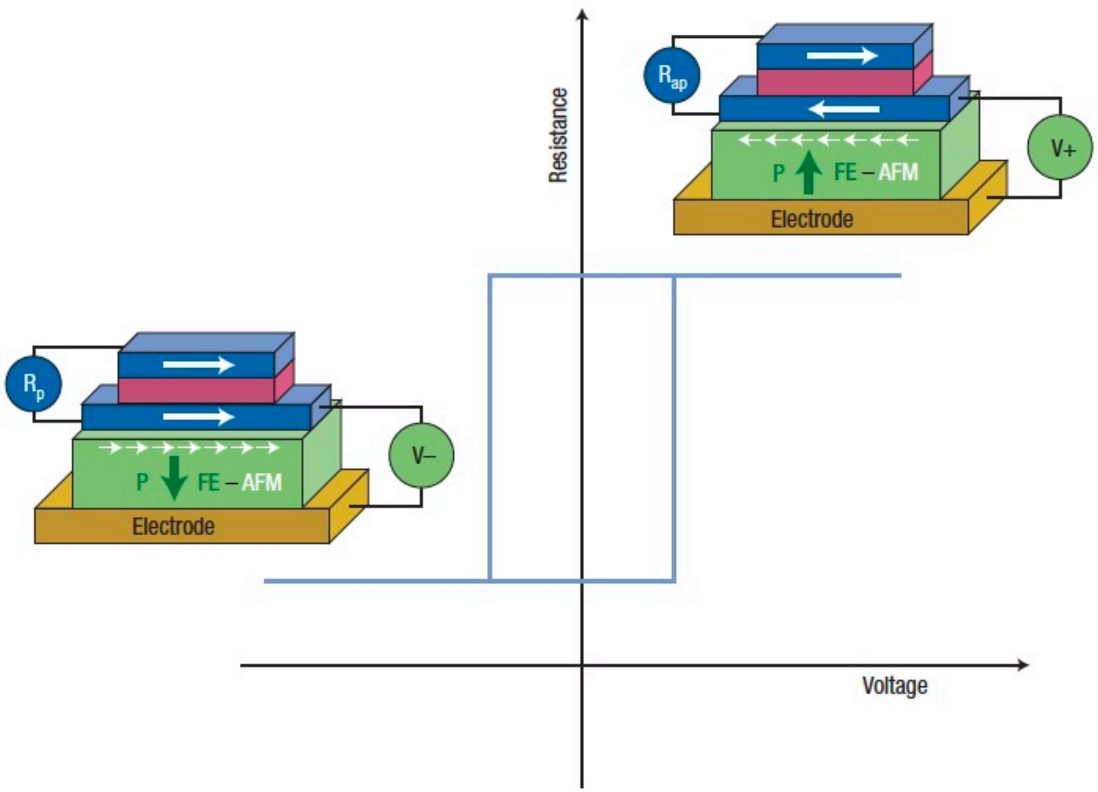


New Field of science: Spintronics

Nobel Prize 2007

A. Fert et al. (1988), P. Grünberg et al. (1989)

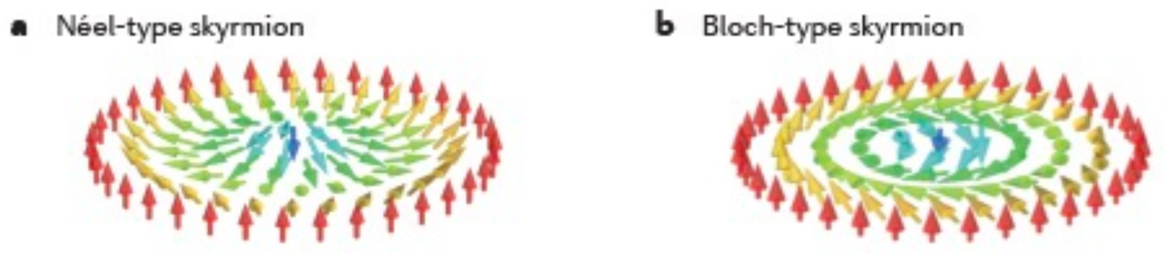
The multiferroic RAM



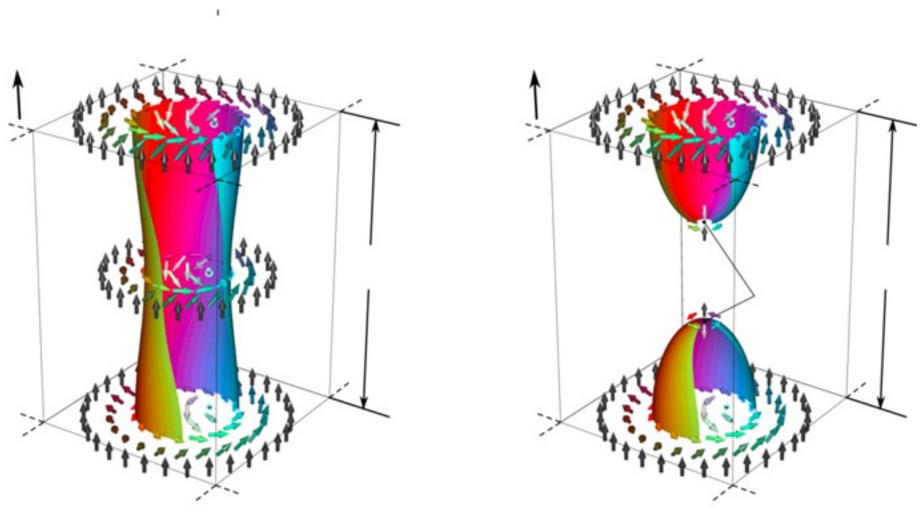
M. Bibes and A. Barthélémy, Nat. Mat. (2008)

Fast, dense, energy-efficient

Magnetic skyrmions in thin films



A. Fert et al. Nature Reviews Materials (2017)



Rybakov et al, NJP (2016)

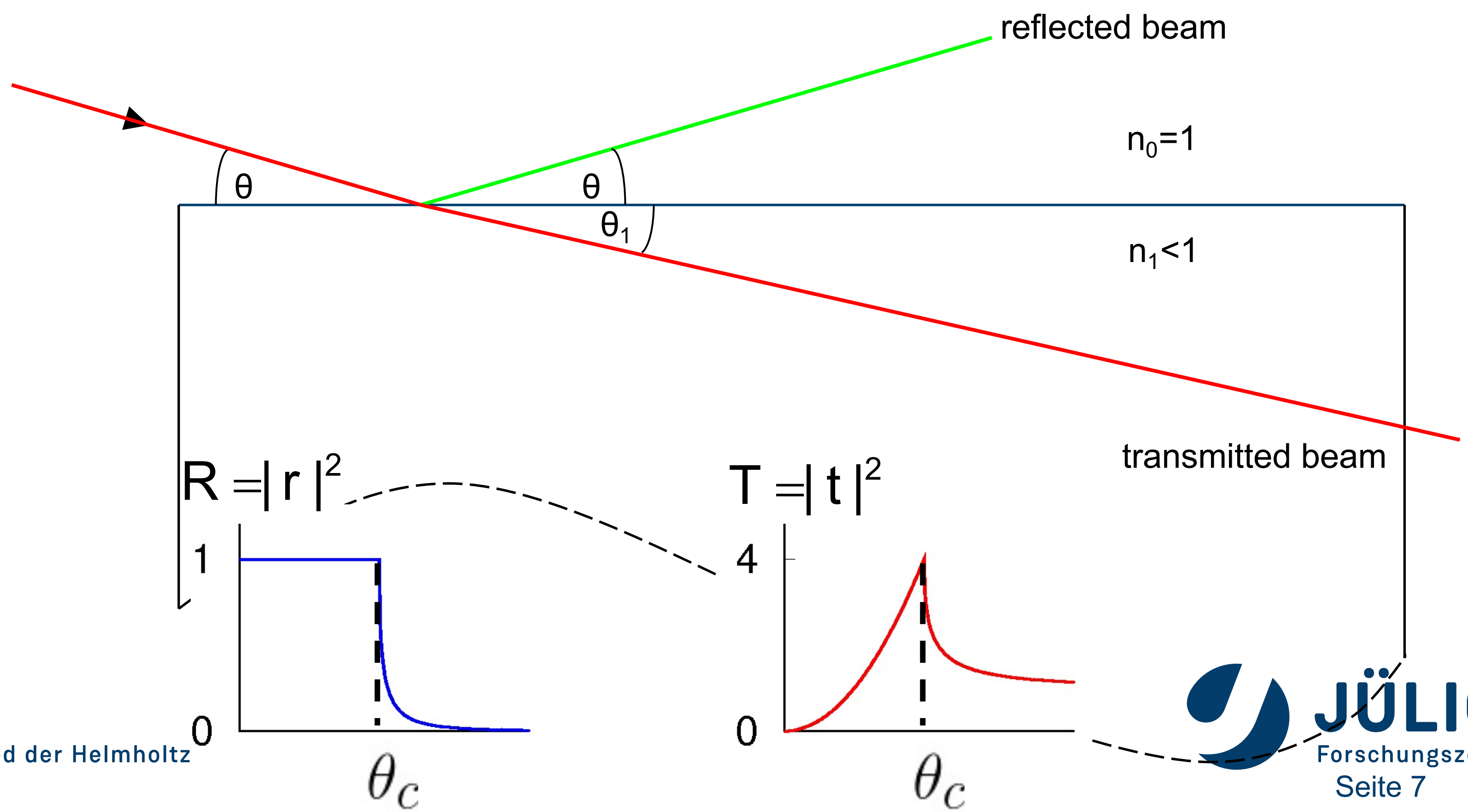
PLAN

- Introduction: Spintronics
- **Method: Reflectivity, off-specular scattering, GISAS and neutron polarization analysis**
- Simulation of specular reflectivity
- Simulation of polarized neutron reflectivity
- Simulation of GISAS intensities within the Distorted Wave Born Approximation
- Structural ordering in assemblies of magnetic nanoparticles
- Magnetic domain structure in FePd with perpendicular-to-plane anisotropy
- Take-Home Message

SPECULAR REFLECTIVITY: FLAT SURFACE

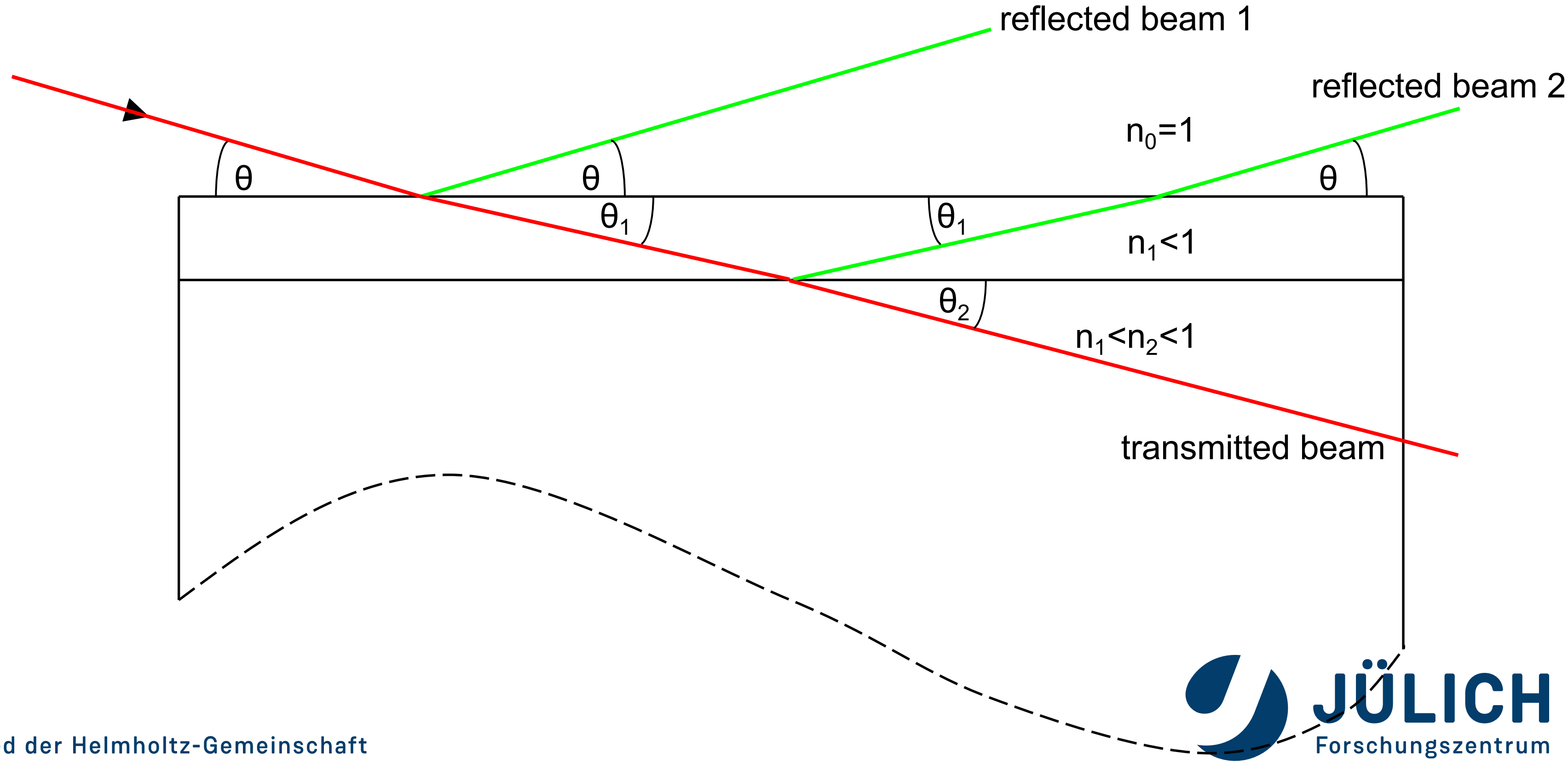
Refraction: $\theta_1 < \theta$, if $n_1 < n_0$

typically n < 1 for neutrons and x-rays



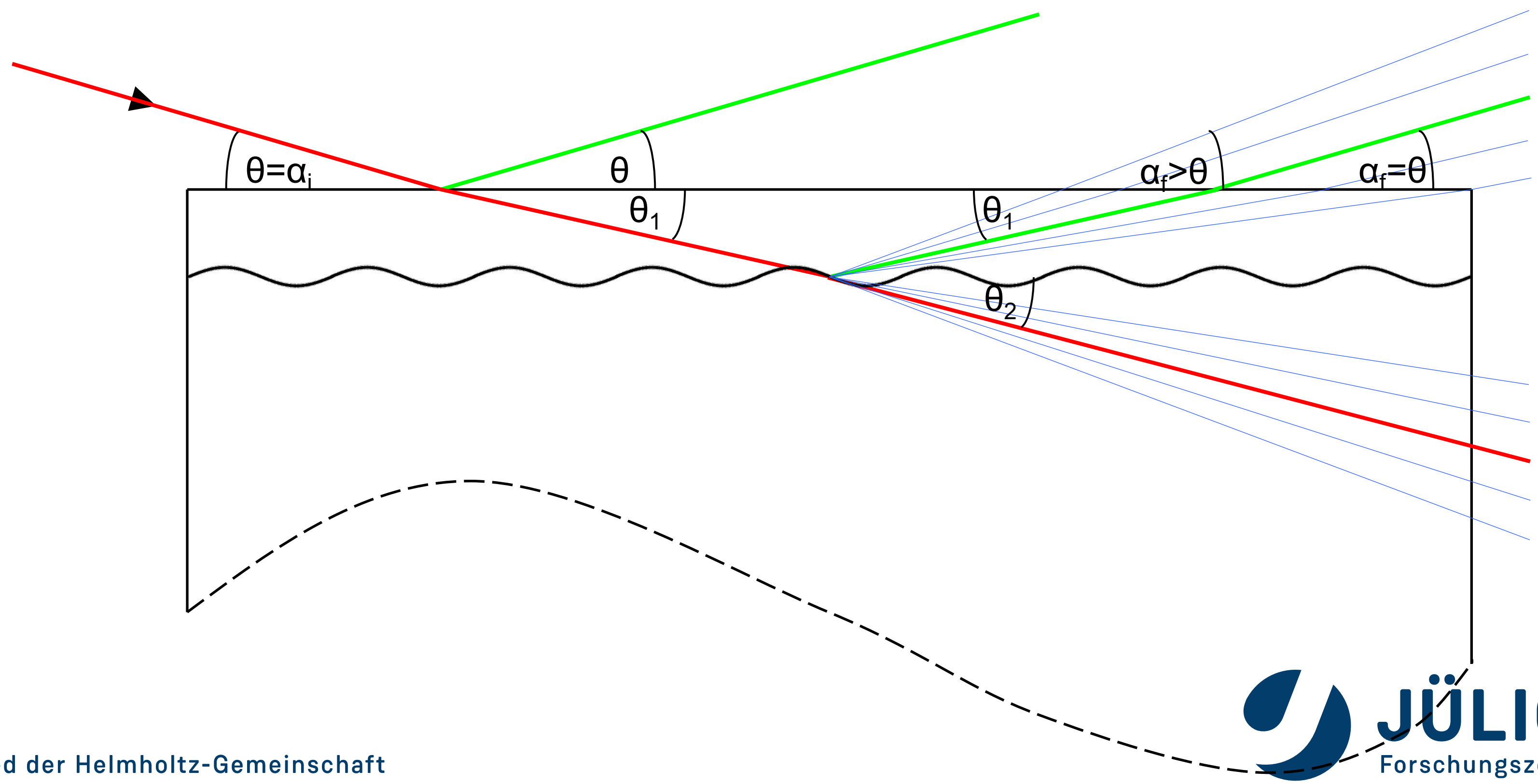
SPECULAR REFLECTIVITY: LAYER ON SURFACE

Interference between reflected beams according to path length difference



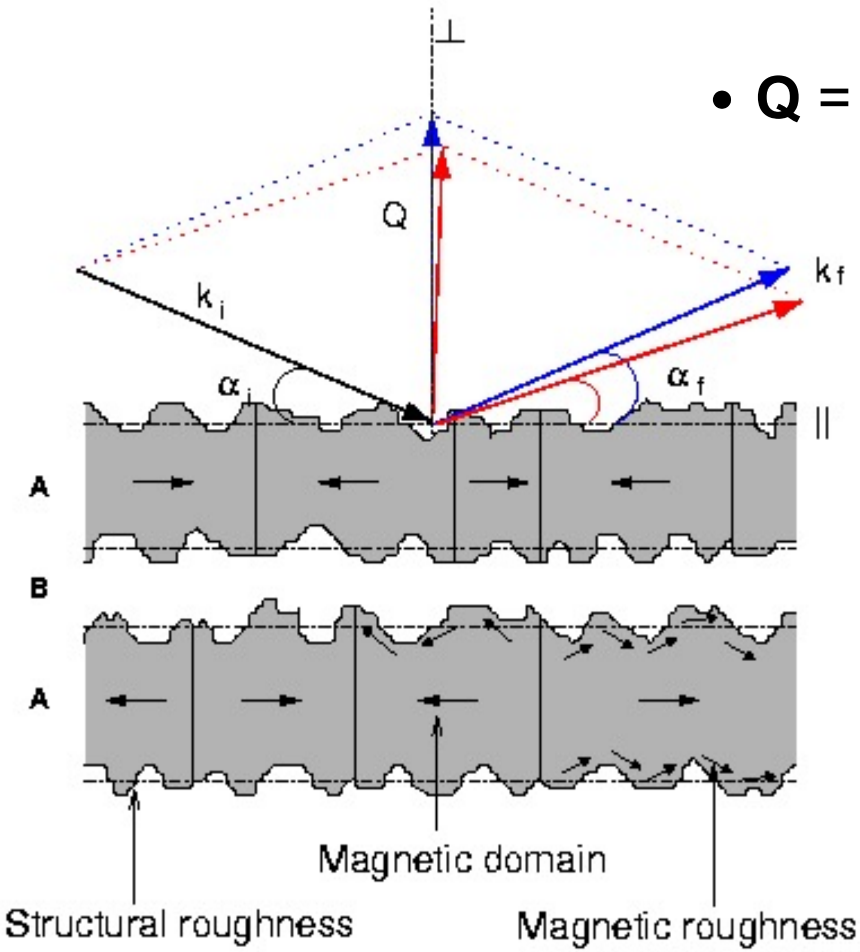
OFF-SPECULAR SCATTERING: ROUGH INTERFACE

Broken translational invariance
→ Off-specular (diffuse) scattering



REFLECTIVITY AND OFF-SPECULAR SCATTERING

- In-plane structure can be investigated by off-specular diffuse scattering:



- $\mathbf{Q} = \mathbf{k}_f - \mathbf{k}_i$, $k = 2\pi / \lambda$

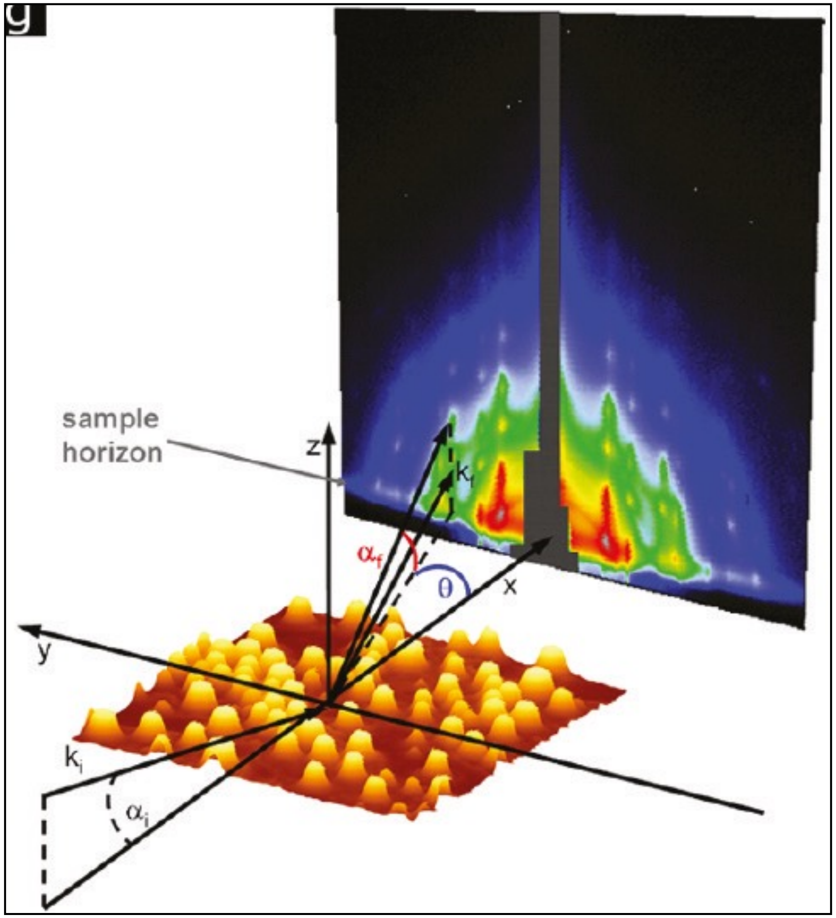
If $\alpha_f = \alpha_i$ then $Q_{||} = 0$:

- specular reflectivity
- average over lateral coordinates

If $\alpha_f \neq \alpha_i$ then $Q_{||} \neq 0$:

- off-specular scattering
- lateral correlations can be probed

Grazing Incidence Small Angle Scattering (GISAS)



$$\boldsymbol{Q} = \boldsymbol{k}_f - \boldsymbol{k}_i = \begin{cases} Q_x \cong k.(\alpha_i{}^2 - \alpha_f{}^2 - \theta^2) \\ Q_y \cong k.\theta \\ Q_z \cong k.(\alpha_i + \alpha_f) \end{cases}$$

$$\text{typically:} \begin{cases} 2\pi / Q_x \approx 1\text{–}20\ \mu m \\ 2\pi / Q_y \approx 1\text{-}300\ nm \end{cases}$$

(neutrons!)

S. Disch, E. Wetterskog et al. Nano Letters **11**, 1651 (2011)

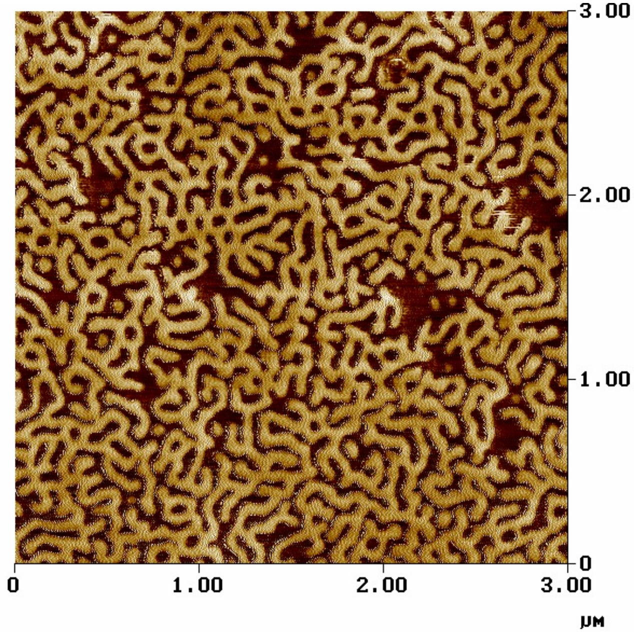
dPS-PB diblock copolymer

(D. Korolkov et al. J. Appl. Cryst. 45, 245 (2012))

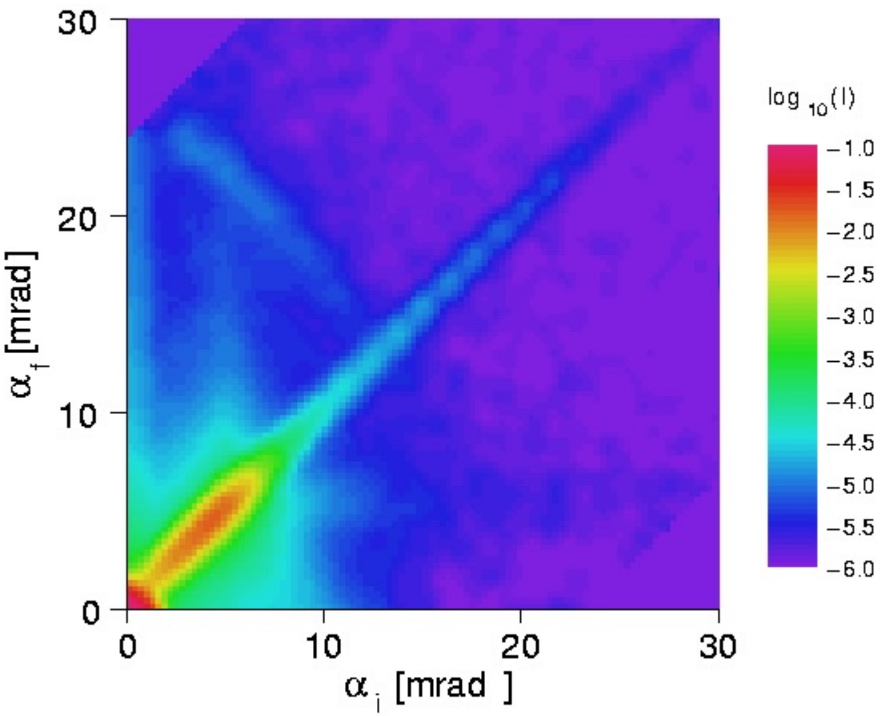
Polymer preparation:

- f = 0.5 → Lamellae
- High Mw → ⊥ ordering

AFM (3x3 μm²):



Off-specular on HADAS@Jülich (now TREFF@MLZ)



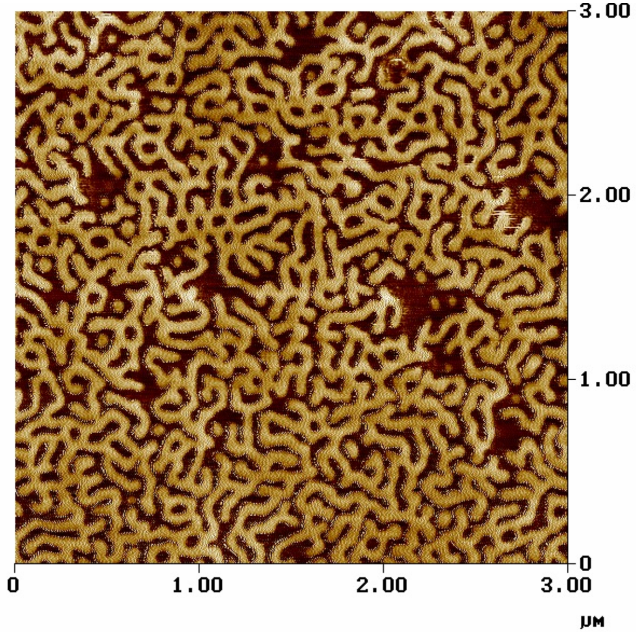
dPS-PB diblock copolymer

(D. Korolkov et al. J. Appl. Cryst. 45, 245 (2012))

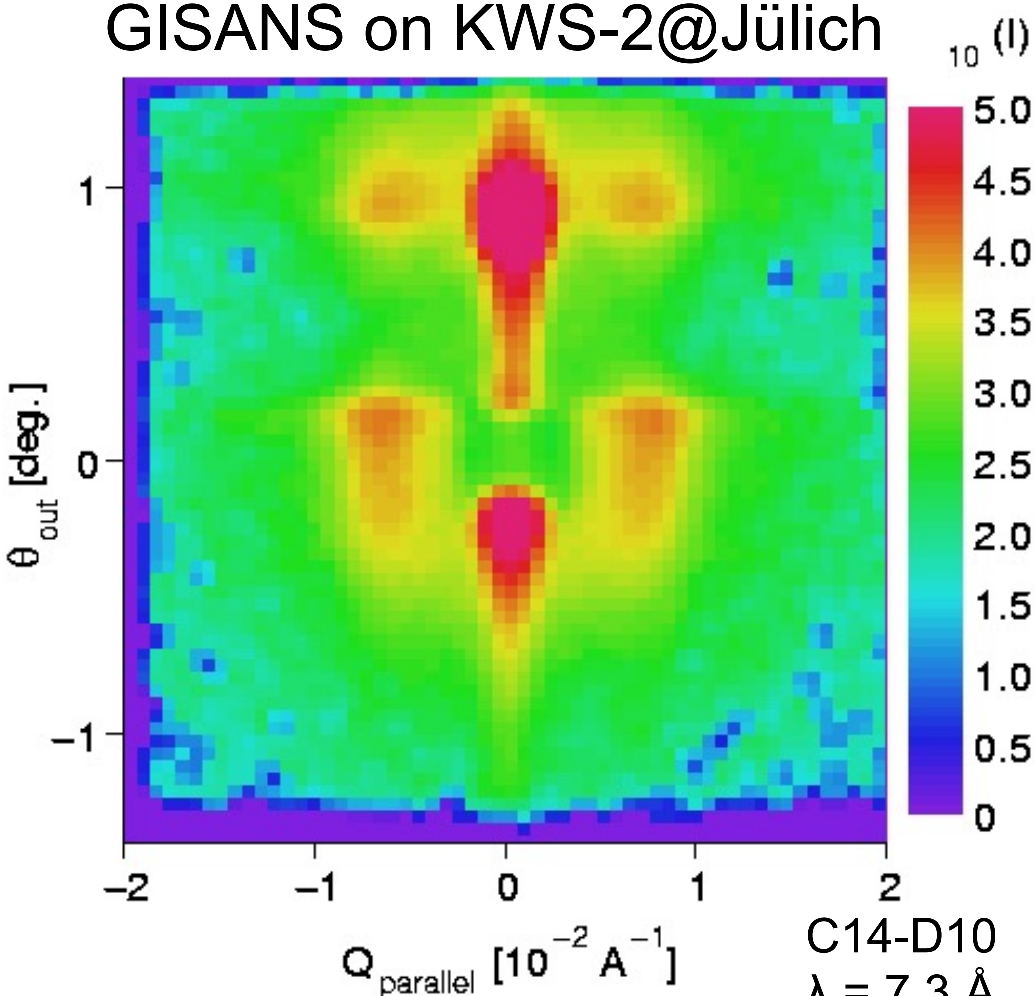
Polymer preparation:

- f = 0.5 → Lamellae
- High Mw → ⊥ ordering

AFM (3x3 μm²):



GISANS on KWS-2@Jülich



C14-D10
λ = 7.3 Å

dPS-PB diblock copolymer

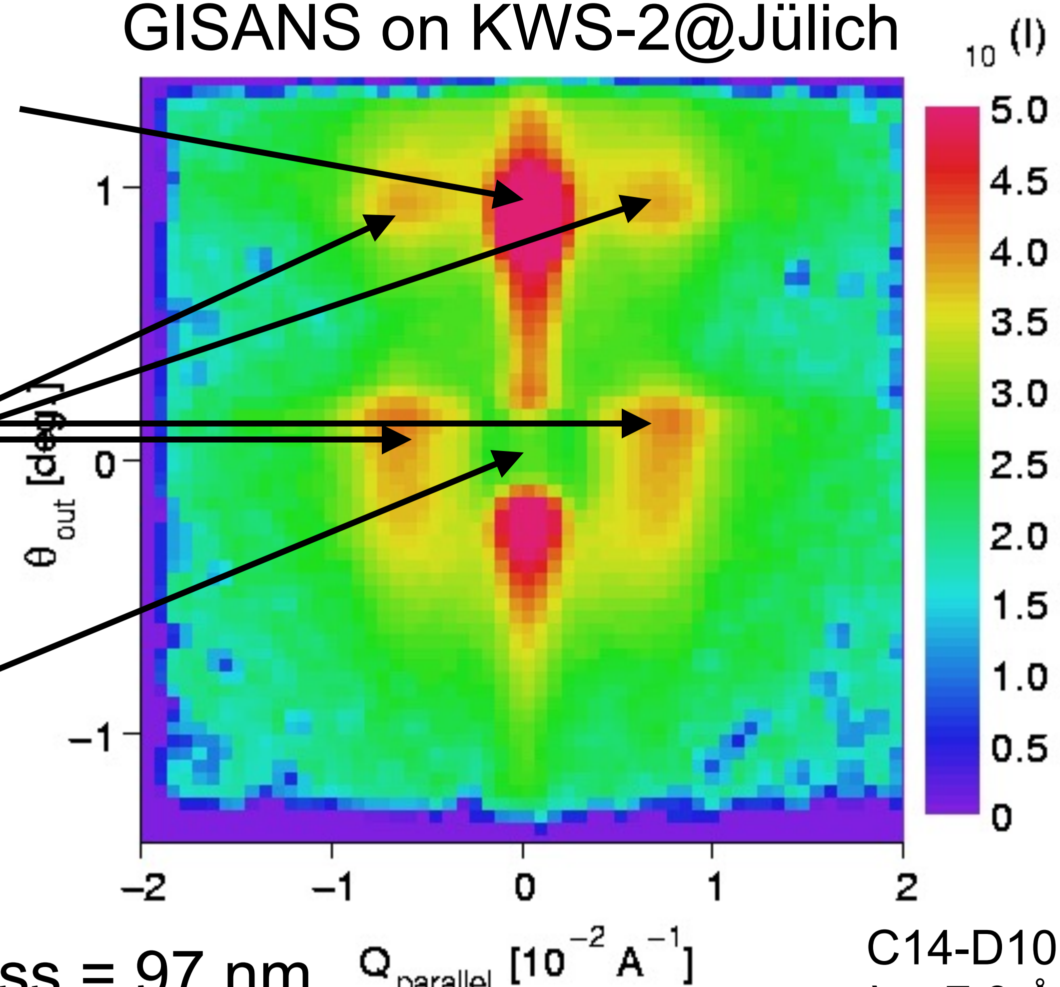
(D. Korolkov et al. J. Appl. Cryst. 45, 245 (2012))

GISANS on KWS-2@Jülich

Specularly reflected beam

Out-of-plane scattering due to perpendicular lamellae

Direct beam covered by beam stop



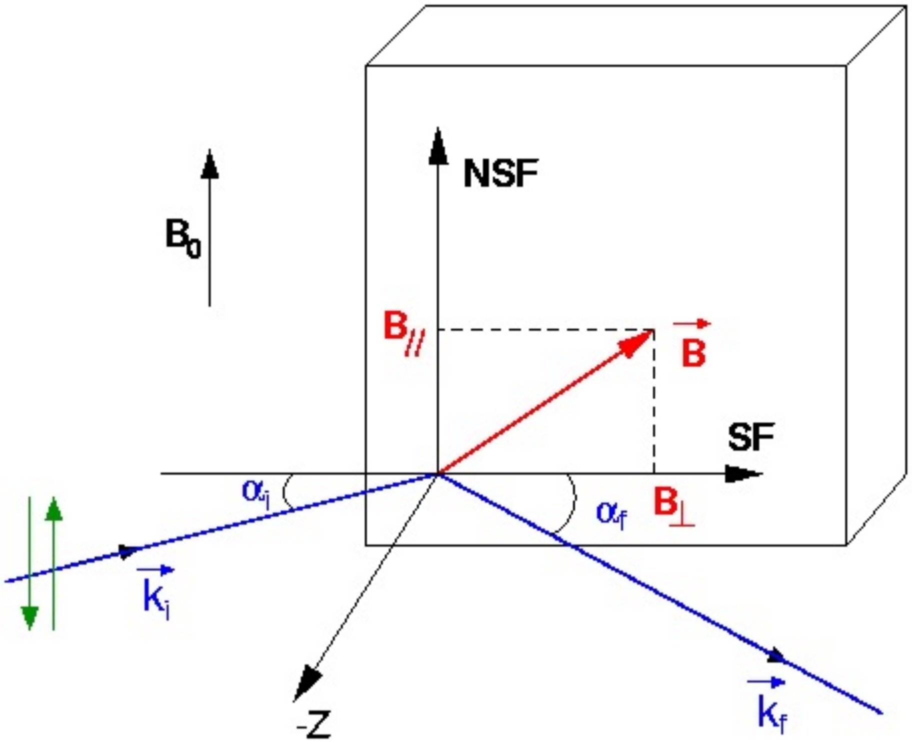
C14-D10
$\lambda = 7.3$ Å

→ Effective *lamellae* thickness = 97 nm

Polarization analysis

The neutron is a spin ½ particle

$$\left|\Psi_{\text{l}}(\mathbf{r})\right\rangle = \Psi_{\text{l}}^{+}(\mathbf{r})\left|+\right\rangle + \Psi_{\text{l}}^{-}(\mathbf{r})\left|-\right\rangle$$

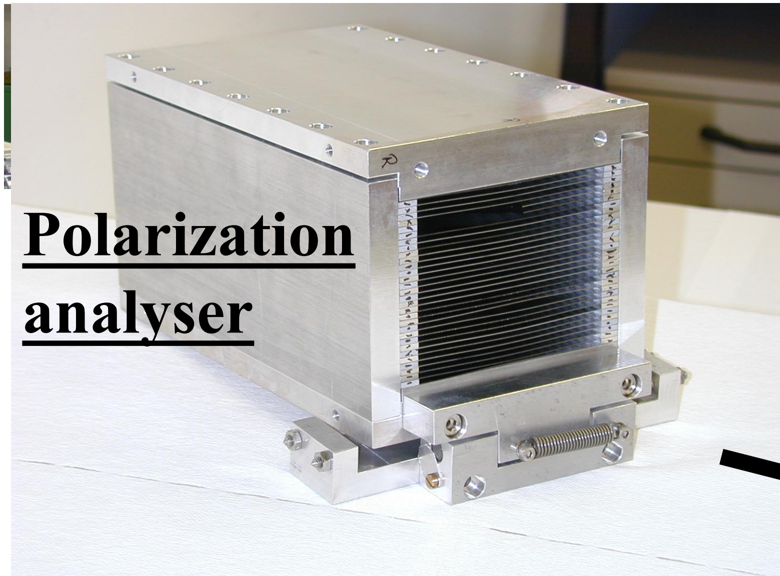


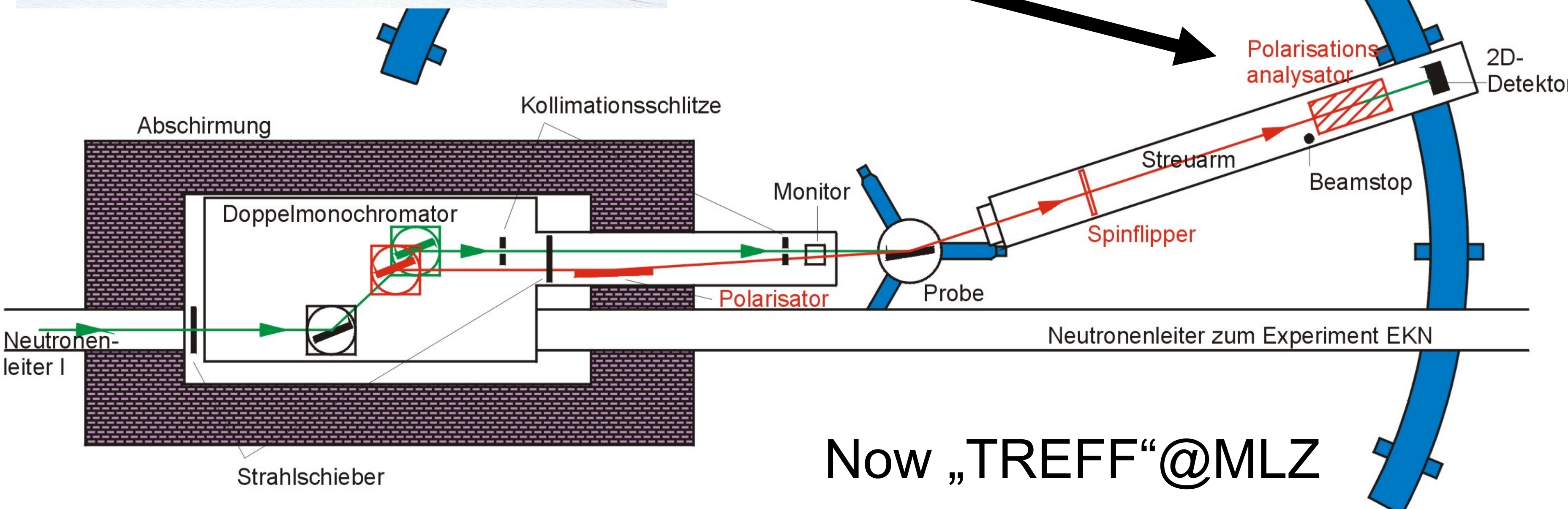
$$I_{++}, I_{--} \Rightarrow \rho_I^N, B_{//}$$

$$I_{+-}, I_{-+} \Rightarrow B_\perp$$

Polarization analysis… HADAS@Jülich (U. Rücker)

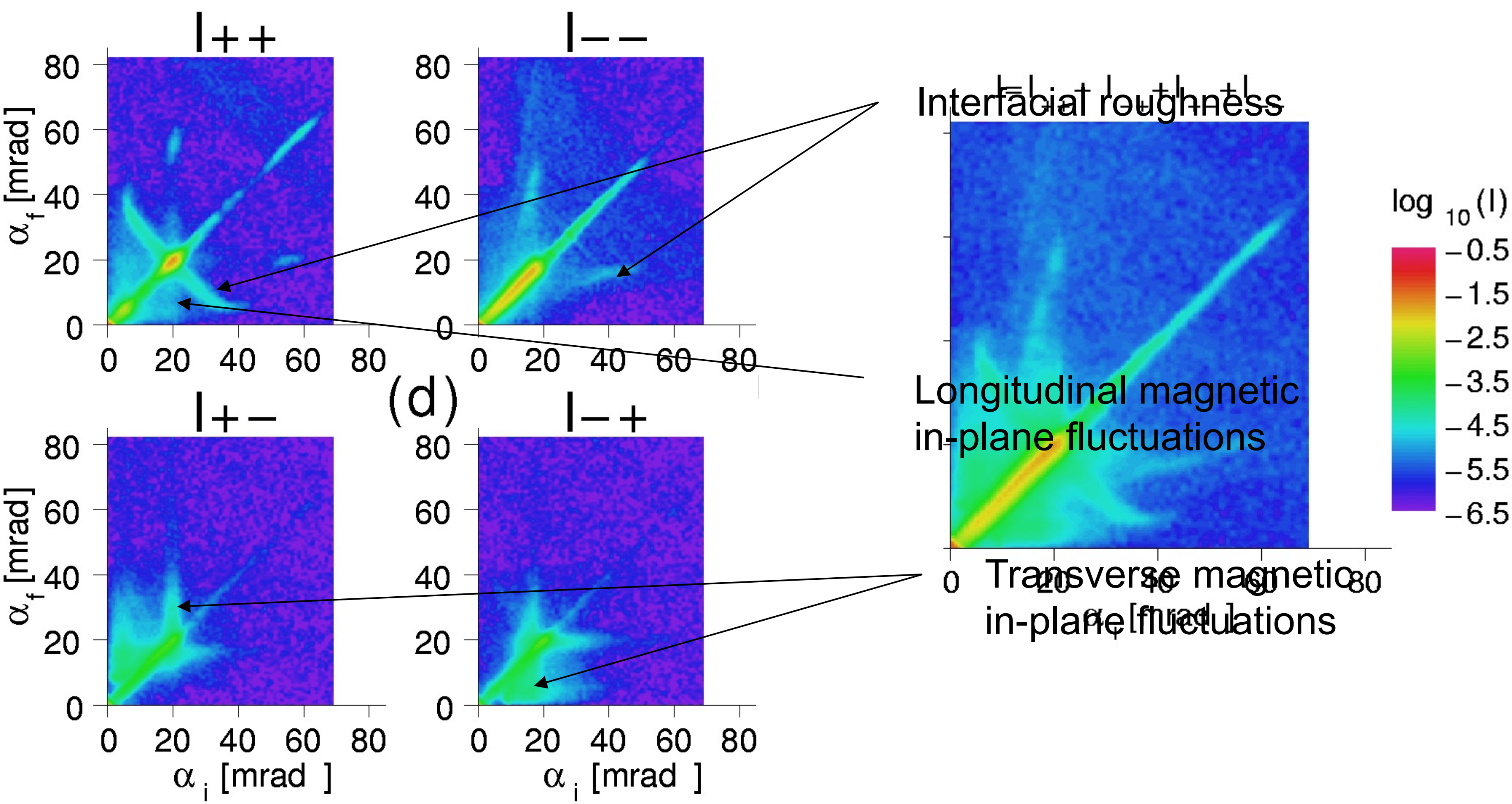
Simulataneous measurement of reflectivity and off-specular scattering with polarization analysis





Now „TREFF"@MLZ

Remnant Polarizing Supermirror

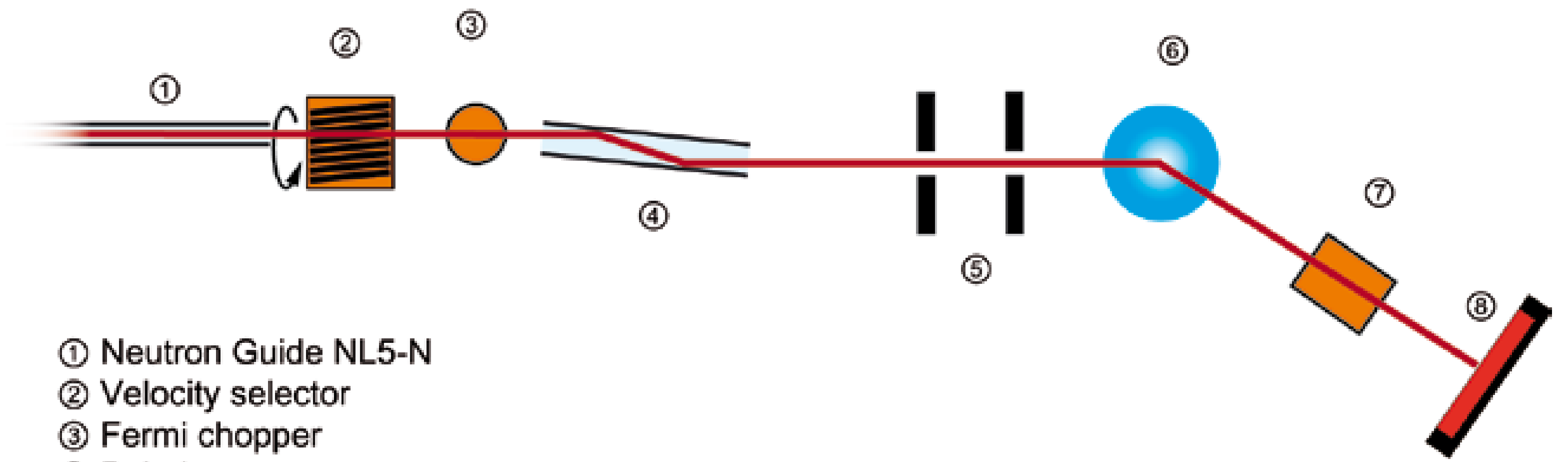


With polarization analysis

Without analysis

E. Kentzinger, U.Rücker, B. Toperverg, F. Ott, Th. Brückel, PRB 77, 104435 (2008)

MARIA @ MLZ (S. Mattauch)

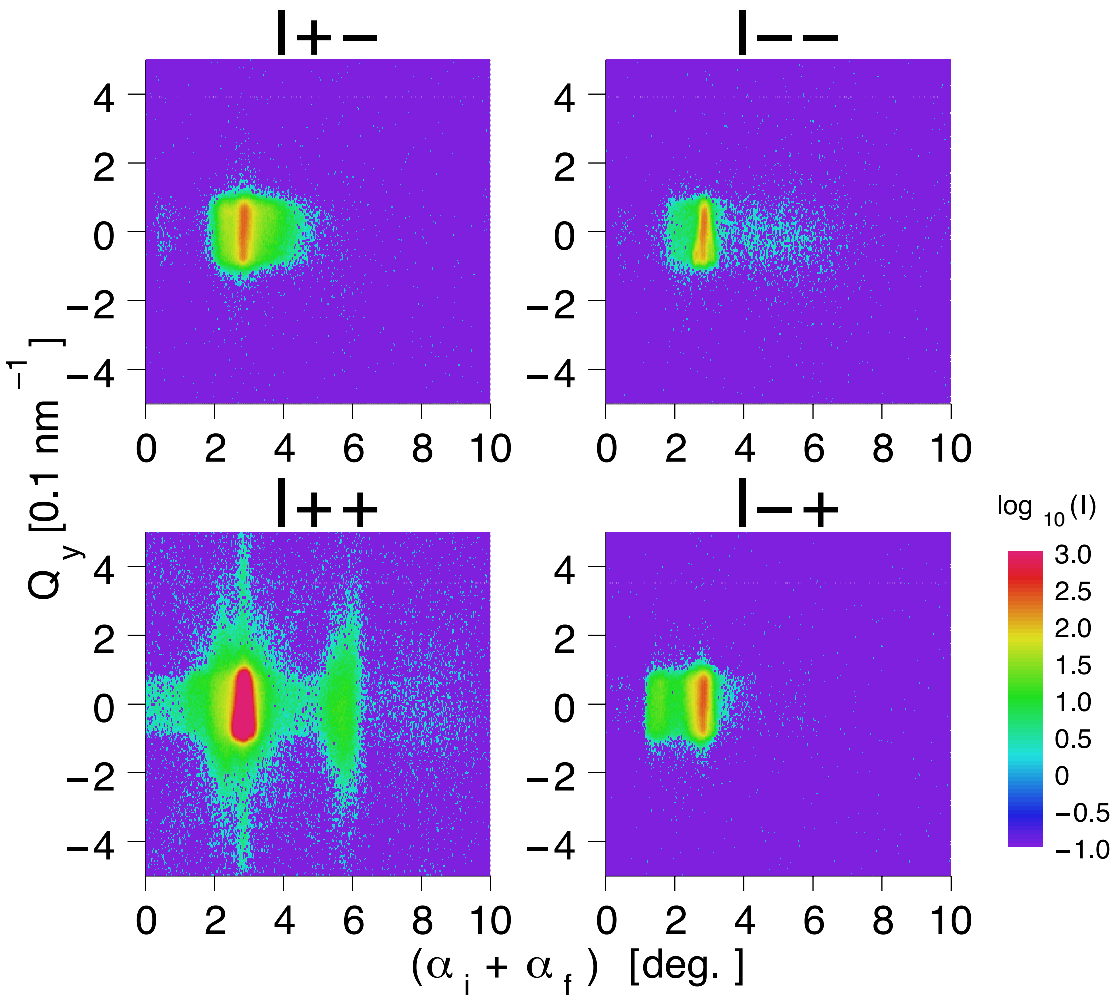


① Neutron Guide NL5-N
② Velocity selector
③ Fermi chopper
④ Polarizer
⑤ Slit pair
⑥ Hexapod sample table
⑦ Polarization analyzer (^3He)
⑧ Detector

GISANS WITH POLARIZATION ANALYSIS @ MARIA

$\alpha i = 1.5°$

$\mu_0 H = 4.4$ mT



PLAN

- Introduction: Spintronics
- Method: Reflectivity, off-specular scattering, GISAS and neutron polarization analysis
- **Simulation of specular reflectivity**
- Simulation of polarized neutron reflectivity
- Simulation of GISAS intensities within the Distorted Wave Born Approximation
- Structural ordering in assemblies of magnetic nanoparticles
- Magnetic domain structure in FePd with perpendicular-to-plane anisotropy
- Take-Home Message

INTERACTION OF NEUTRONS AND X-RAYS WITH MATTER IN THE CONTINUUM LIMIT

Schrödinger equation for the wave function of the neutron:

$$\left[-\frac{\hbar^2}{2m}\Delta + V(\mathbf{r})\right]\psi(\mathbf{r}) = E\psi(\mathbf{r})$$

$$E = \hbar^2 k^2/(2m)$$

$$k = 2\pi/\lambda$$

Interaction potential in layer 1:

$$V_1(\mathbf{r}) = V_1 = \frac{2\pi\hbar^2}{m}\rho$$

neutrons

$$\rho = \sum_j N_j (b'_j - i b''_j)$$

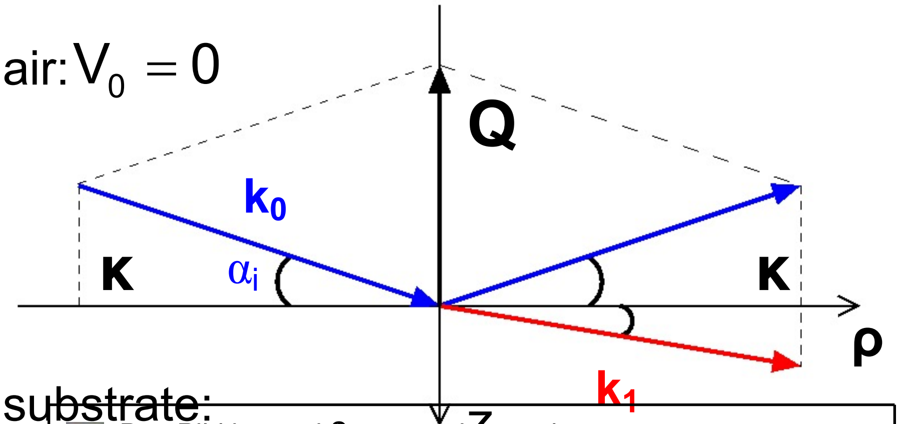
X-rays

$$\rho = r_0 \sum_j N_j (Z_j + f'_j - i f''_j)$$

$$r_0 = 2.82\ fm$$

Reflection/refraction on a flat interface

air: $V_0 = 0$



substrate:

Das Bild kann nicht angezeigt werden.

$$V_1 = \frac{2\pi\hbar^2}{m}\rho^N$$

Solutions of the Schödinger equation:

$$\Psi_0(\mathbf{r}) = e^{i\boldsymbol{\kappa}.\boldsymbol{\rho}}\left(e^{ik_{z,0}.z} + e^{-ik_{z,0}.z}\, r\right)$$

with: $\mathbf{k}_0^2 = \boldsymbol{\kappa}^2 + \mathbf{k}_{z,0}^2 = 2mE/\hbar^2$

$$\Psi_1(\mathbf{r}) = e^{i\boldsymbol{\kappa}.\boldsymbol{\rho}}\left(e^{ik_{z,1}.z}\, t\right)$$

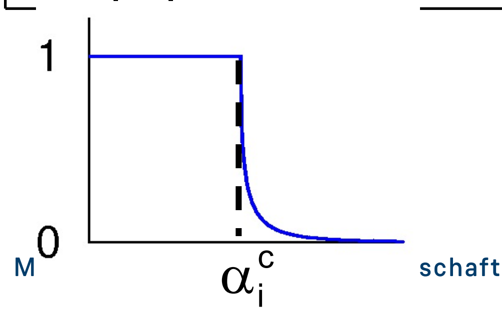
with: $\mathbf{k}_{z,1}^2 = \mathbf{k}_{z,0}^2 - 4\pi\rho^N$

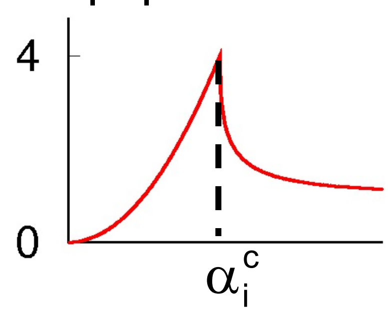
Continuity of Ψ and $\partial\Psi/\partial z$ at interface:

$$r = \frac{k_{z,0} - k_{z,1}}{k_{z,0} + k_{z,1}} \quad \text{and} \quad t = \frac{2k_{z,0}}{k_{z,0} + k_{z,1}}$$

$$\mathbf{k}_{z,0}^c = \sqrt{4\pi\rho^N} \;\Big/\; \alpha_i^c = \lambda\sqrt{\rho^N/\pi}$$

$R = |r|^2$ $\quad$ $T = |t|^2$

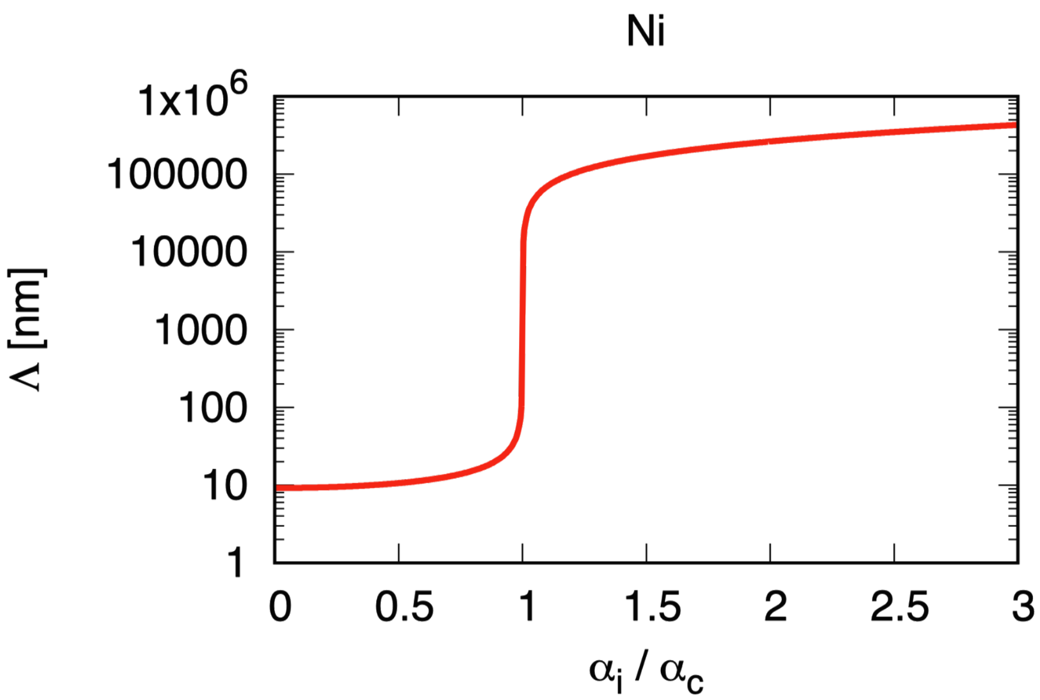




If $\alpha_i < \alpha_i^c$:

- Evanescent wave in the substrate
- Total external reflection
- Small penetration depth

Penetration depth in the substrate: $$\Lambda = \frac{1}{k''_{z,1}}$$



(neutrons)

LAYERS ON SUBSTRATE

Wave function in layer l:

$$\Psi_l(\mathbf{r}) = \mathbf{e}^{\mathbf{i}\kappa\rho}(\mathbf{e}^{\mathbf{ik_{z,l}.z}}\ \mathbf{t_l} + \mathbf{e}^{-\mathbf{ik_{z,l}.z}}\ \mathbf{r_l})$$

N layers

→ 2(N+2) coefficients have to be determined

Continuity of Ψ and $\partial\Psi/\partial$z at interfaces:

→ 2(N+1) equations

$$t_0 = 1$$

$$r_{N+1} = 0$$

➔ Solvable (recursively)

REFLECTIVITY FROM A LAYER ON SUBSTRATE

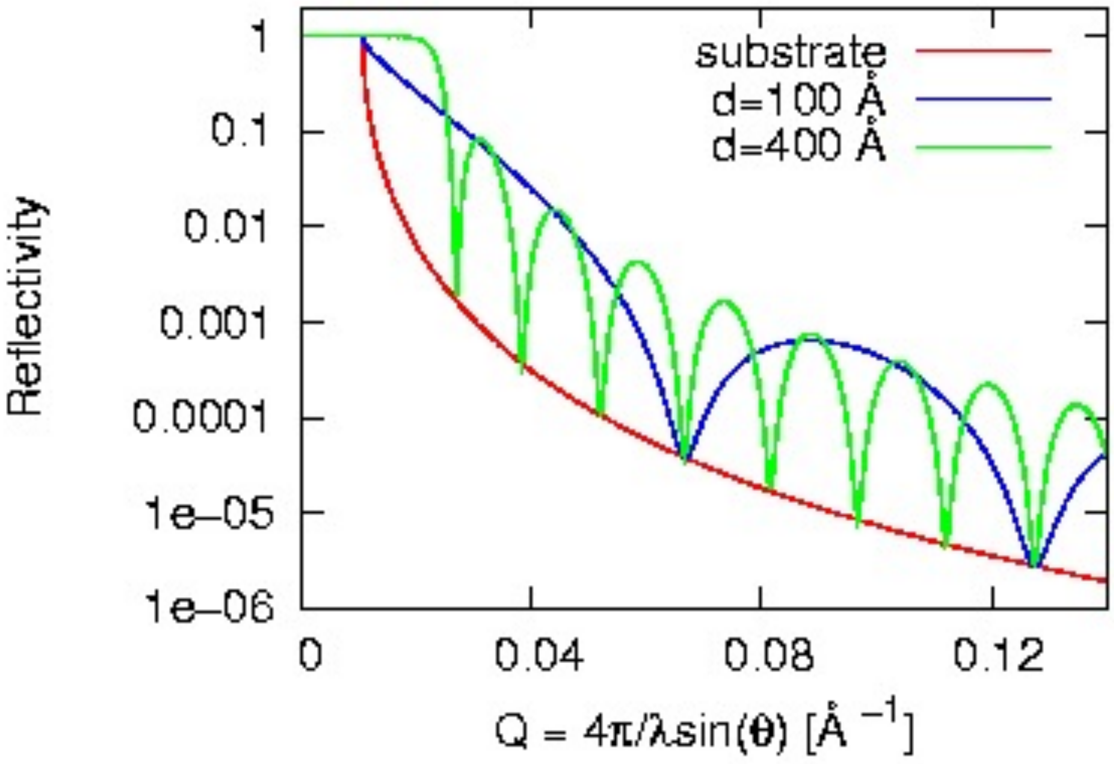
Optical path length difference between beams reflected at surface and interface:

$$\Delta = 2d \sin\theta$$

→ Distance between interference maxima:

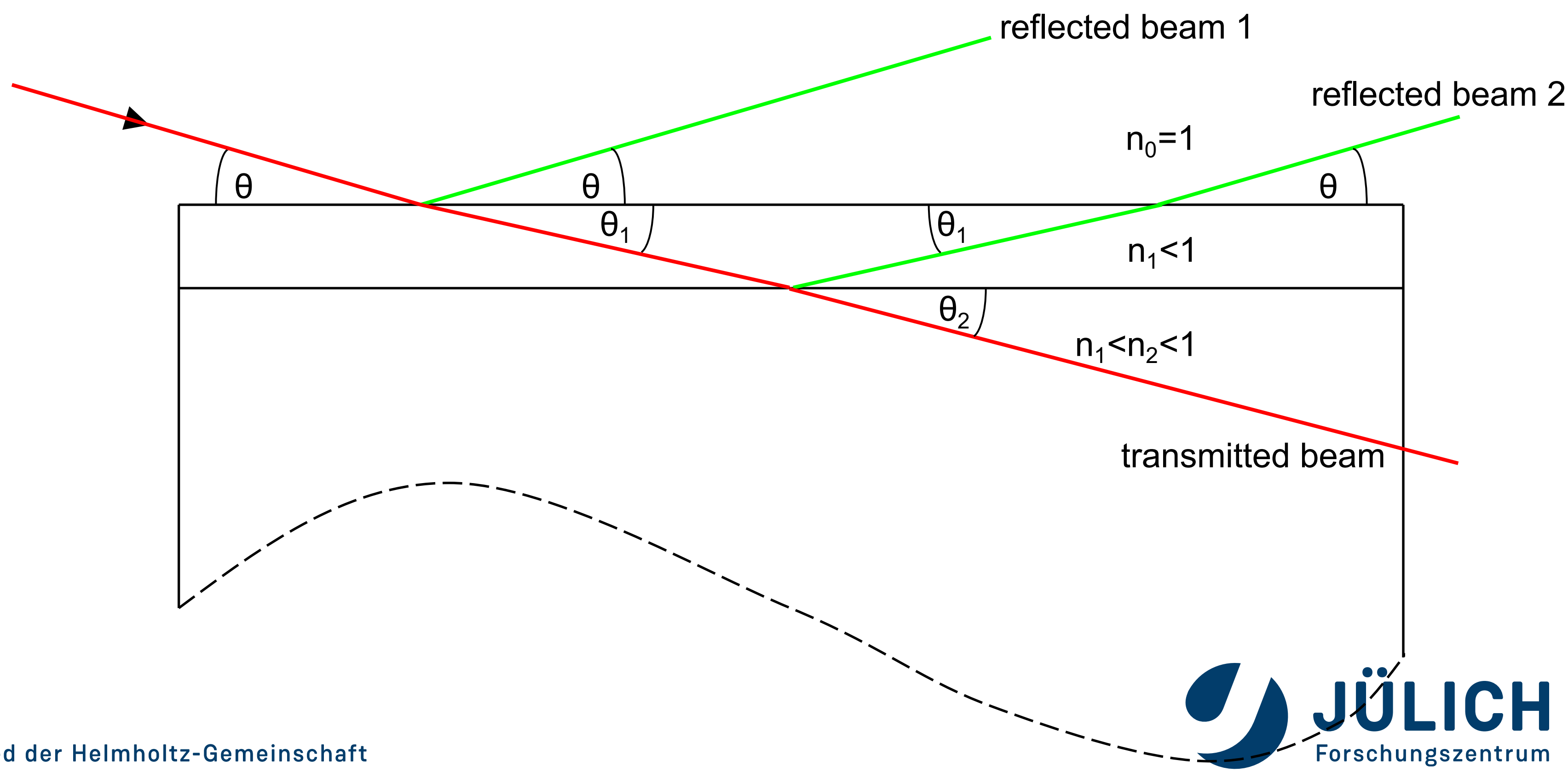
$$\delta Q \simeq \frac{2\pi}{d}$$

Ni layer on Si substrate



SPECULAR REFLECTIVITY: LAYER ON SURFACE

Interference between reflected beams according to path length difference



REFLECTIVITY FROM A LAYER ON SUBSTRATE

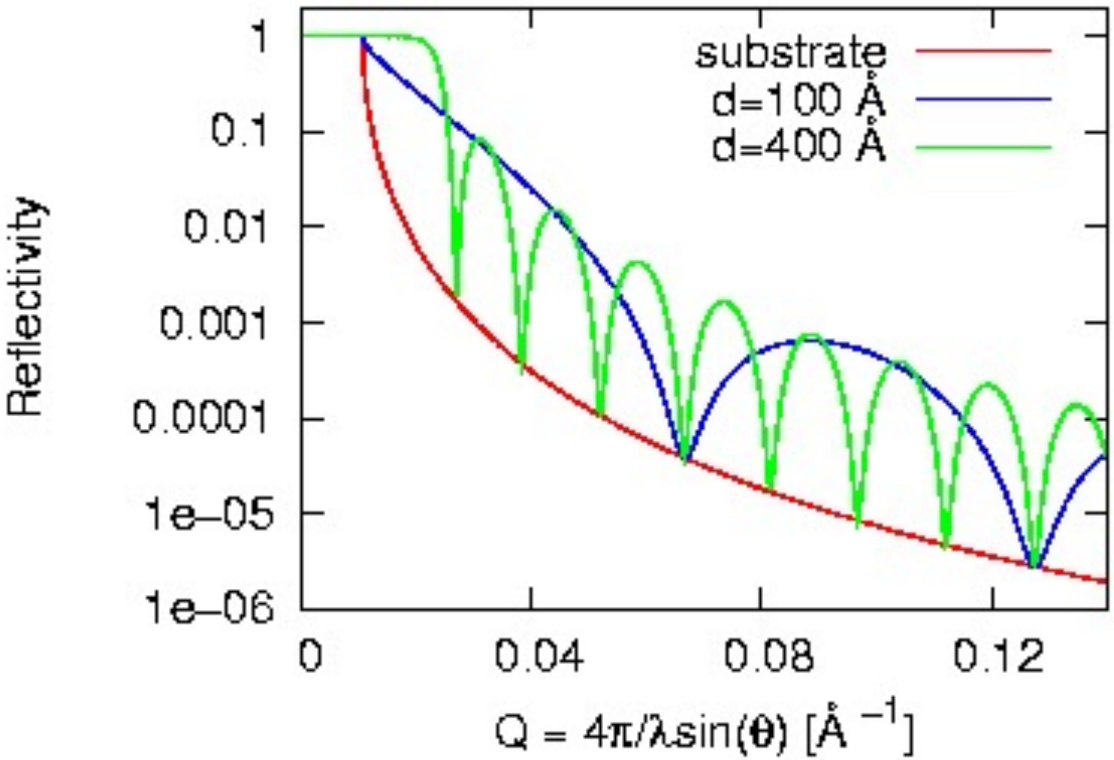
Optical path length difference between beams reflected at surface and interface:

$$\Delta = 2d \sin\theta$$

→ Distance between interference maxima:

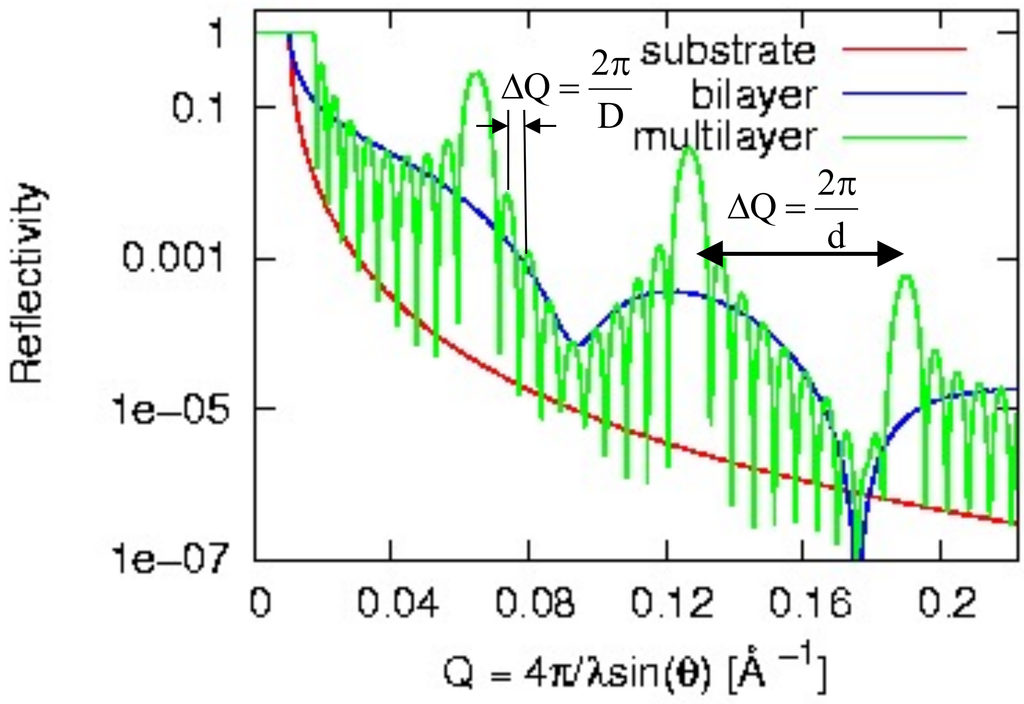
$$\delta Q \simeq \frac{2\pi}{d}$$

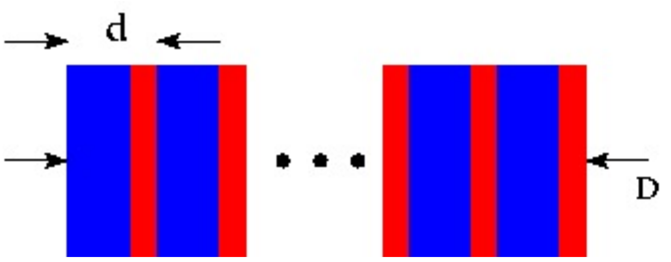
Ni layer on Si substrate



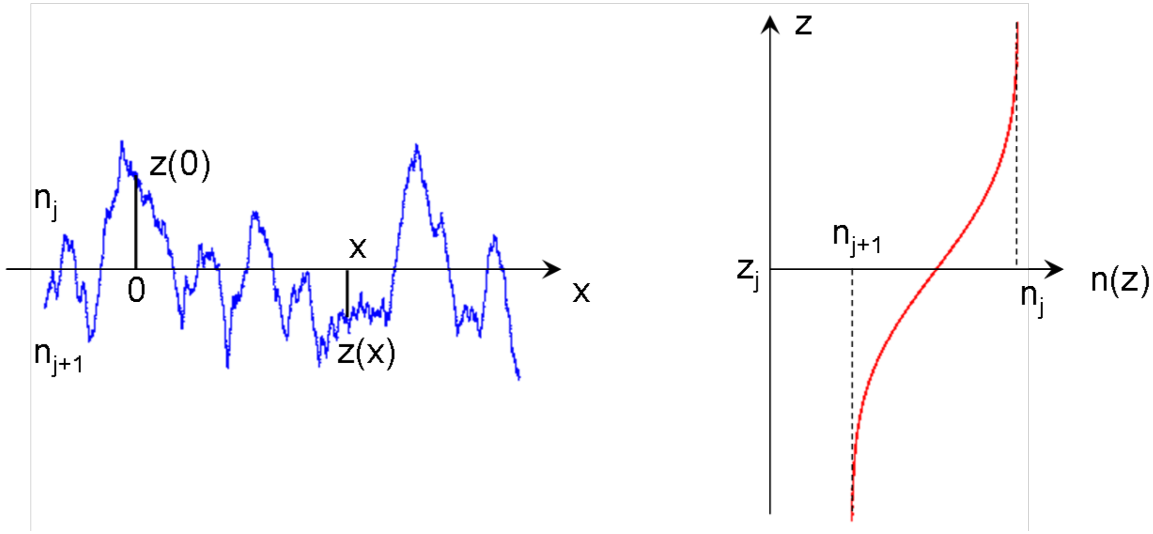
REFLECTIVITY FROM A MULTILAYER

10 Ni/Ti bilayers on Si





ROUGHNESS AND INTERDIFFUSION



z is a gaussian random variable with distribution function:

$$P(z) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{z^2}{2\sigma^2}\right),$$

→ Profile of refraction index between layers j and j+1:

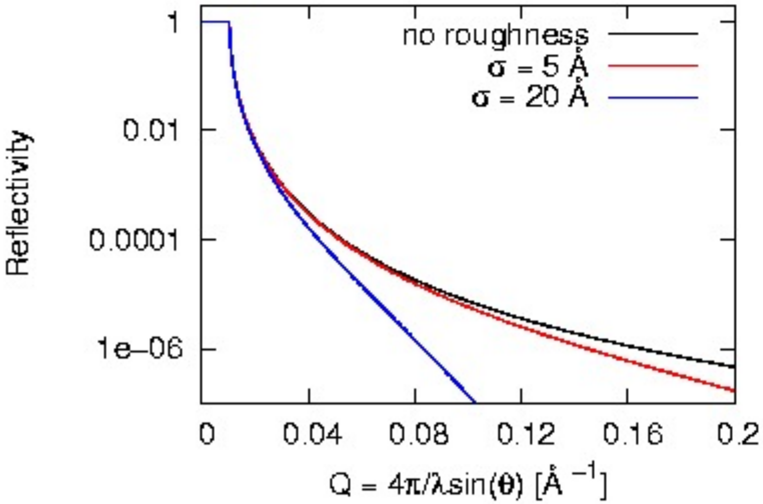
$$n(z) = \frac{n_j + n_{j+1}}{2} - \frac{n_j - n_{j+1}}{2} \mathrm{erf}\left(\frac{z - z_j}{\sqrt{2}\sigma_j}\right)$$ with: $$\mathrm{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt.$$

ROUGHNESS AND INTERDIFFUSION

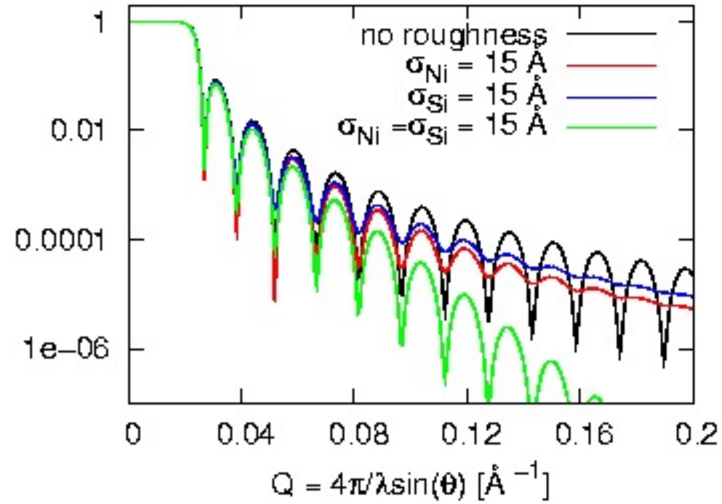
Reflectivity from such a surface obtained by averaging:

$$R_{rough} = R_{flat} \cdot \exp\left(-4\sigma_j^2 k_{zj} k_{zj+1}\right).$$

Si substrate



Ni on Si



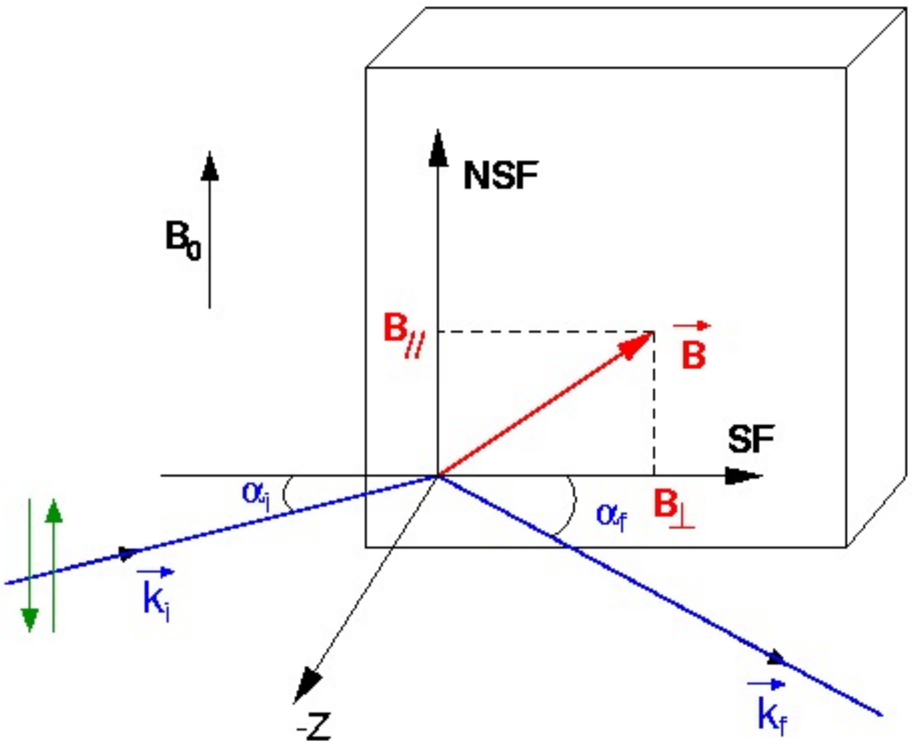
PLAN

- Introduction: Spintronics
- Method: Reflectivity, off-specular scattering, GISAS and neutron polarization analysis
- Simulation of specular reflectivity
- **Simulation of polarized neutron reflectivity**
- Simulation of GISAS intensities within the Distorted Wave Born Approximation
- Structural ordering in assemblies of magnetic nanoparticles
- Magnetic domain structure in FePd with perpendicular-to-plane anisotropy
- Take-Home Message

Interaction of polarized neutrons with magnetic thin films

The neutron is a spin ½ particle

$$|\Psi_l(\mathbf{r})\rangle = \Psi_l^+(\mathbf{r})|+\rangle + \Psi_l^-(\mathbf{r})|-\rangle$$



$$\hat{V}_l^M = -\mu_n \hat{\boldsymbol{\sigma}} \cdot \mathbf{B}_l$$

$\hat{\boldsymbol{\sigma}}$ is the vector of Pauli matrices

Total interaction operator:

$$\hat{V}_l = \frac{2\pi\hbar^2}{m}\left(\rho_l^N \hat{1} + \rho_l^M \hat{\boldsymbol{\sigma}} \cdot \mathbf{b}_l\right)$$

- ρ_l^N is the nuclear scattering length density
- ρ_l^M is the magnetic scattering length density

$$I_{++}, I_{--} \Rightarrow \rho_l^N, B_{//}$$

$$I_{+-}, I_{-+} \Rightarrow B_{\perp}$$

Schrödinger equation

$$|\Psi_l(\mathbf{r})\rangle = \Psi_l^+(\mathbf{r})\,|+\rangle + \mathbf{\Psi_l^-}(\mathbf{r})\,|-\rangle = \begin{pmatrix} \Psi_l^+(\mathbf{r}) \\ \Psi_l^-(\mathbf{r}) \end{pmatrix}$$

$$\Psi_l^{+''}(z) + \left[k_{z,l}^2 - 4\pi\left(\rho_l^N + \rho_l^M b_{\parallel}\right)\right]\Psi_l^+(z) + 4i\pi\rho_l^M b_{\perp}\Psi_l^-(z) = 0$$

$$\Psi_l^{-''}(z) + \left[k_{z,l}^2 - 4\pi\left(\rho_l^N - \rho_l^M b_{\parallel}\right)\right]\Psi_l^-(z) - 4i\pi\rho_l^M b_{\perp}\Psi_l^+(z) = 0$$

Non-spin-flip

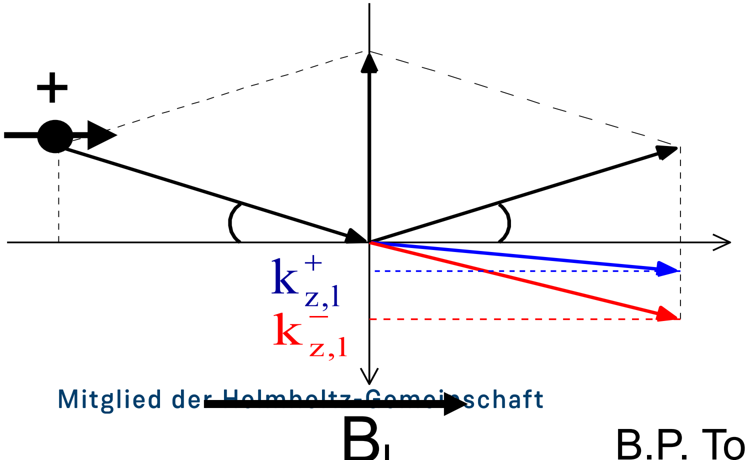
Spin-flip

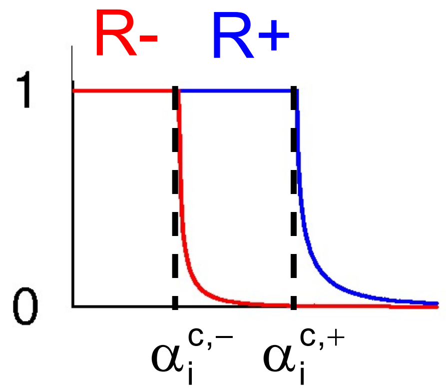
Neutron wave function in layer l

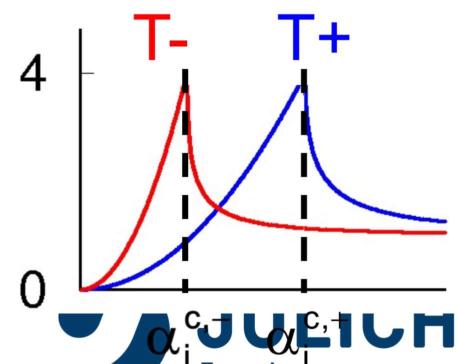
$$\left|\Psi_l(\mathbf{r})\right\rangle = e^{i\,\boldsymbol{\kappa\rho}}\left(e^{i\hat{k}_{z,l}.z}\,\hat{t}_l + e^{-i\hat{k}_{z,l}.z}\hat{r}_l\right)\left|\Psi_0\right\rangle$$

$$\hat{k}_{z,l} = \sqrt{\hat{k}_{z,0}^2 - 4\pi(\rho_l^N + \rho_l^M \hat{\boldsymbol{\sigma}}.\mathbf{b}_l)}$$

- $\hat{k}_{z,l}$, $\hat{t}_l$ and $\hat{r}_l$ have different eigenvalues depending on the projection of the spin on the quantization axis defined by $\mathbf{b}_l$ (i.e. $\hat{\boldsymbol{\sigma}}.\mathbf{b}_l = \pm 1$).



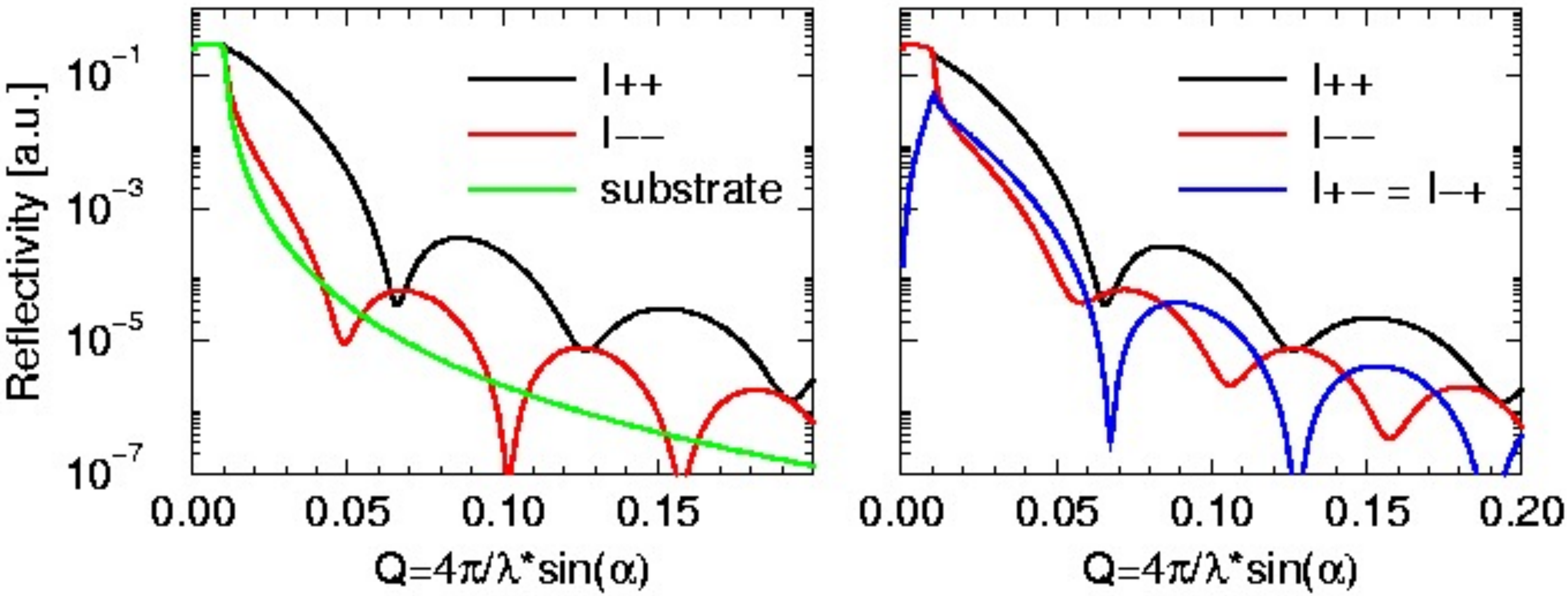




B.P. Toperverg, The Physics of Metals and Metallography (2015)

Magnetization collinear / non-collinear to B_0

M_{Fe} // B_0 **$(M_{Fe}, B_0) = 45°$**

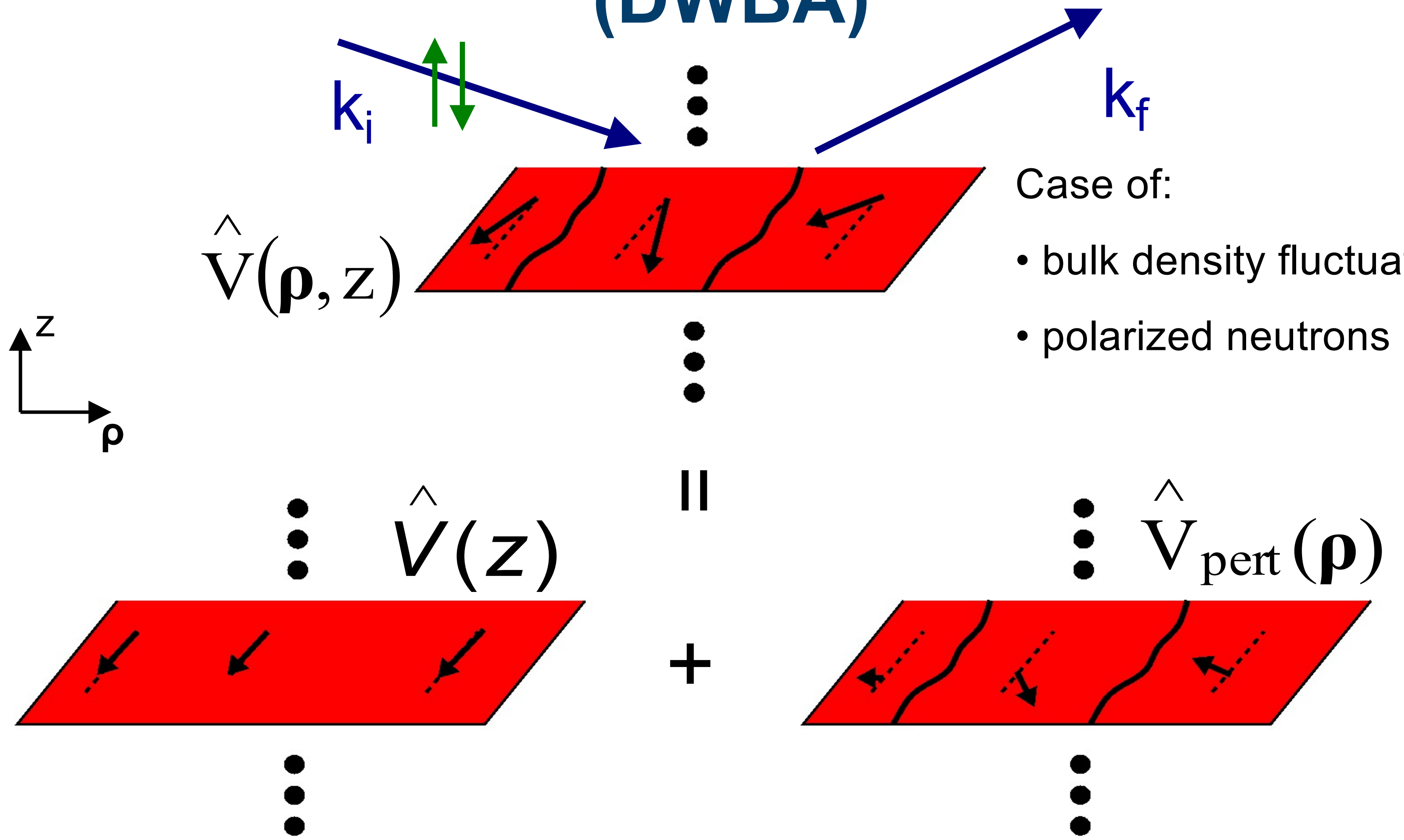


Fe (15 nm) / Au (2nm) on Si

PLAN

- Introduction: Spintronics
- Method: Reflectivity, off-specular scattering, GISAS and neutron polarization analysis
- Simulation of specular reflectivity
- Simulation of polarized neutron reflectivity
- **Simulation of GISAS intensities within the Distorted Wave Born Approximation**
- Structural ordering in assemblies of magnetic nanoparticles
- Magnetic domain structure in FePd with perpendicular-to-plane anisotropy
- Take-Home Message

DISTORTED WAVE BORN APPROXIMATION (DWBA)



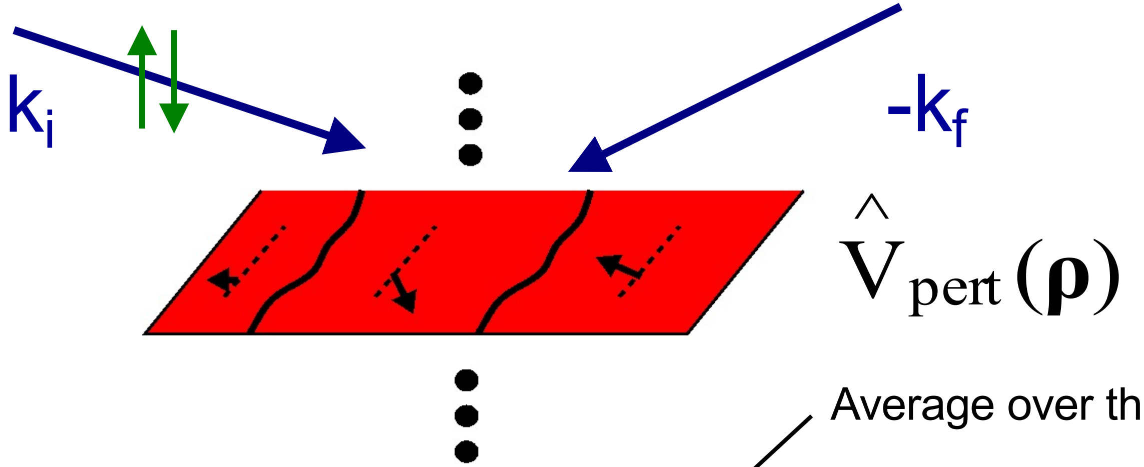
Case of:

- bulk density fluctuations
- polarized neutrons

Leads to specular reflectivity

Leads to scattering

SCATTERING CROSS SECTION WITHIN DWBA



$$\frac{d\sigma}{d\Omega}(\mathbf{k}_i,\mathbf{k}_f) = \left\langle \overline{\left| \frac{m}{2\pi\hbar^2} \left\langle \Psi^f \middle| \hat{V}_{pert} \middle| \Psi^i \right\rangle \right|^2} \right\rangle$$

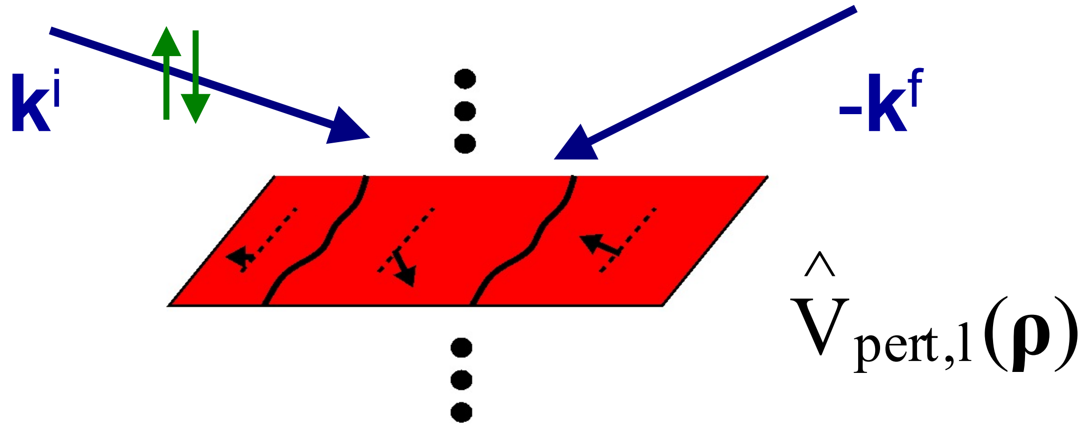
$\left.\begin{matrix} \left|\Psi^i\right\rangle \\ \left\langle\Psi^f\right| \end{matrix}\right\}$ are solutions of the Schrödinger equation for $\hat{V}(z)$

and incoming wave vectors $\left\{\begin{matrix} \mathbf{k}_i \\ -\mathbf{k}_f \end{matrix}\right.$

JÜLICH Forschungszentrum

Demonstration: L.I. Schiff, „Quantum Mechanics“ (1968)

SCATTERING AMPLITUDE WITHIN DWBA



$$F\left(\mathbf{Q}_{\|}, k^f_{z,0}, k^i_{z,0}\right) = \sum_l \int dz \; \langle \Psi^f_0(\mathbf{k}^f, 0)| \cdot \hat{S}^{f+}_l(z) \cdot \hat{\mathbf{F}}_l(\mathbf{Q}_{\|}) \cdot \hat{S}^i_l(z) \cdot |\Psi^i_0(\mathbf{k}^i, 0)\rangle$$

with:

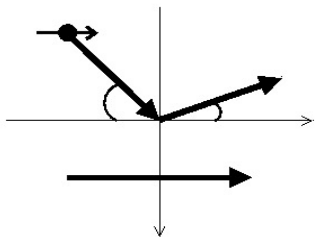
$$\hat{\mathbf{F}}_l(\mathbf{Q}_{\|}) = -\frac{m}{2\pi\hbar^2} \int d\boldsymbol{\rho} \; e^{-i\mathbf{Q}_{\|}\cdot\boldsymbol{\rho}} \; \hat{V}_{pert,l}(\boldsymbol{\rho}) \qquad \text{and} \qquad \mathbf{Q}_{\|} = \boldsymbol{\kappa}^f - \boldsymbol{\kappa}^i$$

- $\hat{\mathrm{F}}_1(\mathbf{Q}_{//})$: Fourier transform of the fluctuations. Like in BA!
- $\hat{\mathrm{S}}^{\mathrm{i}}_1(\mathrm{z})$ and $\hat{\mathrm{S}}^{\mathrm{f}}_1(\mathrm{z})$ depend only on the reference potential $\hat{V}(z)$!

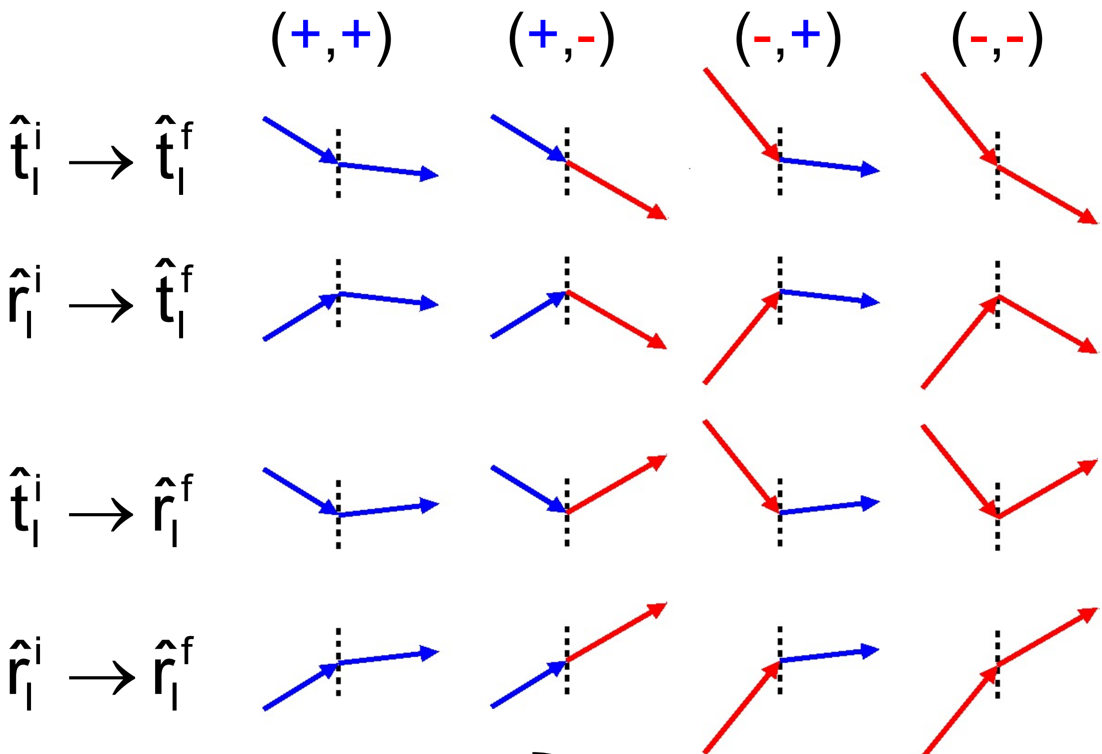
B.P. Toperverg, The Physics of Metals and Metallography (2015)

SCATTERING AMPLITUDE WITHIN DWBA

$$\left|\Psi_l^{i(f)}(\boldsymbol{r})\right\rangle = e^{i\boldsymbol{\kappa}^{i(f)}\cdot\boldsymbol{\rho}}\left(e^{(\pm)i\hat{k}_{z,l}^{i(f)}\cdot z}\ \hat{\boldsymbol{t}}_l^{i(f)} + e^{(\mp)i\hat{k}_{z,l}^{i(f)}\cdot z}\ \hat{\boldsymbol{r}}_l^{i(f)}\right)\left|\Psi_0^{i(f)}\right\rangle$$



The scattering amplitude inside layer l decomposes virtually into 16 terms:



(+,+), (-,-) } are illuminated by <u>nuclear</u> and <u>longitudinal magnetic</u> fluctuations

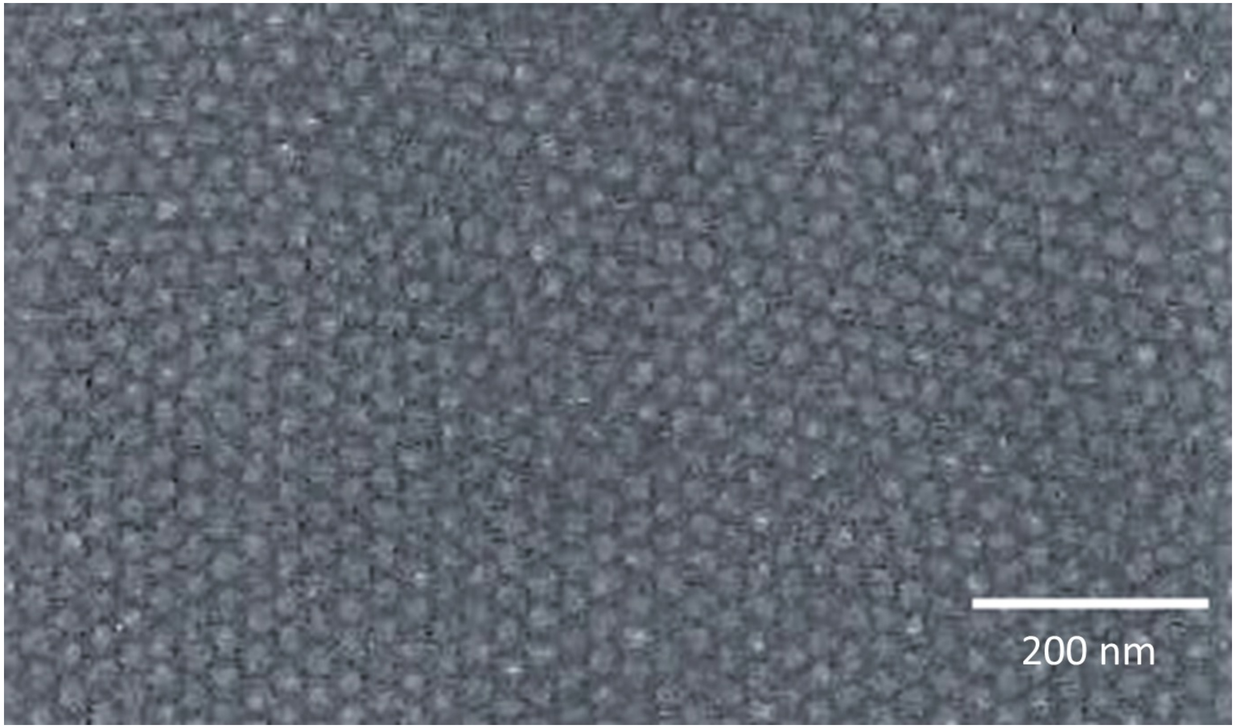
(+,-), (-,+) } are illuminated by <u>transverse magnetic</u> fluctuations

B.P. Toperverg, The Physics of Metals and Metallography (2015)

PLAN

- Introduction: Spintronics
- Method: Reflectivity, off-specular scattering, GISAS and neutron polarization analysis
- Simulation of specular reflectivity
- Simulation of polarized neutron reflectivity
- Simulation of GISAS intensities within the Distorted Wave Born Approximation
- **Structural ordering in assemblies of magnetic nanoparticles**
- Magnetic domain structure in FePd with perpendicular-to-plane anisotropy
- Take-Home Message

Ordered assembly of $CoFe_2O_4$ nanoparticles (Asmaa Qdemat, JCNS)



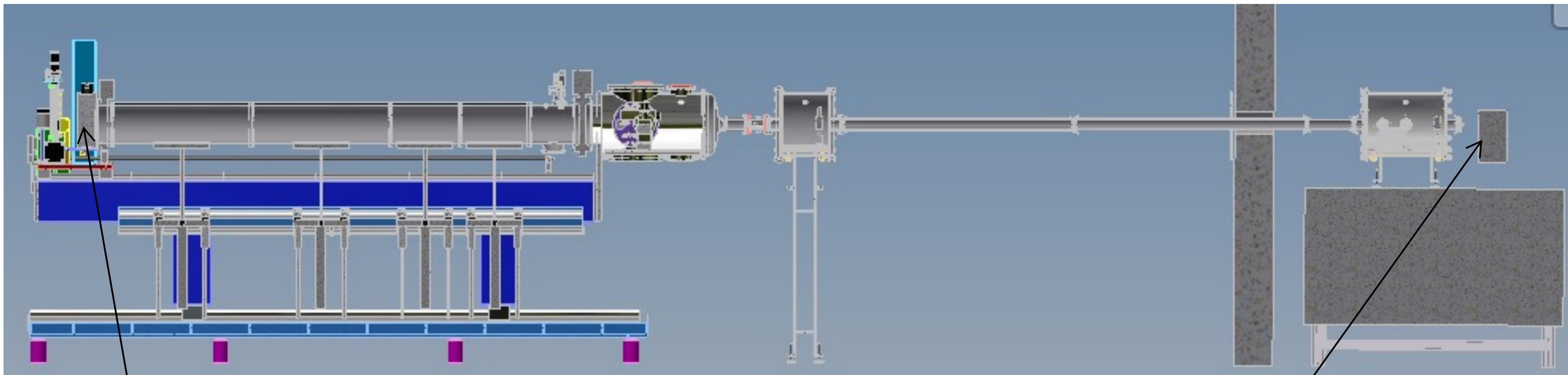
Giuseppe Portale
(Groningen, NL)

- Size ~ 20 nm
- Hexagonal ordering

GALAXI@JCNS

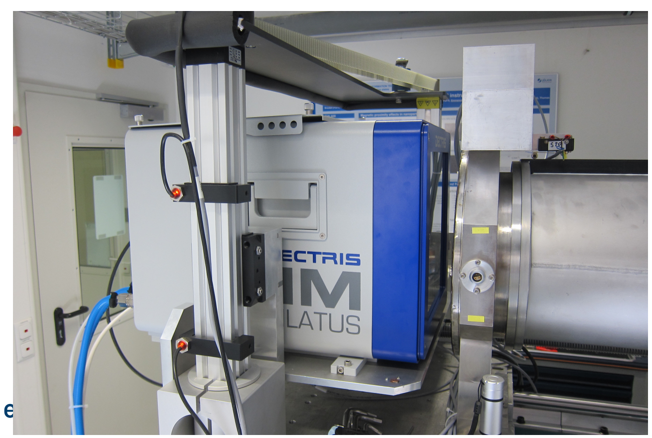
- High brillance laboratory GISAXS diffractometer

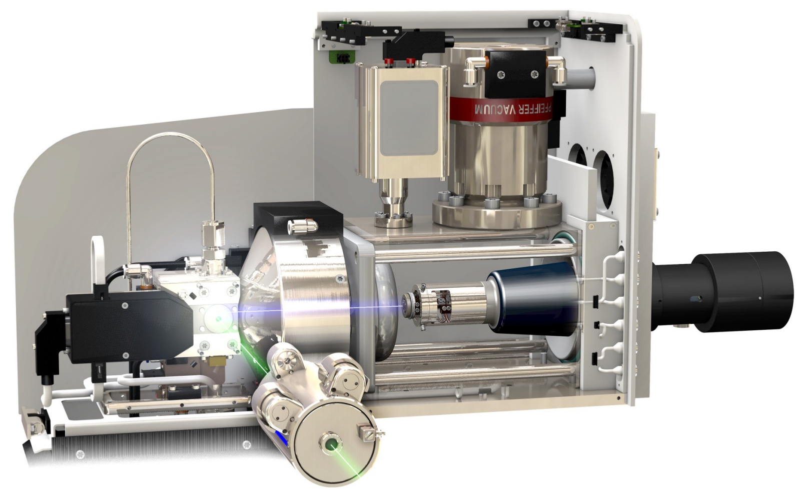
Ulrich Rücker



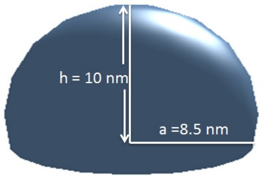
1M Pilatus from Dectris

Metaljet from Bruker AXS

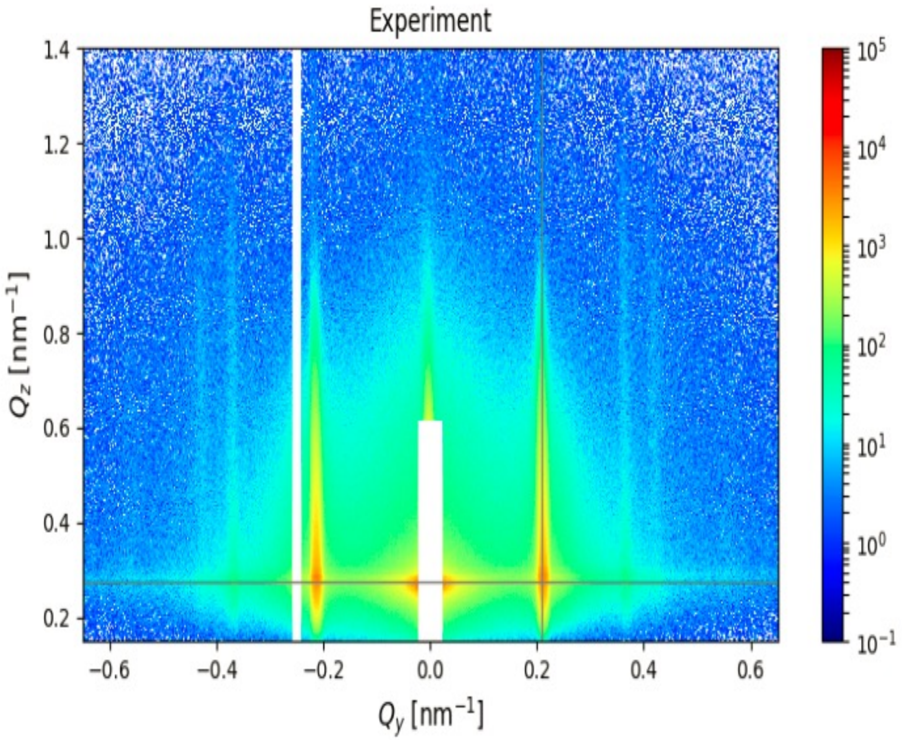




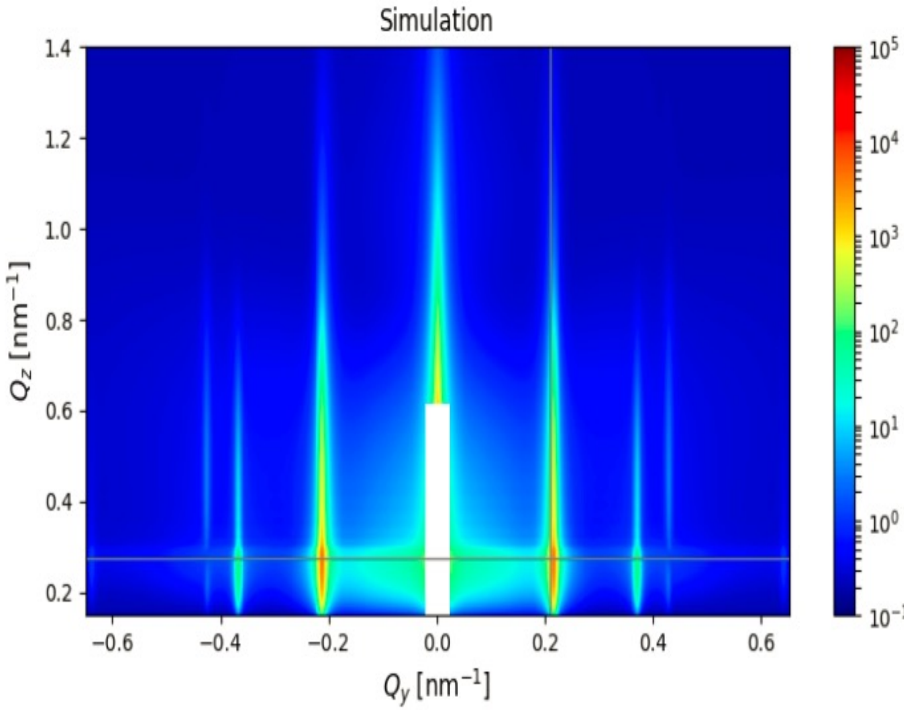
1stnn=28 nm
a=8.5 nm
h=10 nm



$\alpha_i = 0.17^\circ$



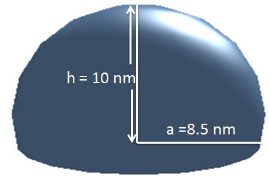
GALAXI



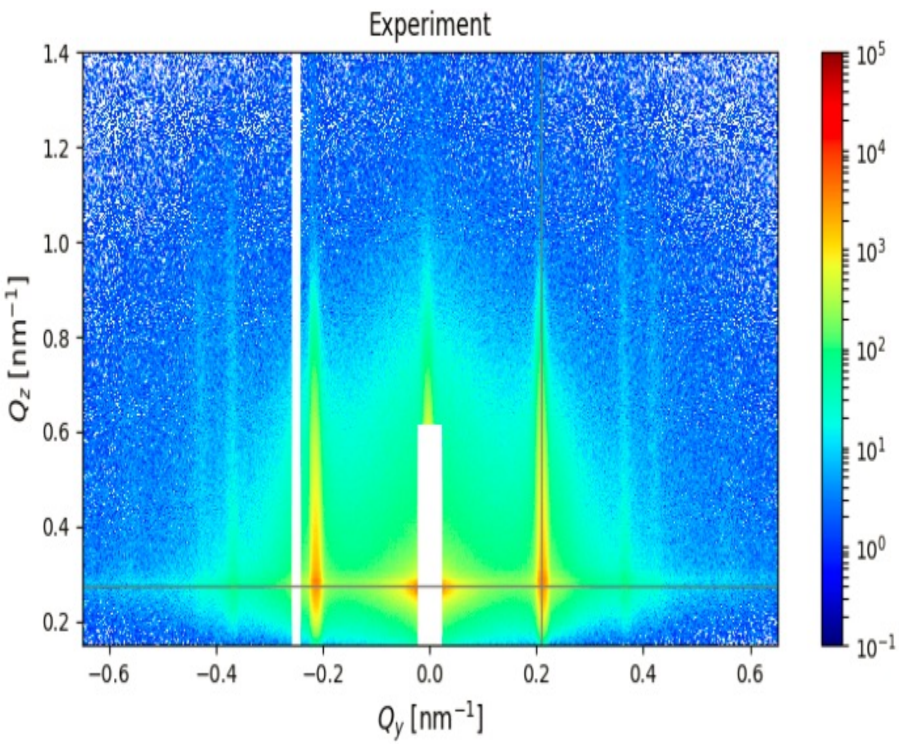
BornAgain program :

www.bornagainproject.org

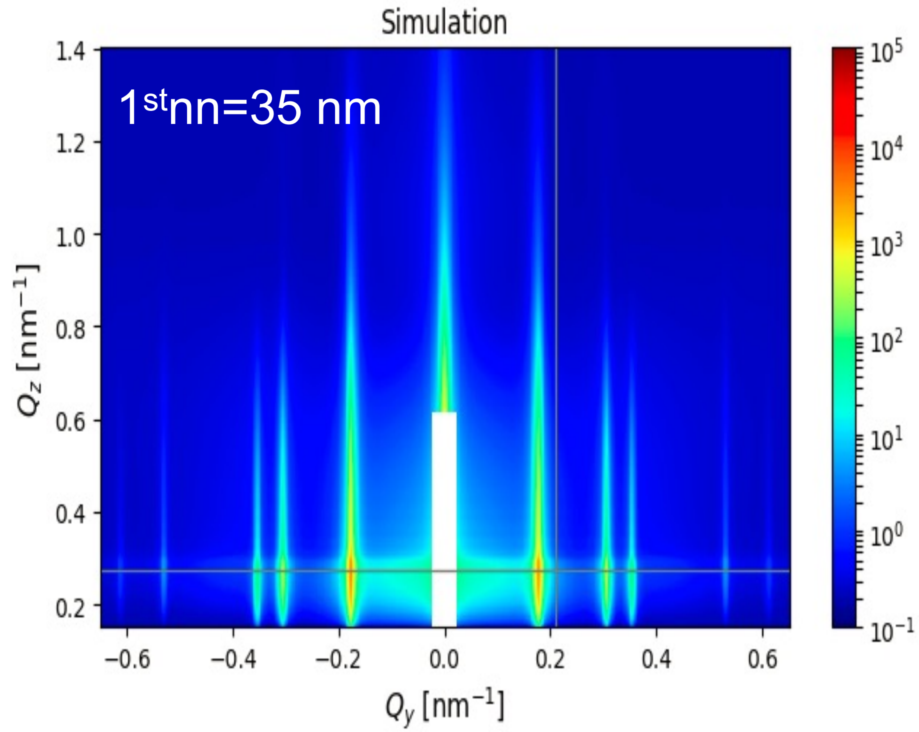
1stnn=28 nm
a=8.5 nm
h=10 nm



$\alpha_i = 0.17^\circ$



GALAXI



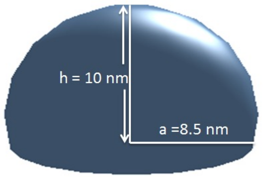
BornAgain program :

www.bornagainproject.org

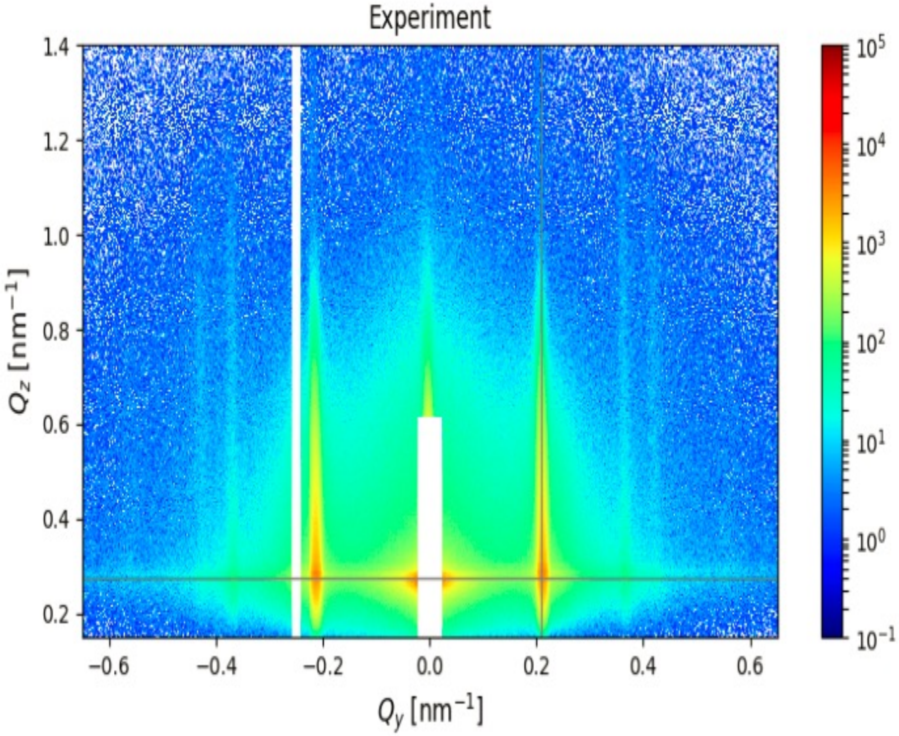
1stnn=28 nm

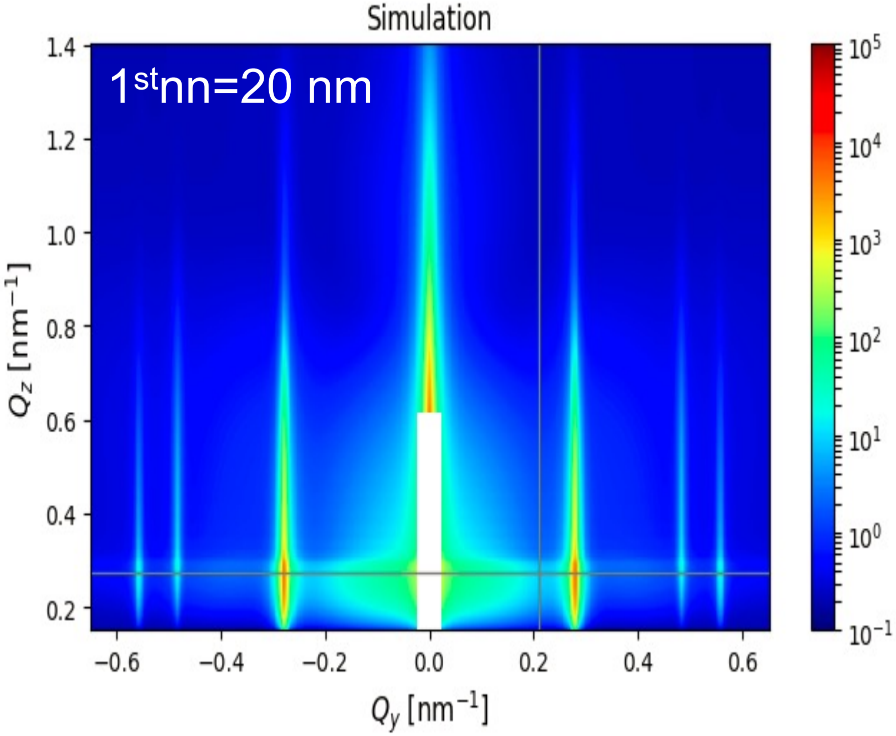
a=8.5 nm

h=10 nm



$\alpha_i = 0.17^\circ$





GALAXI

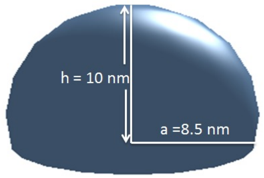
BornAgain program :

www.bornagainproject.org

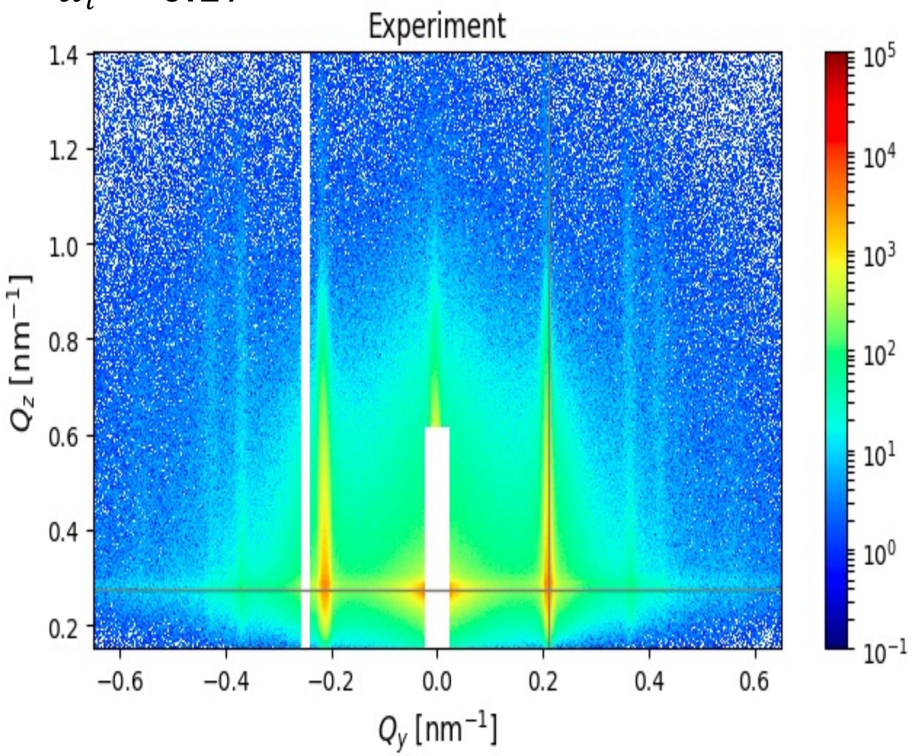
1^{st}nn=28 nm

a=8.5 nm

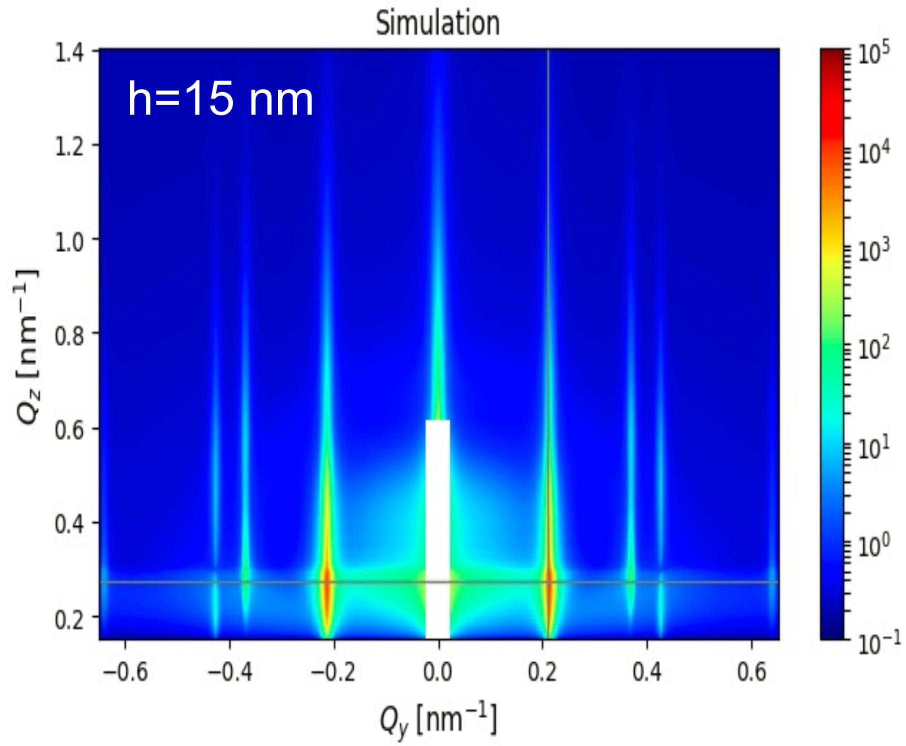
h=10 nm



$\alpha_i = 0.17^{\circ}$



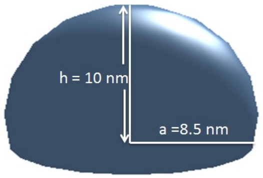
GALAXI



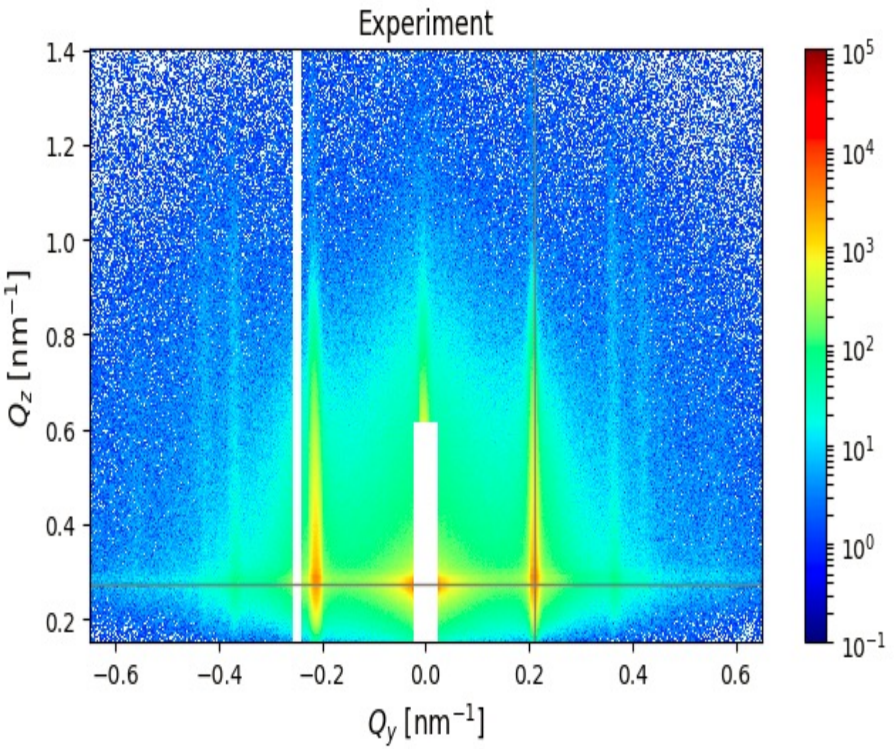
BornAgain program :

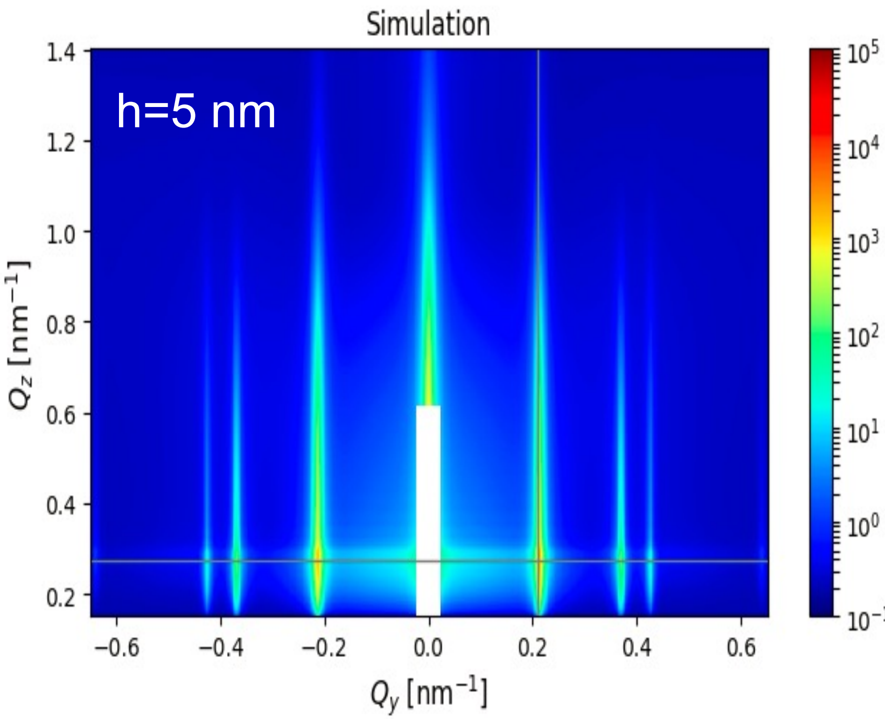
www.bornagainproject.org

1st nn=28 nm
a=8.5 nm
h=10 nm



$\alpha_i = 0.17^\circ$





GALAXI

BornAgain program :

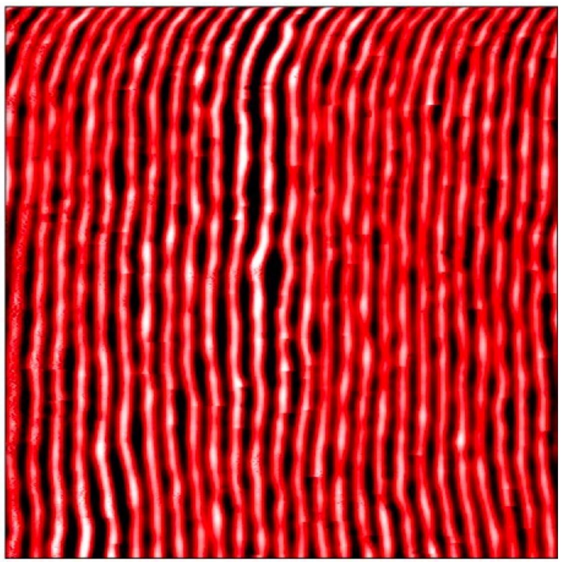
www.bornagainproject.org

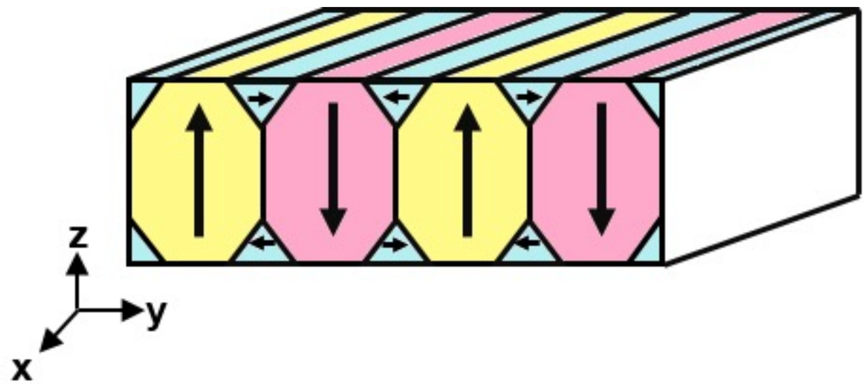
PLAN

- Introduction: Spintronics
- Method: Reflectivity, off-specular scattering, GISAS and neutron polarization analysis
- Simulation of specular reflectivity
- Simulation of polarized neutron reflectivity
- Simulation of GISAS intensities within the Distorted Wave Born Approximation
- Structural ordering in assemblies of magnetic nanoparticles
- **Magnetic domain structure in FePd with perpendicular-to-plane anisotropy**
- Take-Home Message

FePd layer with perpendicular magnetic anisotropy (Annika Stellhorn, JCNS)

MFM

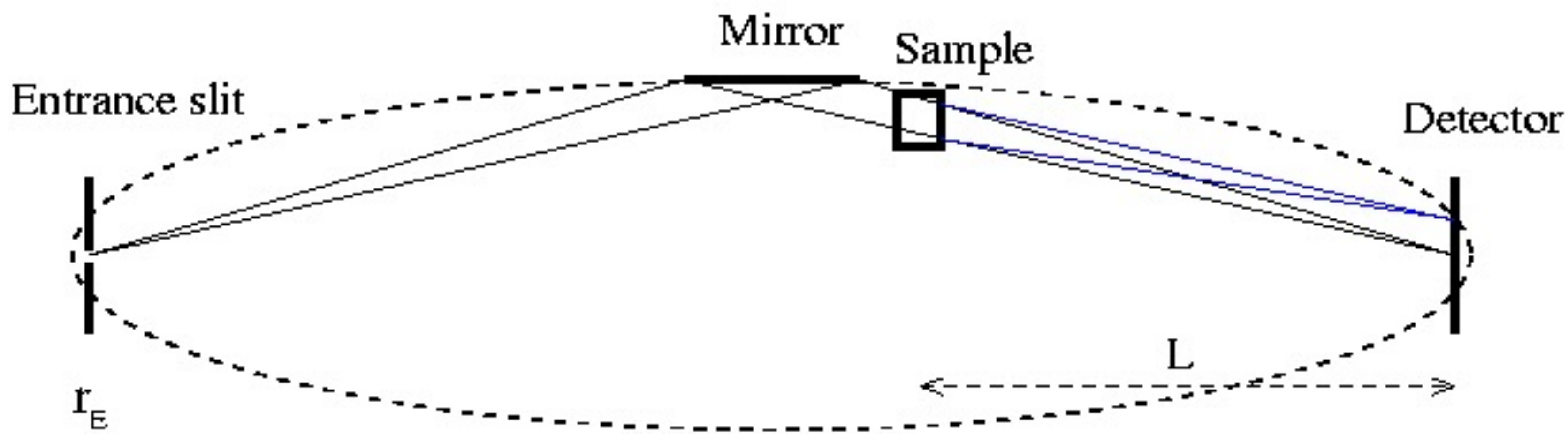




A. Stellhorn et al. JMMM **476,** 483 (2019)

KWS-3 @ MLZ (V. Pipich)

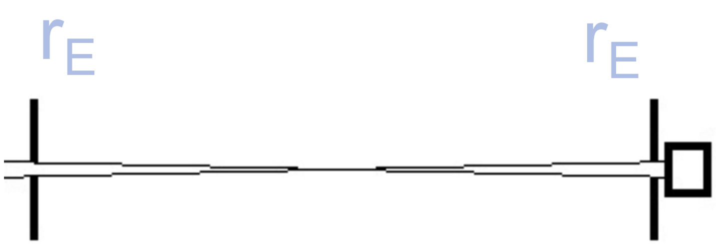
1:1 imaging of an entrance aperture onto a detector by reflection on an ellipsoidal mirror



$$\delta Q = \frac{k.r_E}{L} \qquad \left(k = \frac{2\pi}{\lambda}\right) \qquad \left.\begin{array}{l} k = 0.5\ \text{Å}^{-1} \\ r_E = 2\ mm \\ L = 10\ m \end{array}\right\} \rightsquigarrow \delta Q = 10^{-4}\ \text{Å}^{-1}$$

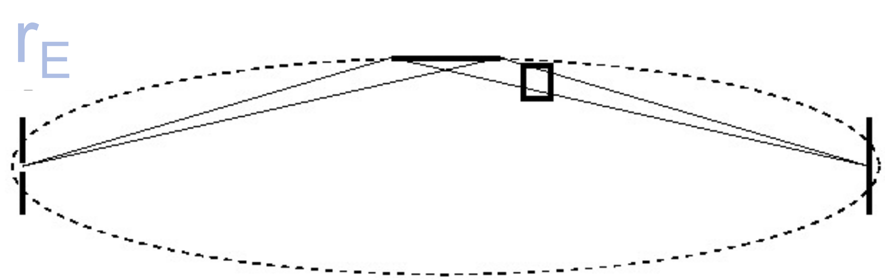
→ Any physical issue at the µm length scale!

Comparison:
Pinhole / Focusing mirror SANS



$I_P \propto r_E^{\,4}$ $\delta Q \propto r_E$

$\rightarrow \; I_P \propto \delta Q^4$



$I_F \propto r_E^{\,2}$ $\delta Q \propto r_E$

$\rightarrow \; I_F \propto \delta Q^2$

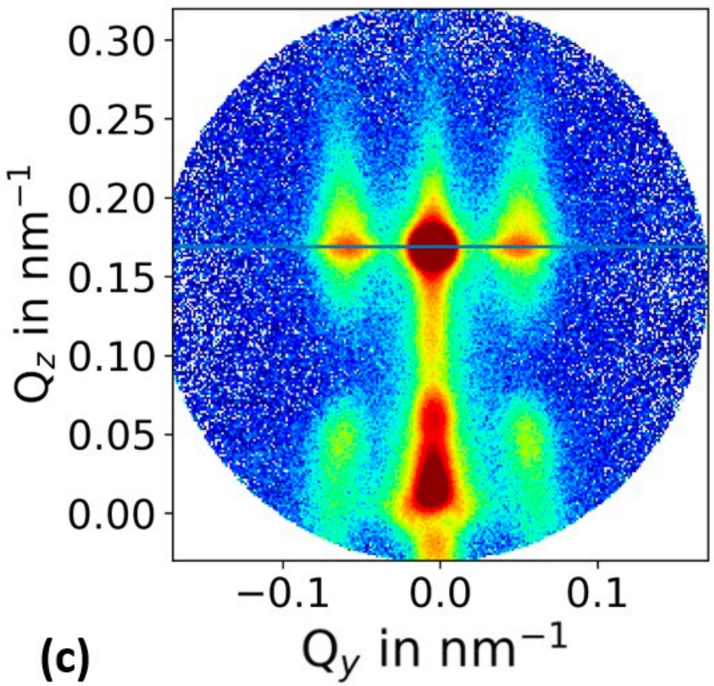
Therefore: $\dfrac{I_F}{I_P} \propto \dfrac{1}{\delta Q^2}$

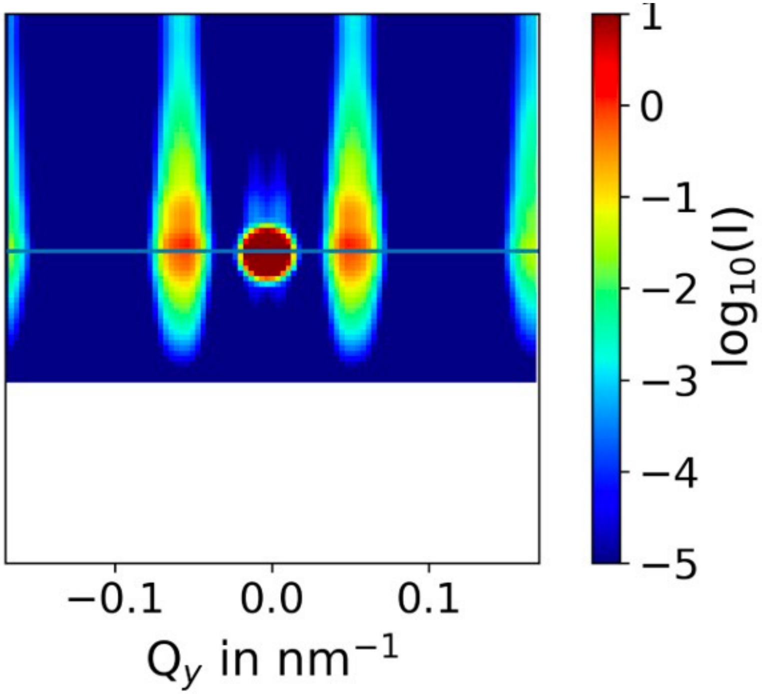
$$\frac{I_F}{I_P} > 1 \;\; \text{für} \;\; \delta Q < 7.6 \times 10^{-3}\, \mathring{A}^{-1}$$

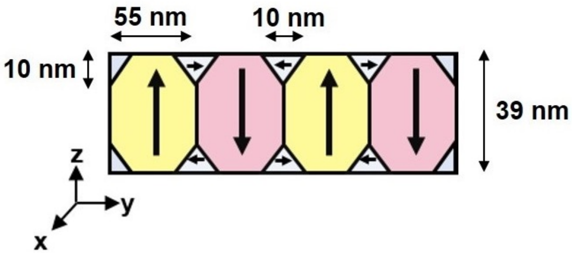
B. Alefeld, D. Schwahn,T. Springer, Nucl. Inst. Methods (1989)

The KWS-3 Mirror

GISANS @ KWS-3 DWBA simulation

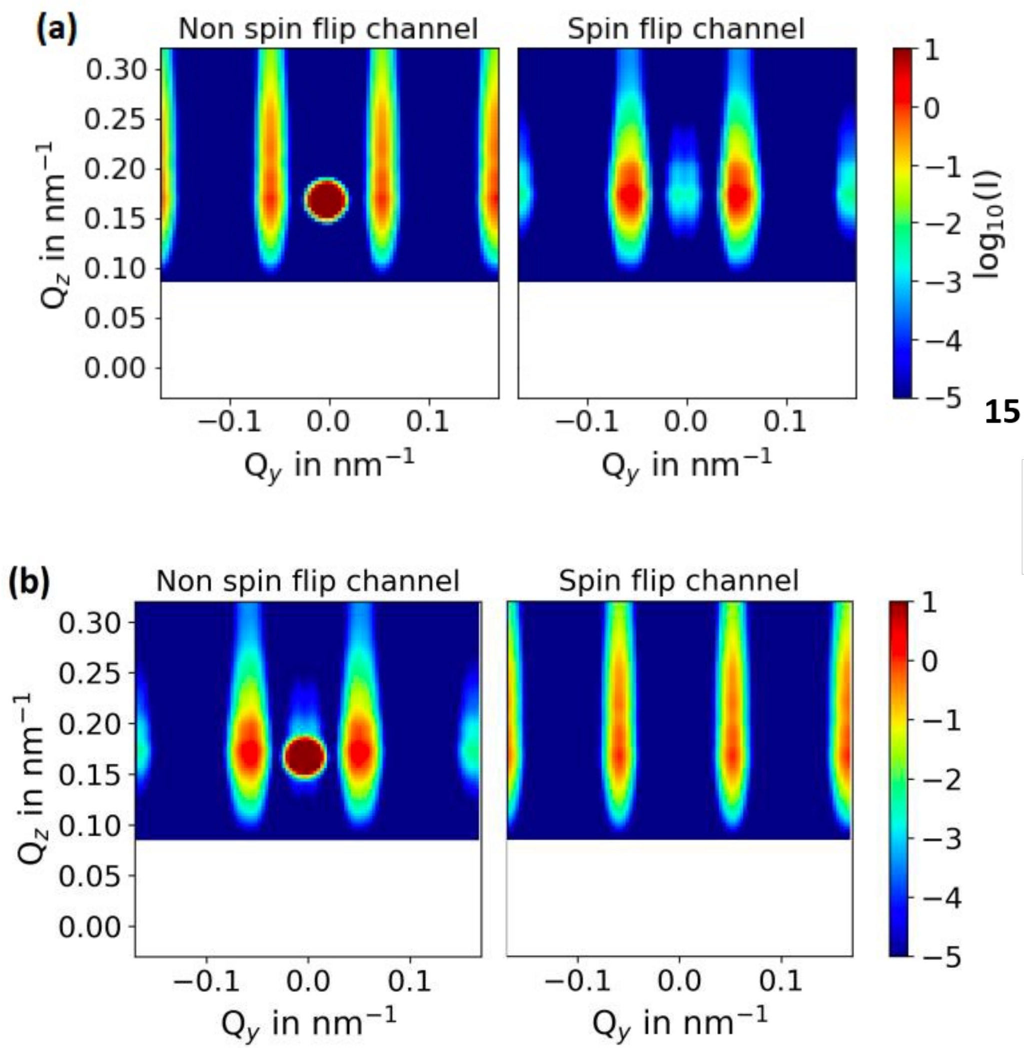




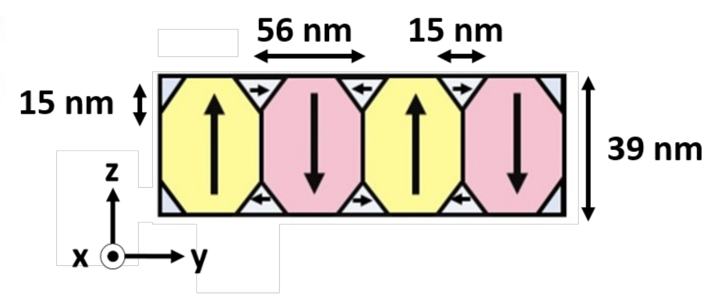


A. Stellhorn et al. JMMM **476,** 483 (2019)

3D vector magnetometry by GISANS with polarization analysis (DWBA simulations)



Polarization:



Polarization:

PLAN

- Introduction: Spintronics
- Method: Reflectivity, off-specular scattering, GISAS and neutron polarization analysis
- Simulation of specular reflectivity
- Simulation of polarized neutron reflectivity
- Simulation of GISAS intensities within the Distorted Wave Born Approximation
- Structural ordering in assemblies of magnetic nanoparticles
- Magnetic domain structure in FePd with perpendicular-to-plane anisotropy
- **Take-Home Message**

TAKE-HOME MESSAGE

- Reflectometry from thin films:
  1. Scattering length density profile along their depth
  2. Information averaged over in-plane coordinates

- Grazing Incidence Small Angle Scattering:
  1. In-plane correlations can be investigated
  2. Depth-resolution accessed by interpreting signal as a function of angles of incidence and exit

- Neutron polarization analysis:
  3D vector magnetometry

THANKS TO…

The Students:
- Asmaa Qdemat
- Annika Stellhorn
- Tanvi Bhatnagar
- Patrick Schöffmann

Simulations:
- Marina Ganeva

The Instrument Scientists:
- Anirban Sarkar
- Vitaliy Pipich
- Stefan Mattauch
- Ulrich Rücker
- Earl Babcock

Everything:
- Thomas Brückel

…AND YOU FOR YOUR ATTENTION