Study of the in-plane magnetic structure of neutron polarizing multilayer mirrors

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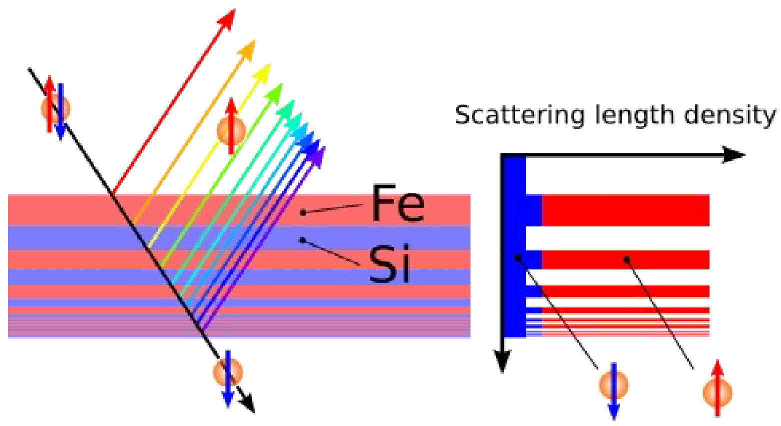
Outline

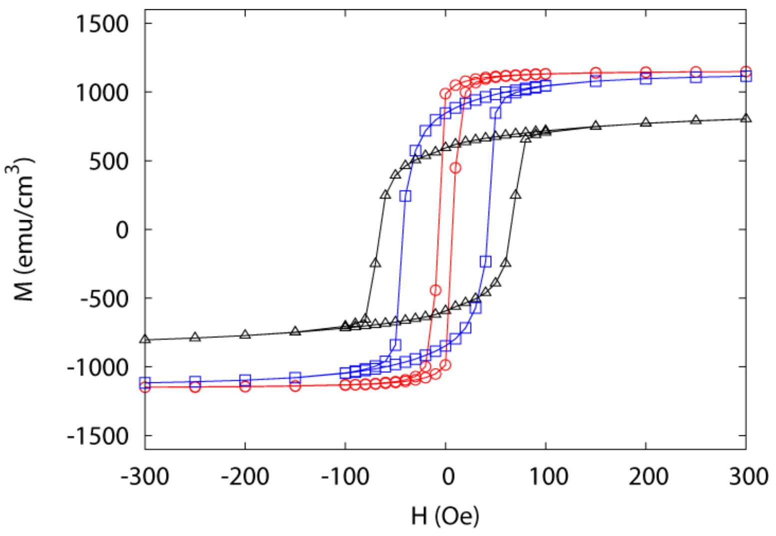
- Introduction
- Sample preparation
- Polarized neutron off-specular scattering (OSS) and grazing incidence small angle scattering (GISAS) measurements
- Summary

Improvement of the magnetic properties

- Polarizing supermirror
  - A stack of alternating layers of ferromagnetic and non-magnetic materials
  - A neutron beam is polarized by making use of the dependence of the scattering length density on the neutron spin



- Advantages
  - High spin-polarization without loss of intensity
  - Uniform polarization over a wide bandwidth
  - Maintenance free



- Soft magnetic properties
  - Polarizing supermirrors need to display high polarization efficiencies at low external field to meet a variety of research demands. (collaboration with the ILL)

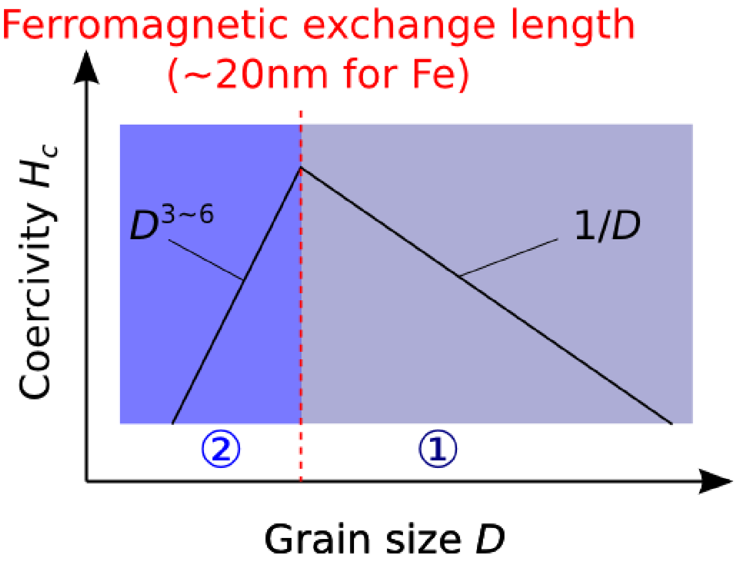
Mechanism that controls the magnetic properties?

- Dependence of the magnetic properties on the grain size

  ① Formation and movement of domain walls

  ② Exchange interaction between neighboring spins

  → Random anisotropy model (RAM)



- The magnetic layers consisting of a polarizing supermirror are nanocrystalline.

- Our interest lies in verifying whether the RAM is valid in our system by observing the in-plane magnetic structure.

Sample fabrication

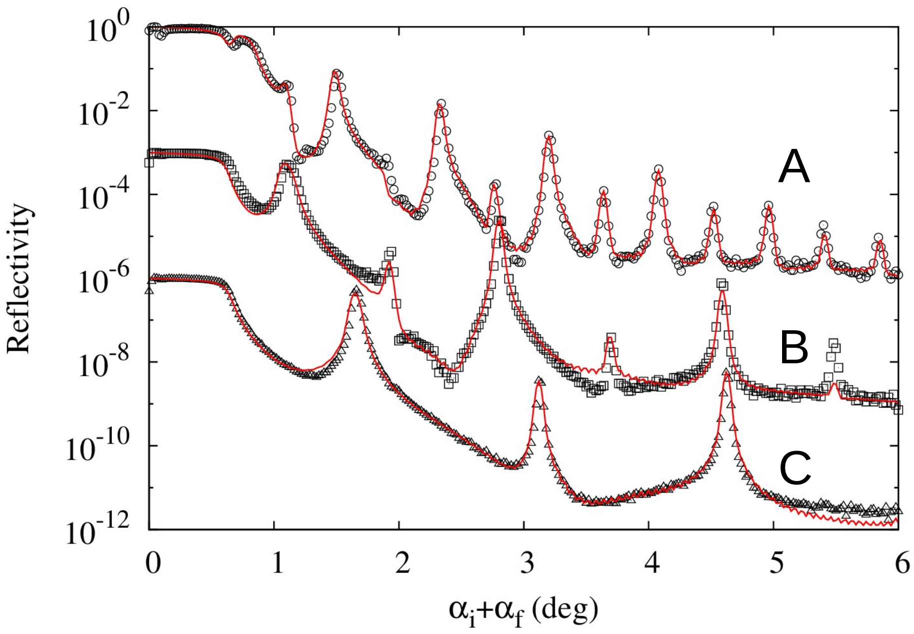
- Samples were prepared with a magnetron sputtering system at the ILL

  Fe/Si multilayers (unit: nm)

  A: $[Fe(10)/Si(10)]_{15}$

  B: $[Fe(5)/Si(5)]_{30}$

  C: $[Fe(3)/Si(3)]_{50}$

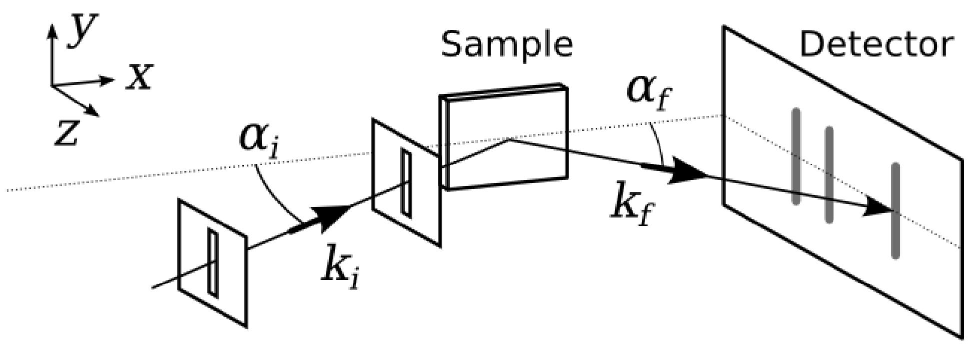
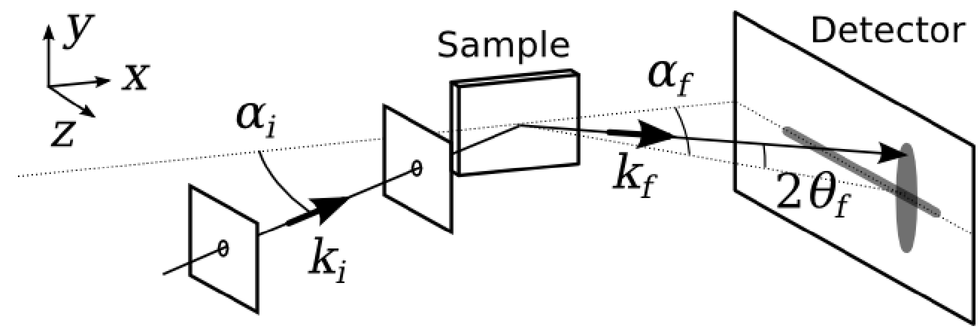


- X-ray reflectivity measurement

	A	B	C
Fe thickness (nm)	10.12	4.83	3.13
Si thickness (nm)	9.59	4.87	2.65

The samples were prepared as we designed.

Characteristics of the OSS and GISAS

Off-specular scattering (OSS)	Grazing incidence small angle scattering (GISAS)
	

OSS		GISAS
$q_x < 0.05$ nm^{-1}	In-plane q range	Unlimited
1-100 μm	Length scale ($2\pi/\delta q_{x(y)}$)	0.1-10 μm
Yes	Effect of Fresnel coefficient?	No

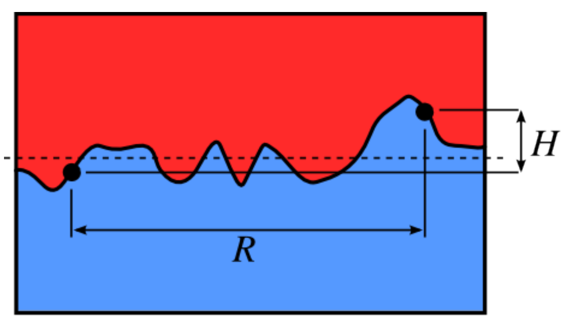
- Resolution for the in-plane structure: GISAS > OSS
- The GISAS combined with the OSS gives complementary information on overlapping length scales.

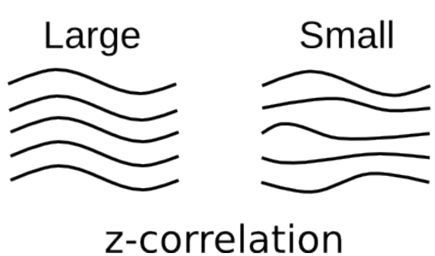
Data analysis using the DWBA

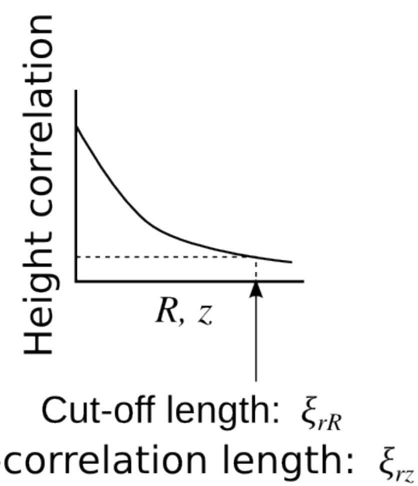
- Distorted wave Born approximation (DWBA)

Model for interface roughness

- The height of the interface is Gaussian random variables.
- Cut-off length : ξ_{rR}
- z-correlation length : ξ_{rz}

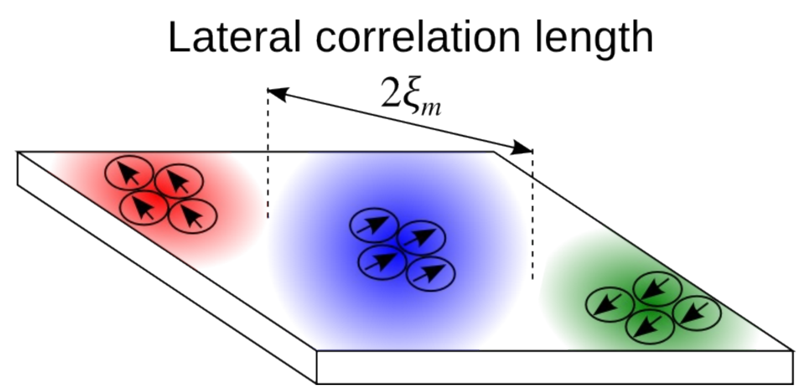






Model for in-plane magnetic structure

- The deviated angle of the spins with respect to the external field have a Graussian distribution.
  Mean value：Φ、 Variance：$(\delta\Phi)^2$
- Lateral correlation length : $\xi_{mx(y)}$
- z-correlation length : ξ_{mz}



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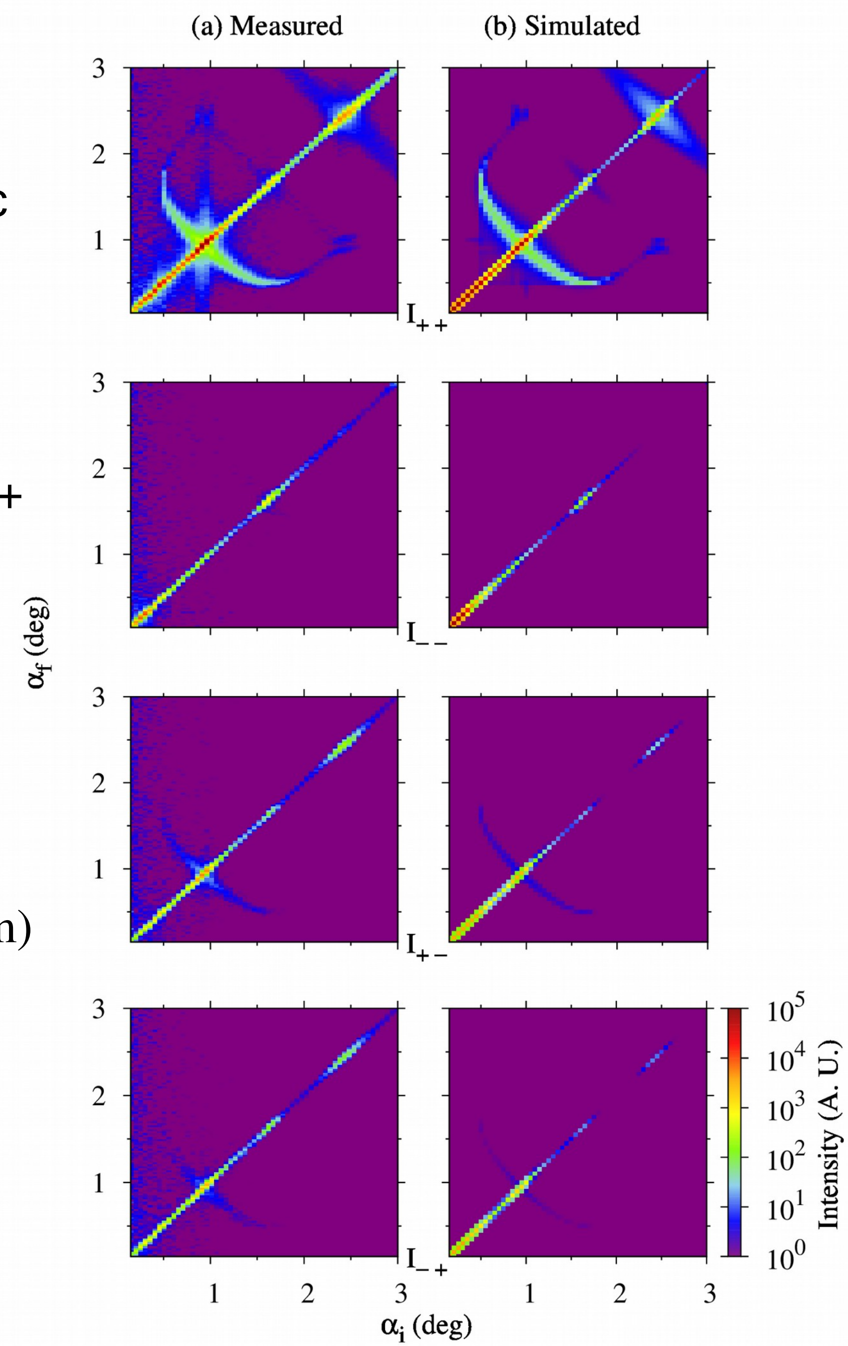
OSS measurement at saturation   ILL D17

Sample A: $[Fe(10)/Si(10)]_{15}$ @ 4.8 kOe

- Scattering due to interface roughness correlation is seen at saturation magnetization (No magnetic scattering).

- Intense scattering is observed on the first and third Bragg condition ($\alpha_i + \alpha_f$=1.9°、4.8°) in the ++ channel (Bragg sheet).

Parameters for the interface roughness
- Cut-off length : ξ_{rR}<300 nm
- z-correlation length: ξ_{rz}=200±80 nm (>> d=20 nm)



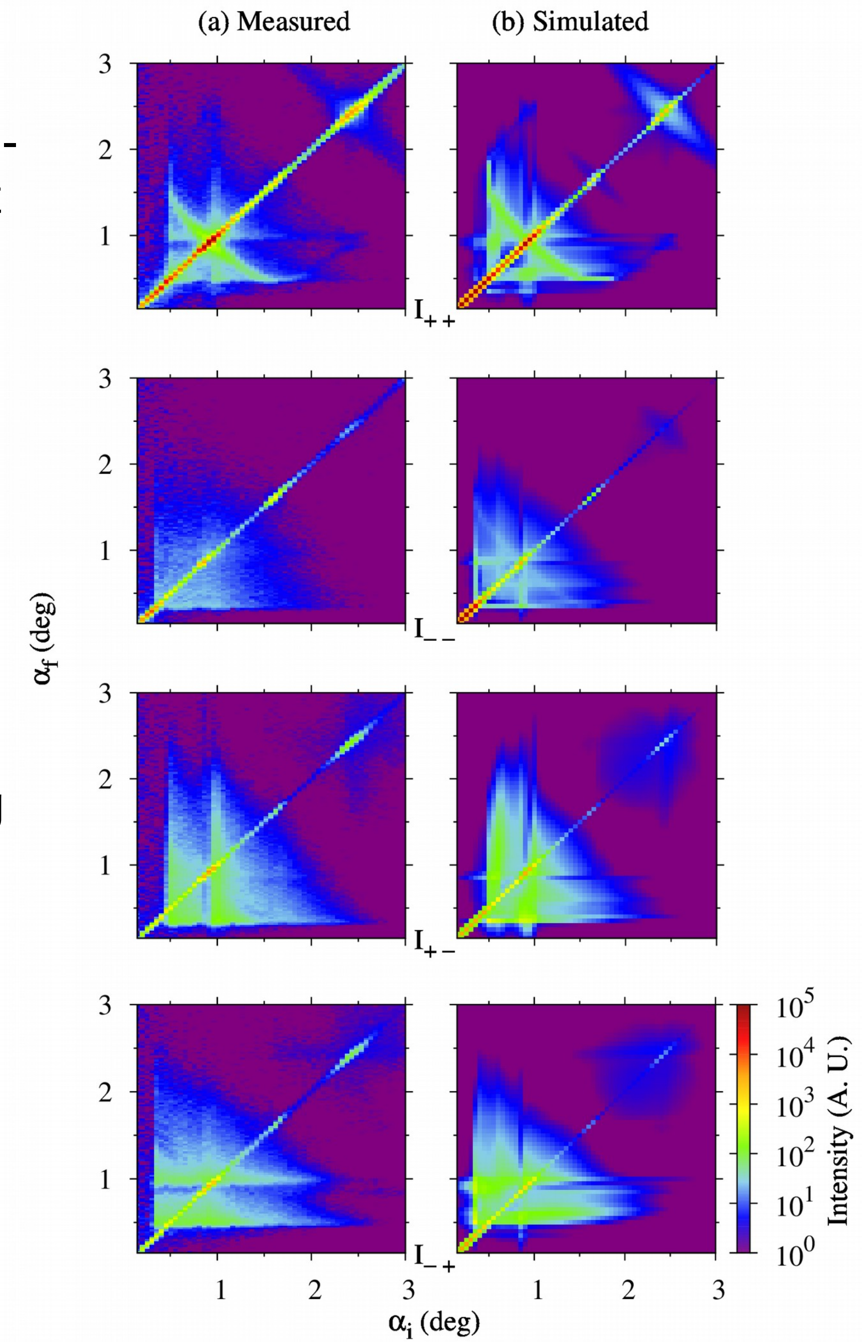
OSS measurement at 70% of saturation   ILL D17

Sample A: $[Fe(10)/Si(10)]_{15}$ @ 68 Oe

- The magnetic scattering is expected in both spin-flip and non-spin-flip channels because Φ=45° at the external field corresponding to 70% of saturation.
- The magnetic scattering is spread over a wide area of $\alpha_i - \alpha_f$ plane. This means there is no cross-correlation of the spins.
- Intense magnetic scattering along the first Bragg condition for spin-up state in the spin-flip channels.

Parameters for the in-plane magnetic structure

- Lateral correlation length: ξ_{mx}<250 nm
- z-correlation length: ξ_{mz}<1.0 nm (<< d=20 nm)



OSS measurement at 70% of saturation   ILL D17

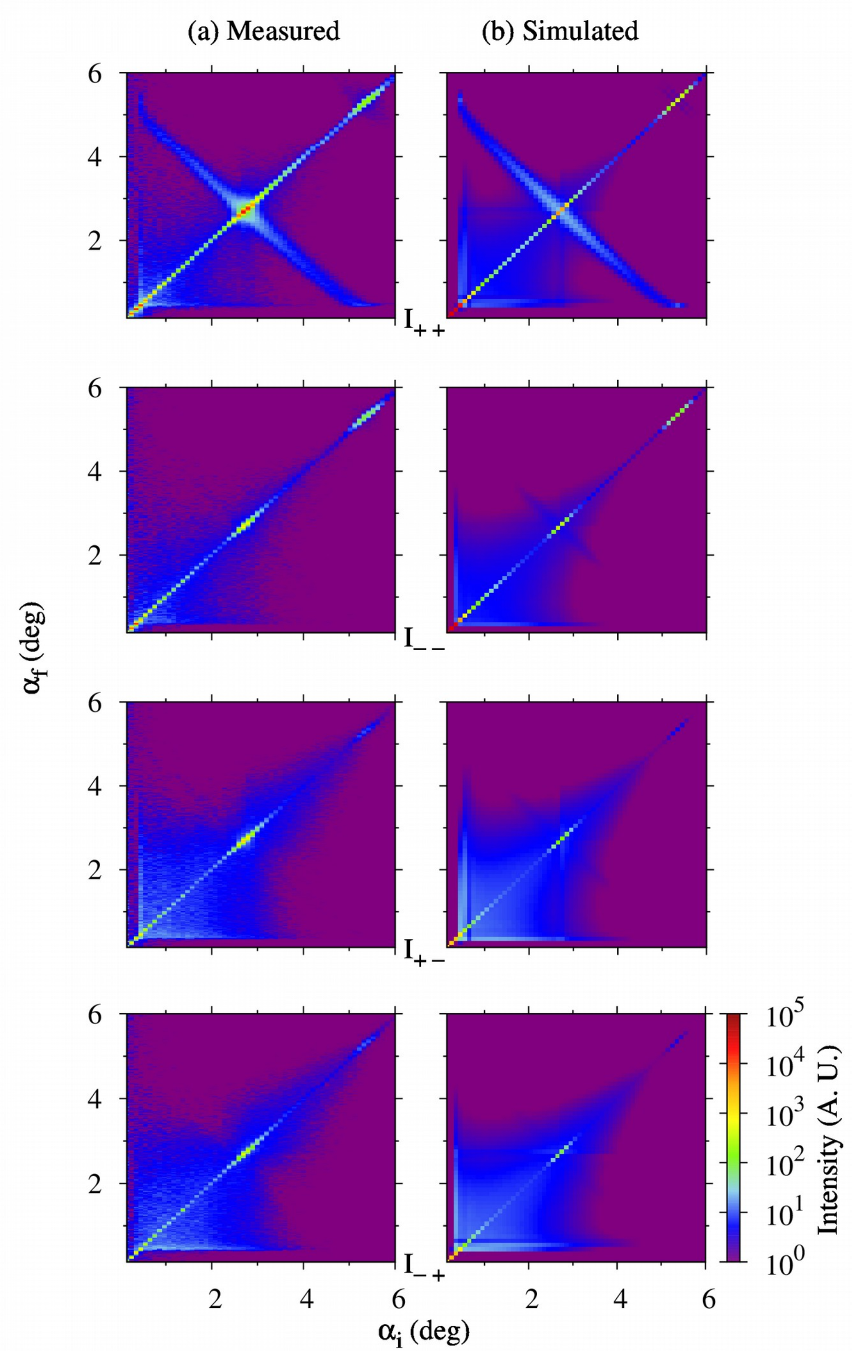
Sample C: $[Fe(3)/Si(3)]_{50}$ @ 87 Oe

- The magnetic scattering has a broader distribution in q_x direction. This implies a smaller in-plane structure than that of the sample A.

- It is difficult to determine the parameters for the in-plane magnetic structure due to the limited range of q_x. This requires the GISAS measurement.

Parameters for the in-plane magnetic structure

- Lateral correlation length: ξ_{mx}<125 nm
- z-correlation length: ξ_{mz}<0.3 nm (<< d=6 nm)



GI… % of saturation ILL D33

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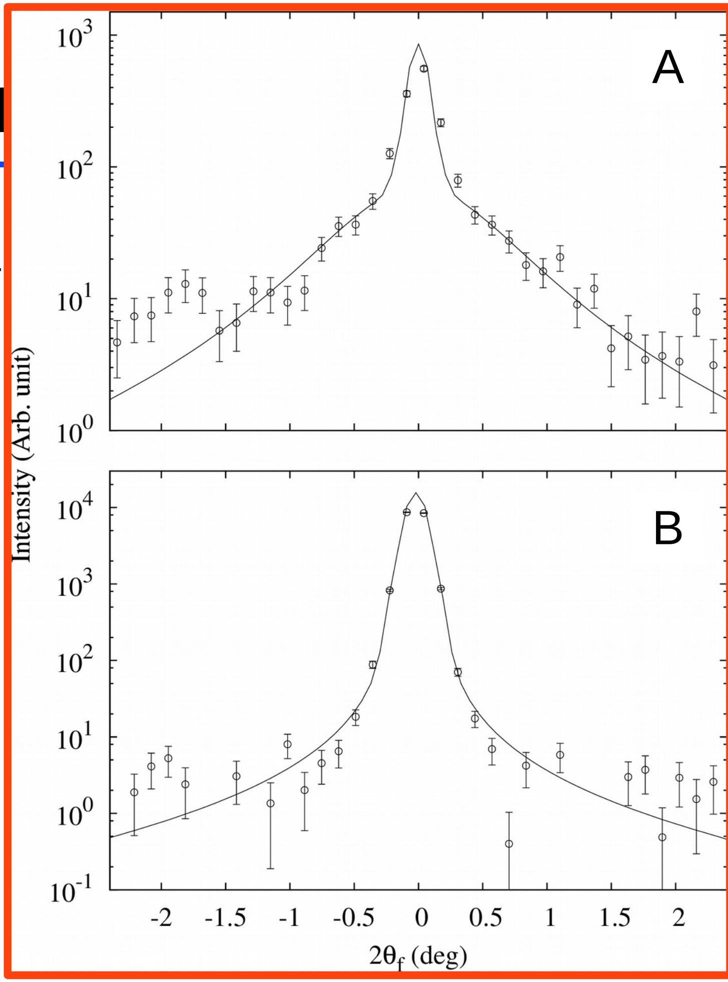

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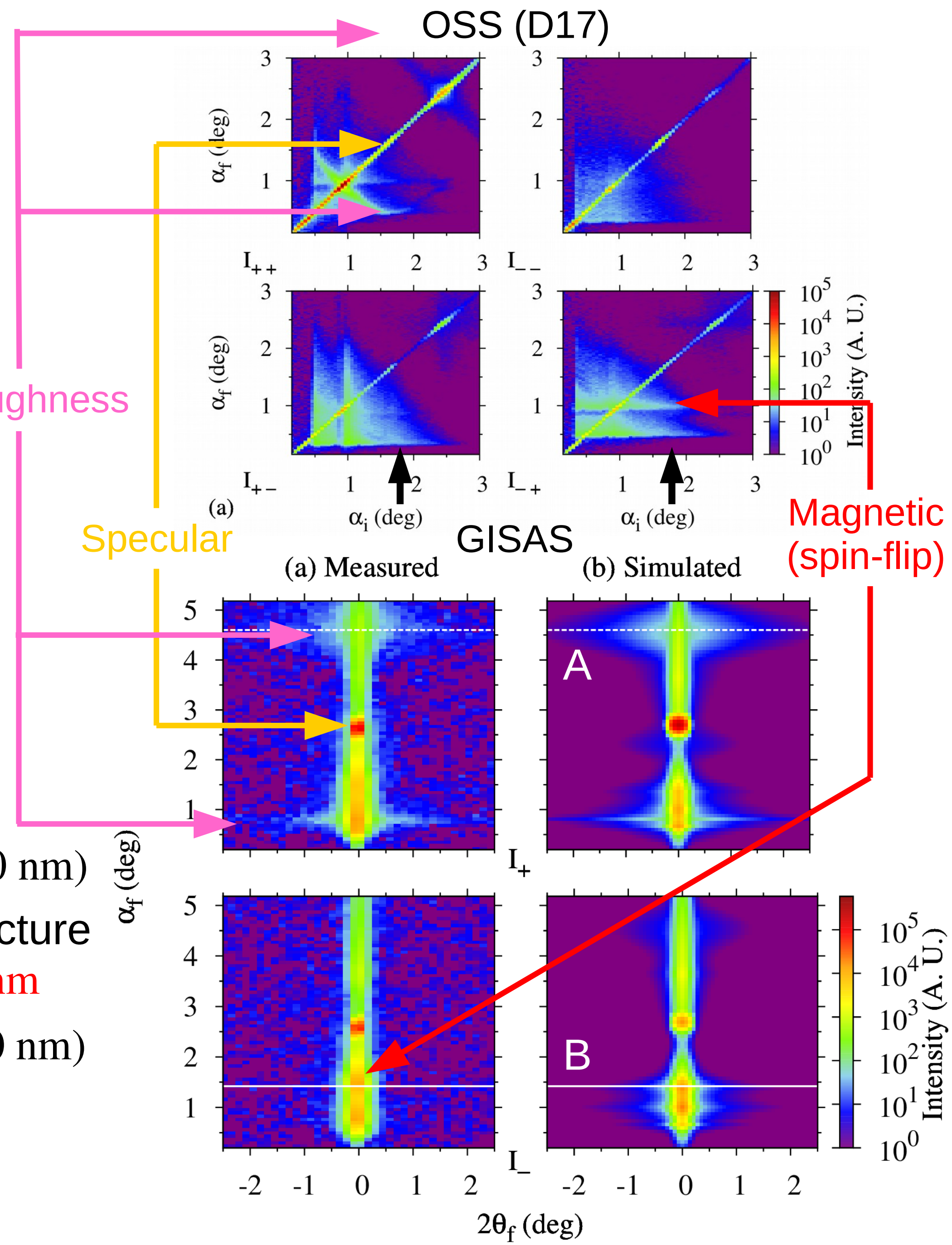

Parameters for the interface roughness

- Cut-off length: ξ_{rR} =10±3 nm
- z-correlation length: ξ_{rz} =200 nm (>> d=20 nm)

Parameters for the in-plane magnetic structure

- Lateral correlation length: ξ_{my} =500±100 nm
- z-correlation length: ξ_{mz} <1.0 nm (<< d=20 nm)

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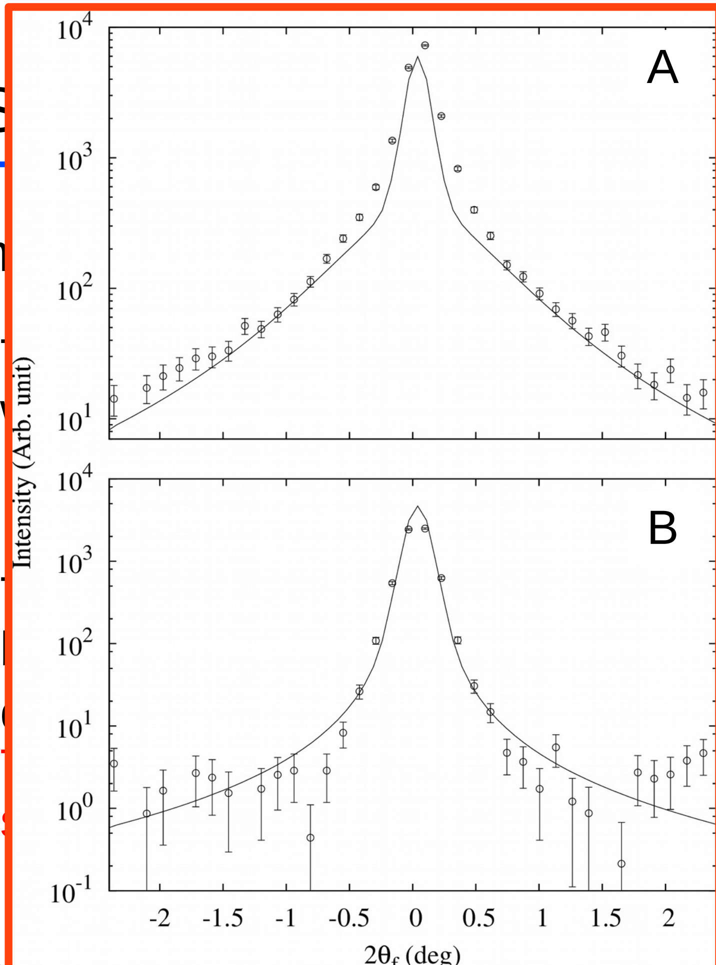
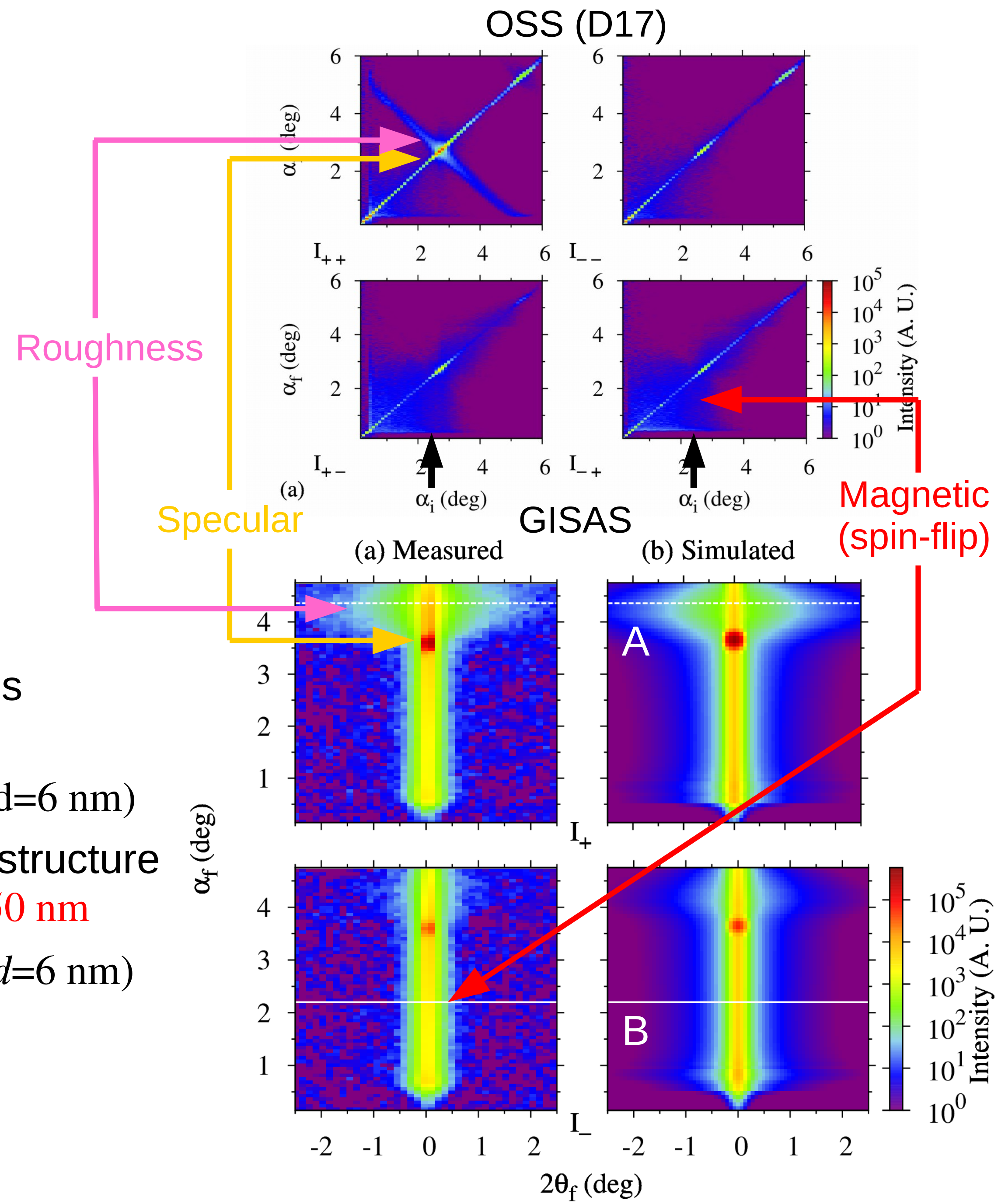




Parameters for the interface roughness

- Cut-off length: ξ_{rR}=10±3 nm
- z-correlation length: ξ_{rz}=100 nm (>> d=6 nm)

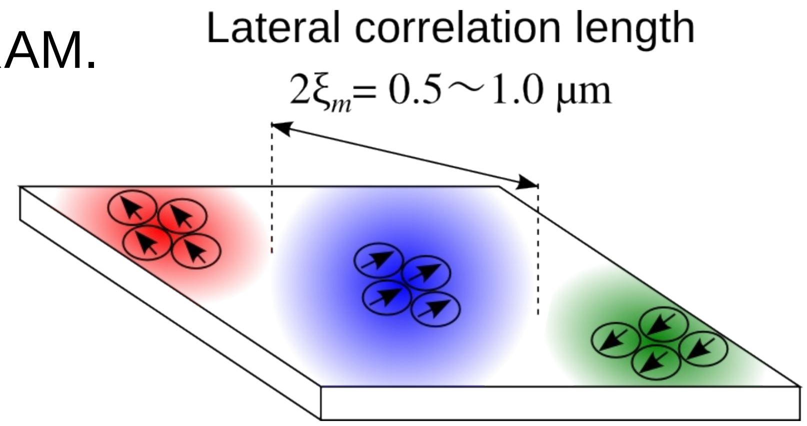
Parameters for the in-plane magnetic structure

- Lateral correlation length: ξ_{my}=250±50 nm
- z-correlation length: ξ_{mz}<0.3 nm (<< d=6 nm)

Is the RAM valid in our system?

Magnetic lateral correlation length: $2\xi_m$=0.5〜1.0 μm >> Grain size (<10 nm)

- The exchange interaction between neighboring spins provides the formation of areas where the spin are aligned to the same direction.
- The local anisotropies of the randomly oriented grains are averaged on a scale of the coupled area and the exchange interaction becomes dominant over the average anisotropy.
- Measured result is consistent with the RAM.



- Further study with a wider range of the grain size is needed to verify whether the dependence of the coercive field and the lateral correlation length on the grain size satisfies the relation predicted in the RAM.

R. Maruyama, T. Bigault, A. R. Wildes, C. D. Dewhurst, K. Soyama, and P. Courtois, NIM A, 819 (2016) 37.

Summary

- Polarized neutron OSS and GISAS measurements were performed for polycrystalline Fe/Si multilayers with a grain size less than the ferromagnetic exchange length.

- This result demonstrated that the polarized neutron OSS and GISAS is efficient in studying the in-plane magnetic structure of a layered system.

- This result implies that the RAM is successfully applied to our system.

- Further study for the samples with a wider range of the grain size would lead to a comprehensive understanding of the mechanism that controls the magnetic properties of layered systems.