Magnetisation Reversal and Morphology in Transition Metal Multilayers

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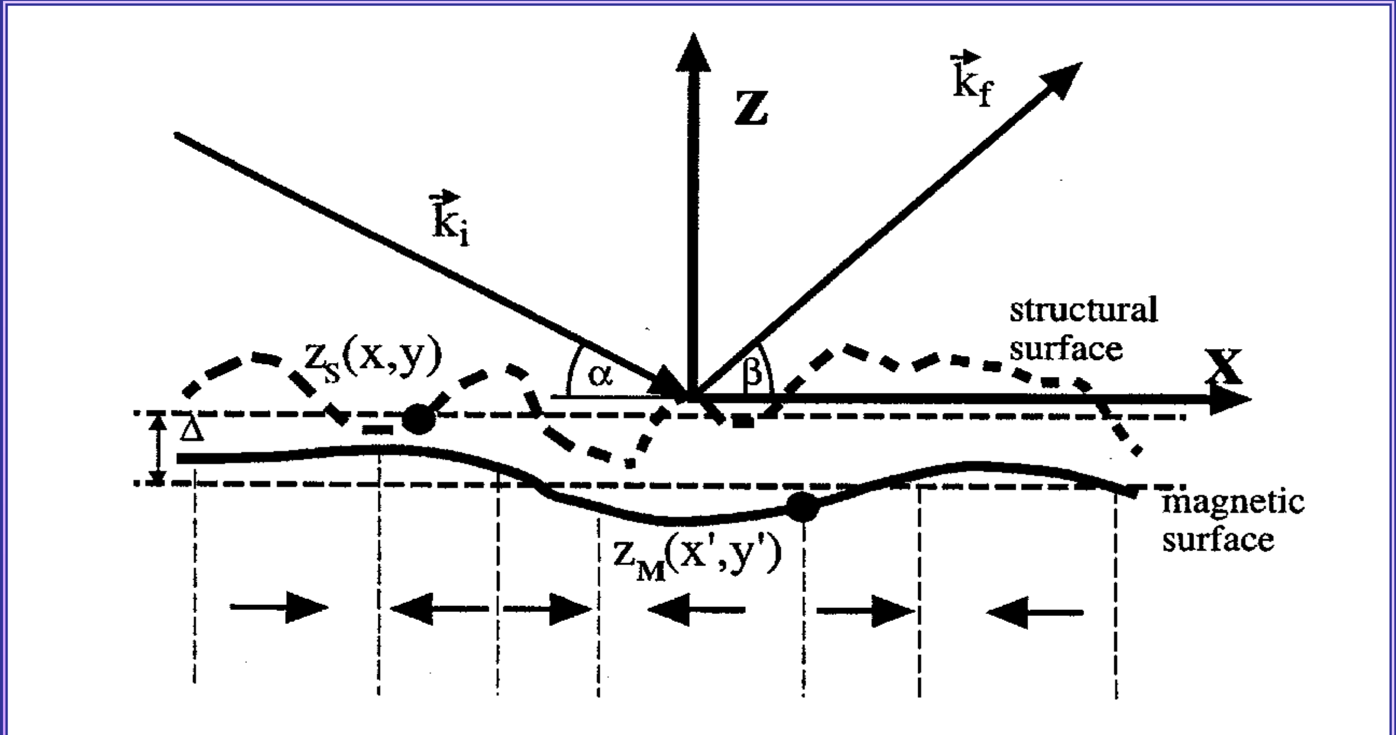
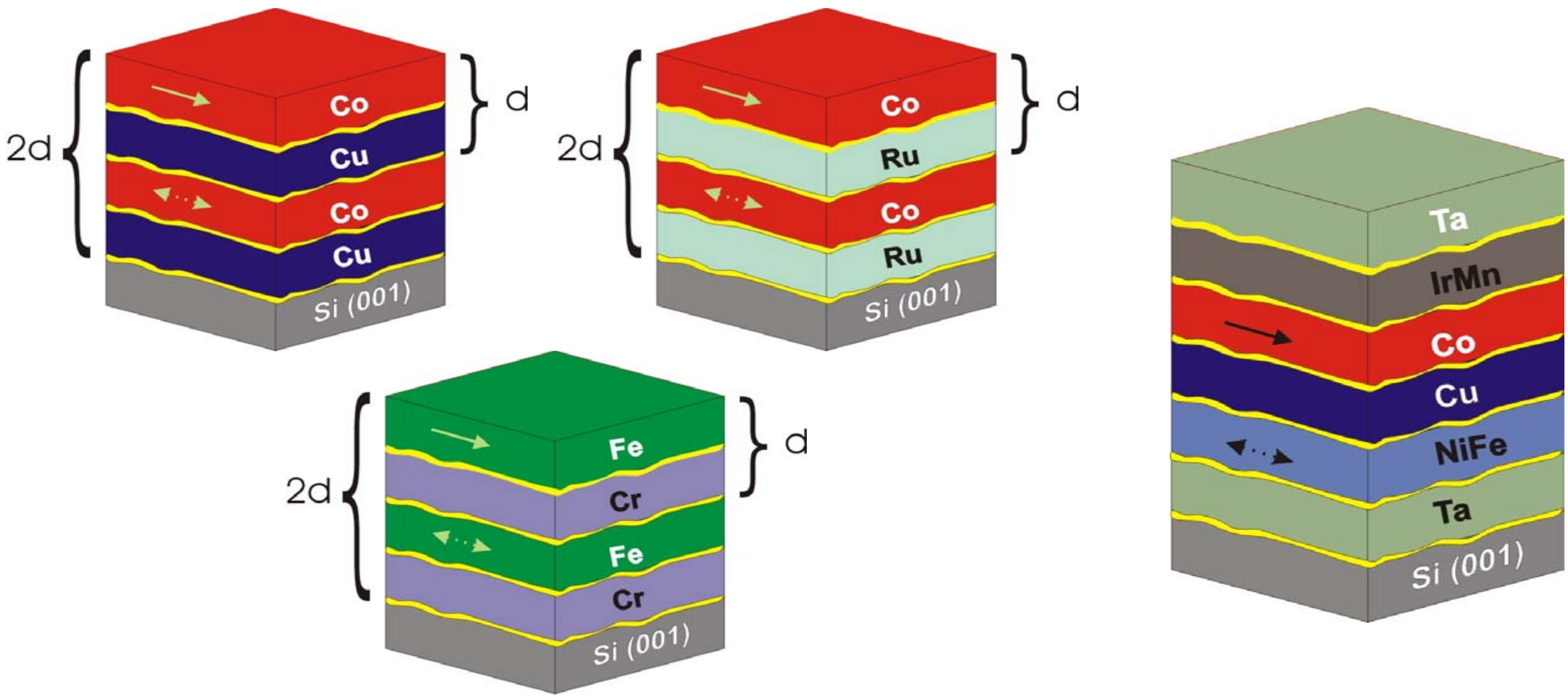
Introduction



Direct comparison between structural and magnetic interface structure

Samples

d.c. magnetron sputtered Transition metal multilayers



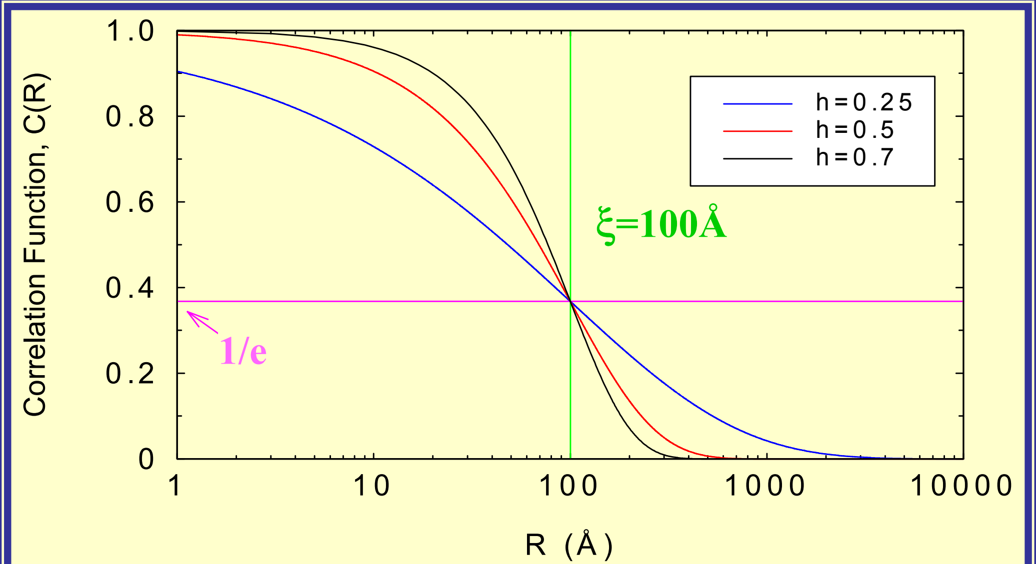
Correlation Functions

Cannot obtain surface morphology by reverse Fourier Transform of diffuse scatter

→ Define Correlation Function to describe surface

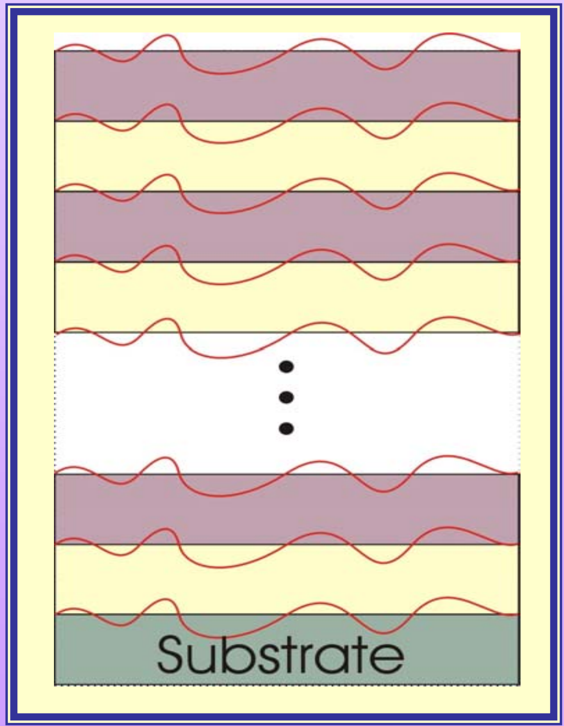
Easiest Mathematically is the Self-affine growth model:

$$C(r) = \sigma^2 \exp\left[-\left(r/\xi\right)^{2h}\right]$$

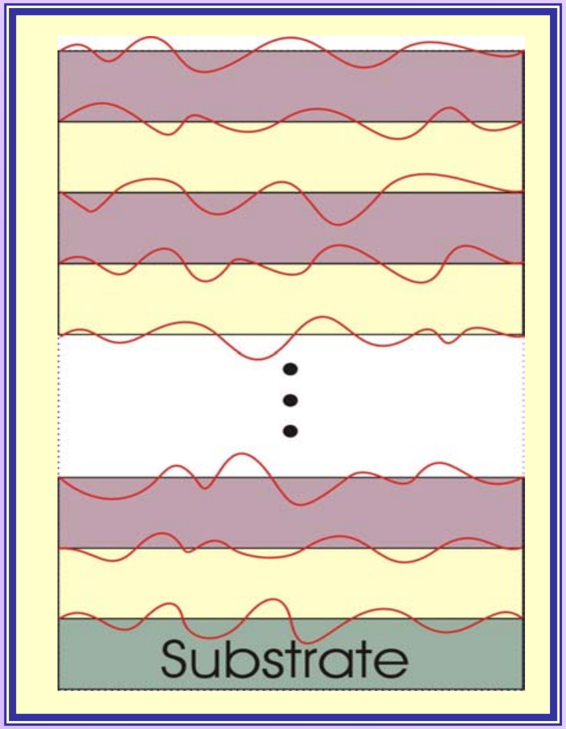


- σ - RMS Roughness
- h – Static Exponent (Fractal Parameter)
- ξ - Cut-off (Correlation Length)

Correlated Roughness

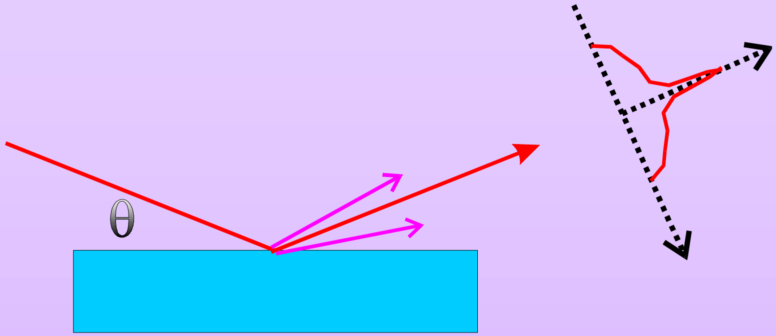


Correlated Roughness



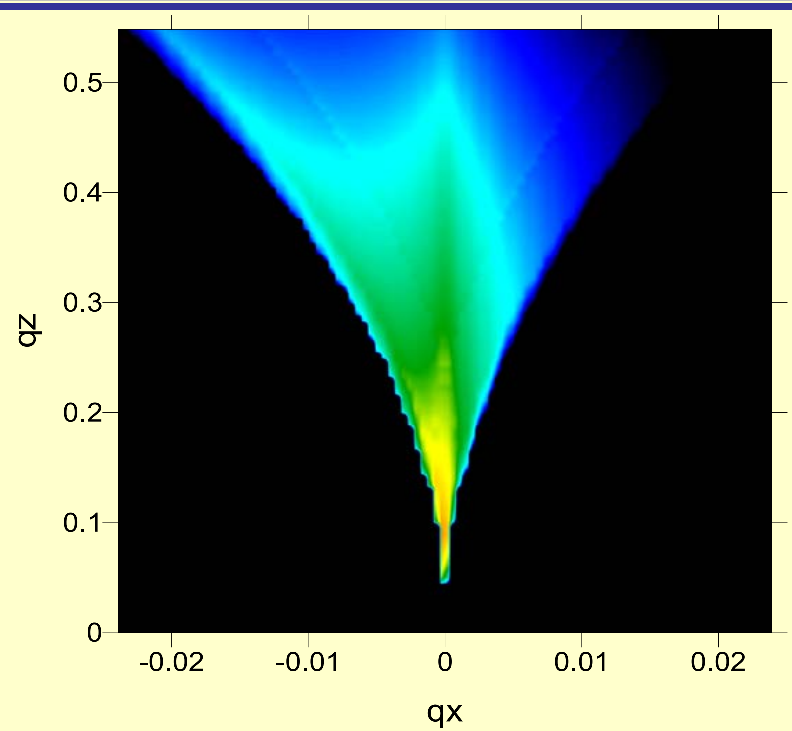
Uncorrelated Roughness

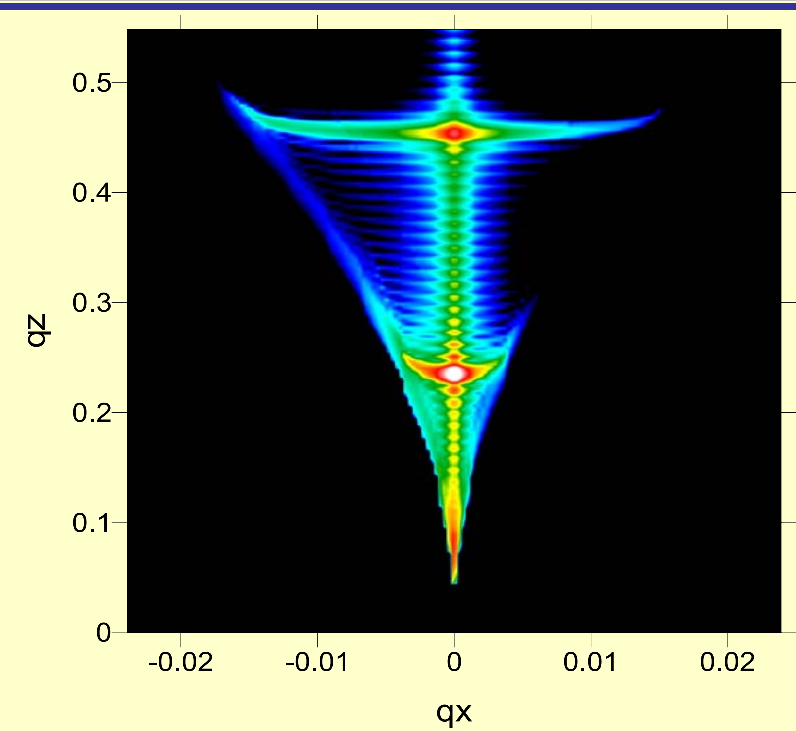
Diffuse Scatter



Detector fixed, sample scanned to probe diffuse scatter

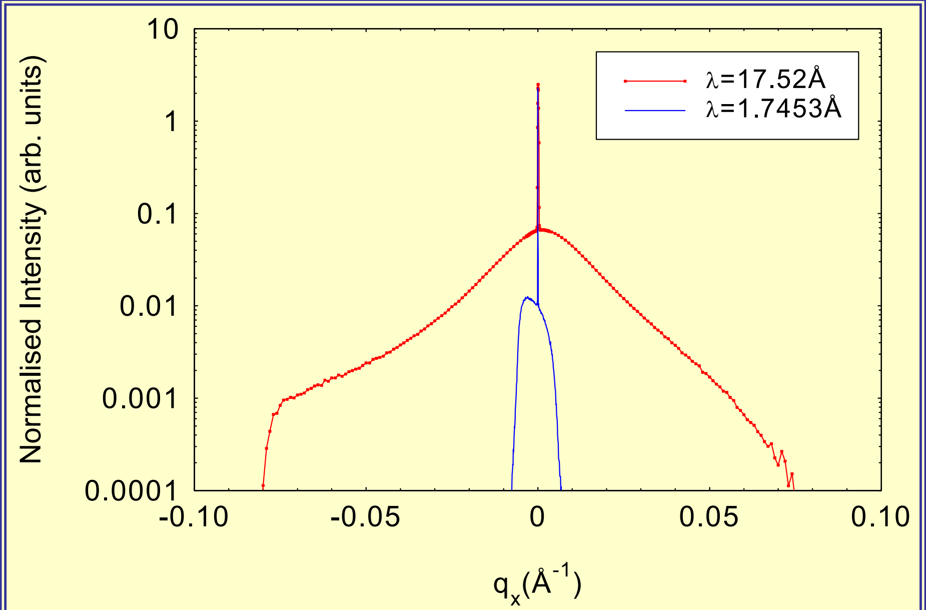
Scattering vector has in-plane component

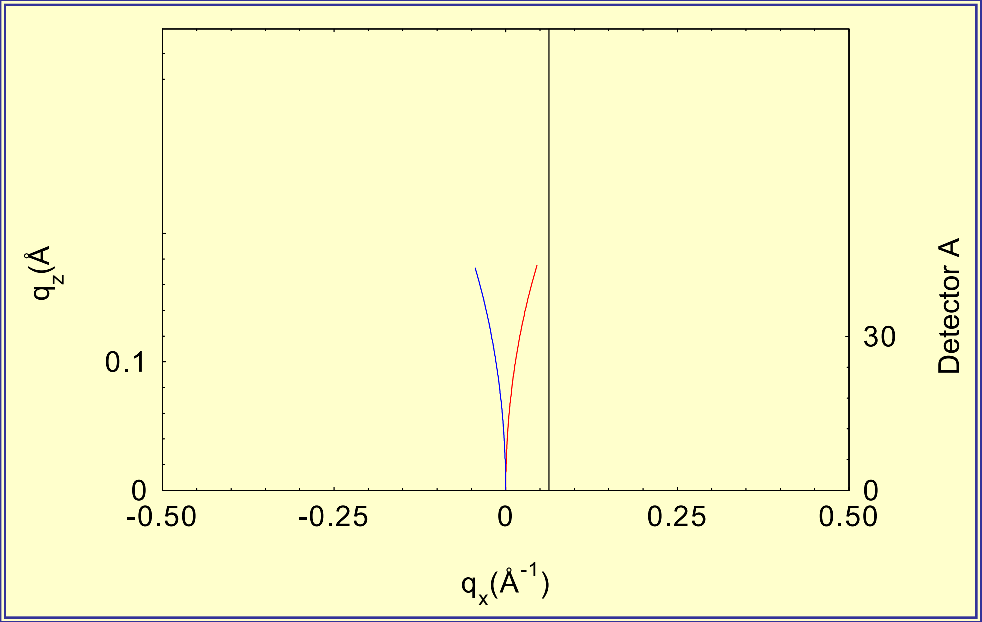




Diffuse at Soft Energies

Constant q_x scans at the Structural Bragg peak of an Fe/Cr Multilayer





Can now directly probe length scales below 100Å

PNR or SoXMaS?

PNR

- **Direct probe of atomic moment**
- **Cross Section known accurately**
- Both Ferromagnetic and Antiferromagnetic structures can be studied easily
- Not element specific
- **Low flux**
- Wide range of sample environments

SoXMaS

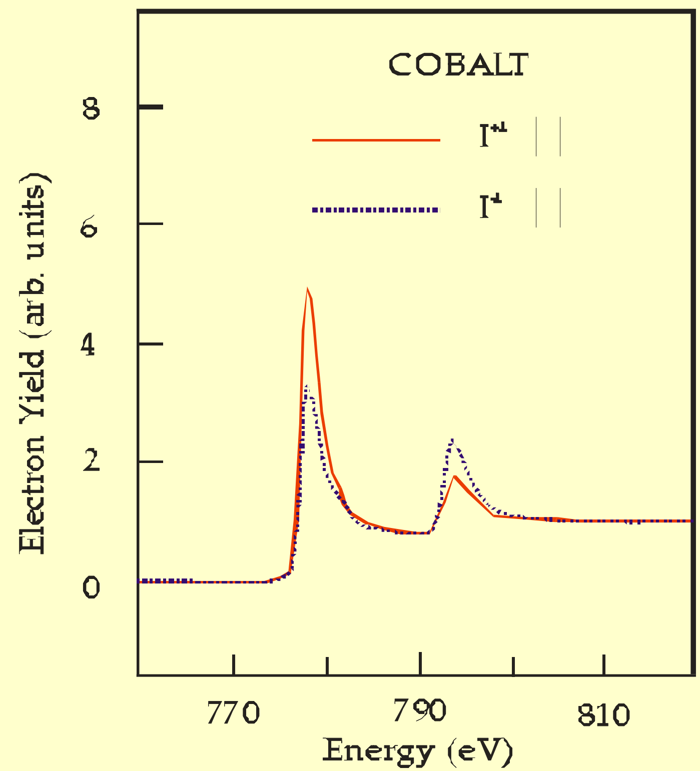
- Indirect probe of the magnetisation
- Unless a unique scattering vector can be found only measure the interference term between charge and magnetism
- **Cross Section not known**
- **High flux** and large ***q***

Can do dynamic experiments

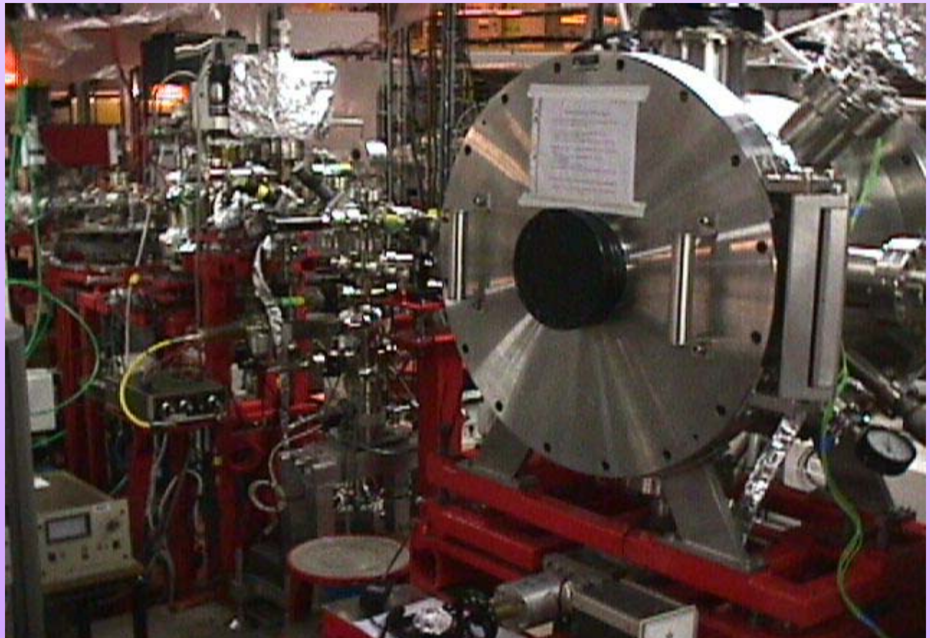
- Element Specific

Soft X-ray Resonant Magnetic Scattering (SoXMaS)

- **Scattering** around the *L* edges of the transition metals: 500 – 1000 eV
- Magnetisation splits empty states giving sensitivity to the magnetisation from a charge, dipole transition.
    - Theory behind MXCD & XPEEM

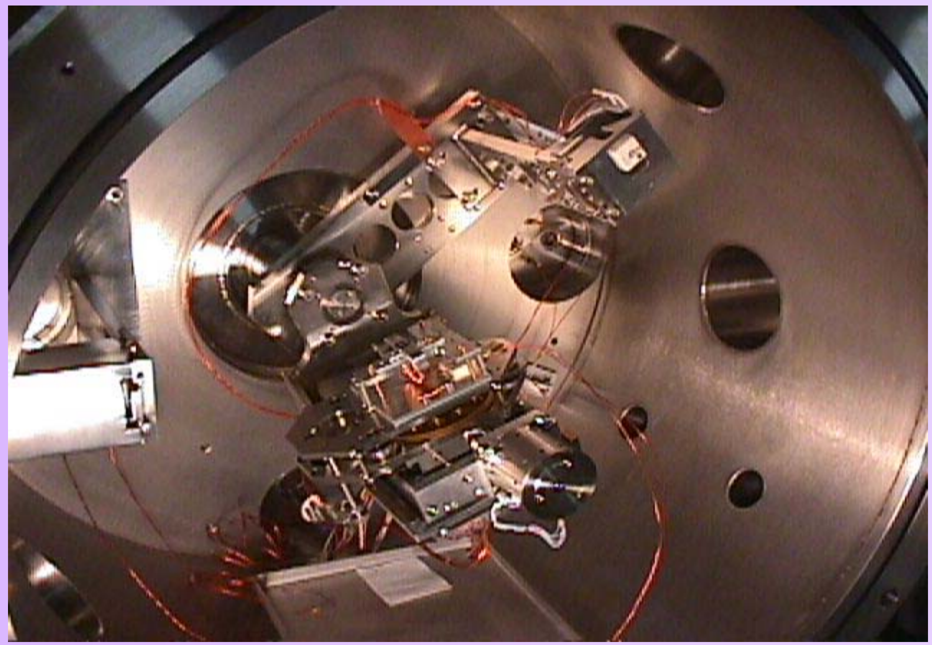


SoXMaS - Experiments



2-circle, *in-vaccu* diffractometer

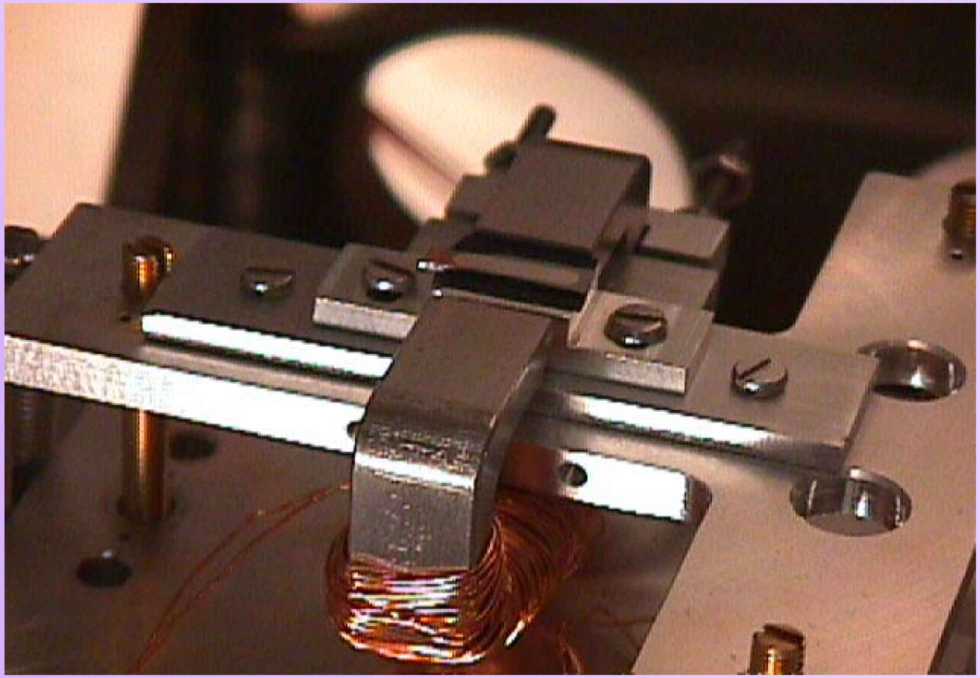
Typical parameters are 300μm resolution and beam defining slits



Linear polarisation using stations 5U1 & 1.1 SRS, Daresbury. Variable polarisation from ID12B at the ESRF

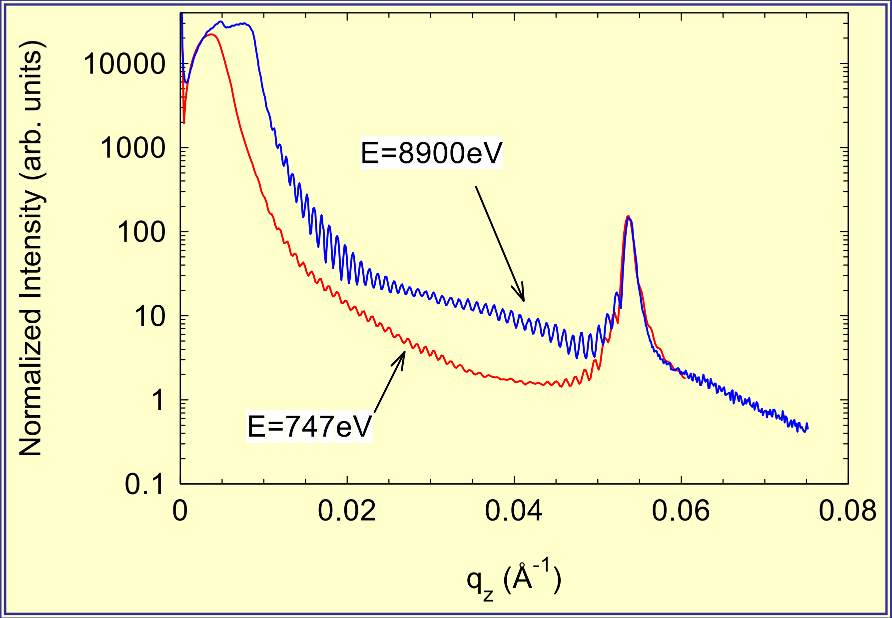
Magnetisation Experiments

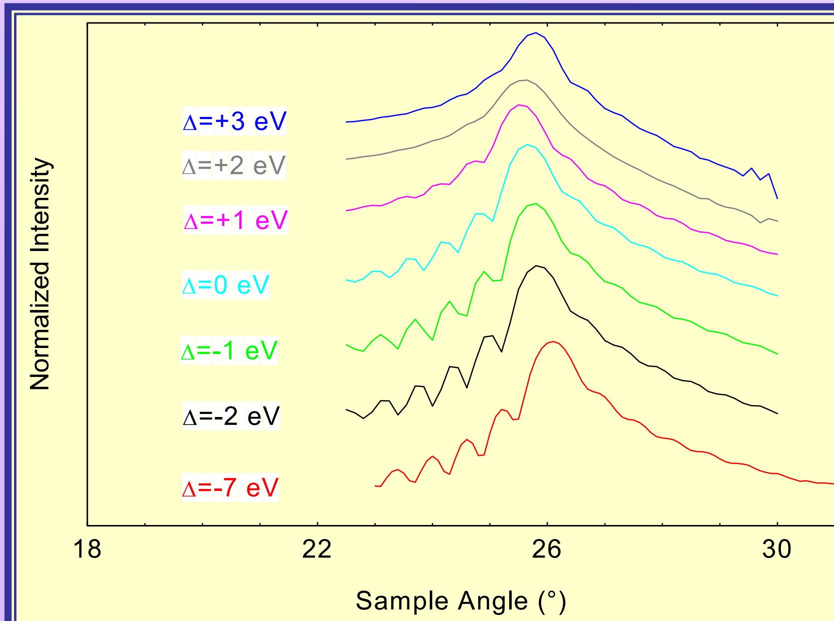
Study the rotation of the magnetisation for fields up-to 70mT applied either orthogonal or parallel to the scattering plane



Element, coupling specific magnetisation experiments in multilayers and spin valves

Absorption issues

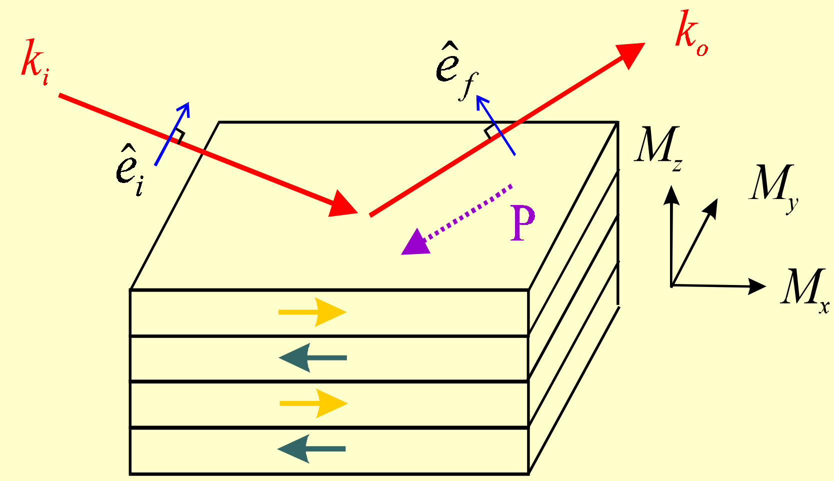




On resonance the absorption is high, but the largest signal occurs just below the edge, and here the x-rays penetrate the whole 1000Å thick sample.

Theory

Combine MXCD with scattering and we can obtain information about the magnetic interface morphology



$$f_{Dipole}^{XRES} = (\hat{e}_i \cdot \hat{e}_f)F^{(0)} - i((\hat{e}_i \times \hat{e}_f)\cdot \hat{M}_n)F^{(1)} + (\hat{e}_i \cdot \hat{M}_n)(\hat{e}_f \cdot \hat{M}_n)F^{(2)}$$

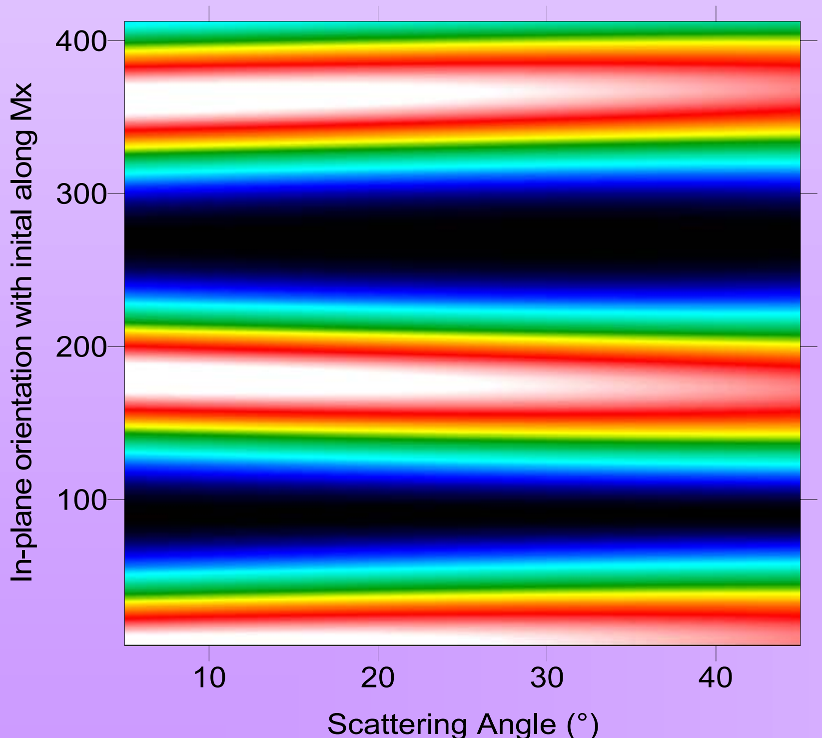
$$f_{Dipole} = f_0 + F^{(0)}\begin{pmatrix} 1 & 0 \\ 0 & \cos 2\theta \end{pmatrix} - iF^{(1)}\begin{pmatrix} 0 & M_x \cos\theta \\ -M_x \cos\vartheta & -M_y \sin 2\theta \end{pmatrix} + F^{(2)}\begin{pmatrix} M_y{}^2 & -M_y M_x \sin\theta \\ M_y M_x \sin\theta & -M_x{}^2 \cos^2\theta \tan^2\theta \end{pmatrix}$$

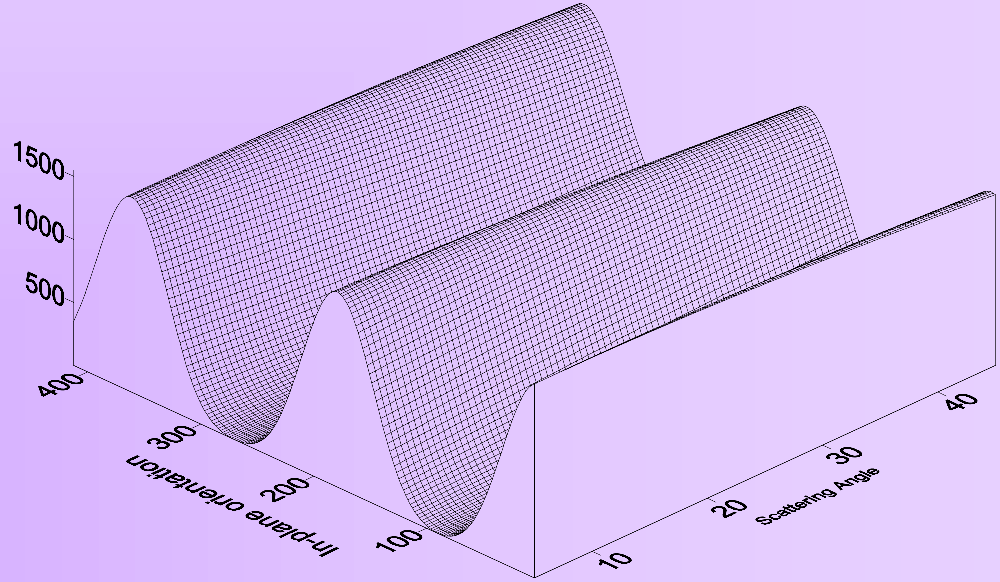
$$\textit{Pure Mag. Scattering} \propto (\hat{e}_f \times \hat{e}_i)\cdot \mathbf{M} = \mathbf{P}\cdot \mathbf{M}$$

J.P. Hill & McMorrow *Acta. Cryst.* A52 236 (1996)

Linear Polarisation

Sigma Polarisation for Co

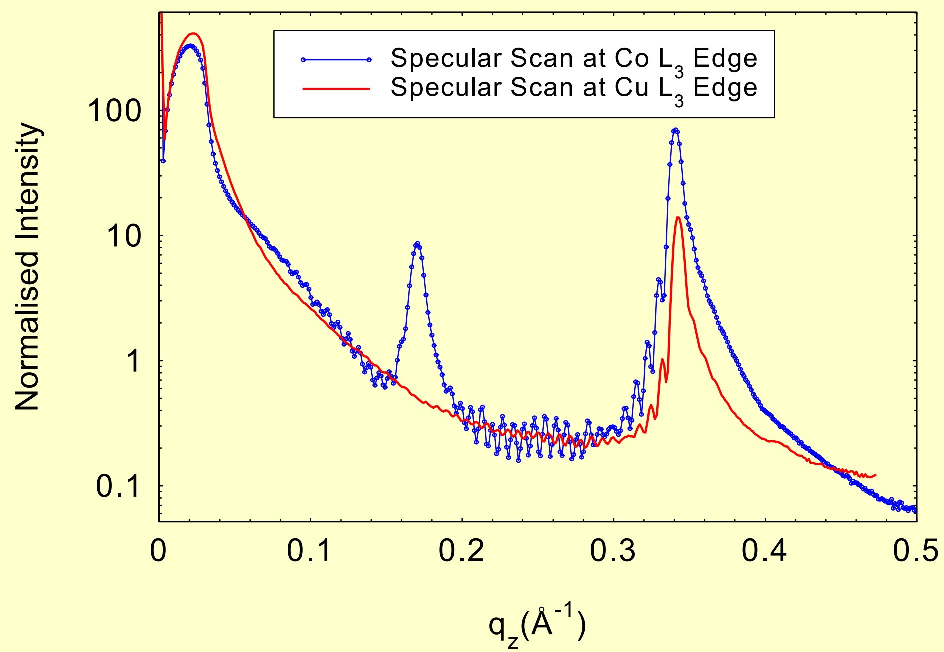




Scattering proportional to component of magnetisation in the scattering plane (along M_x)

Resonant Specular Scatter

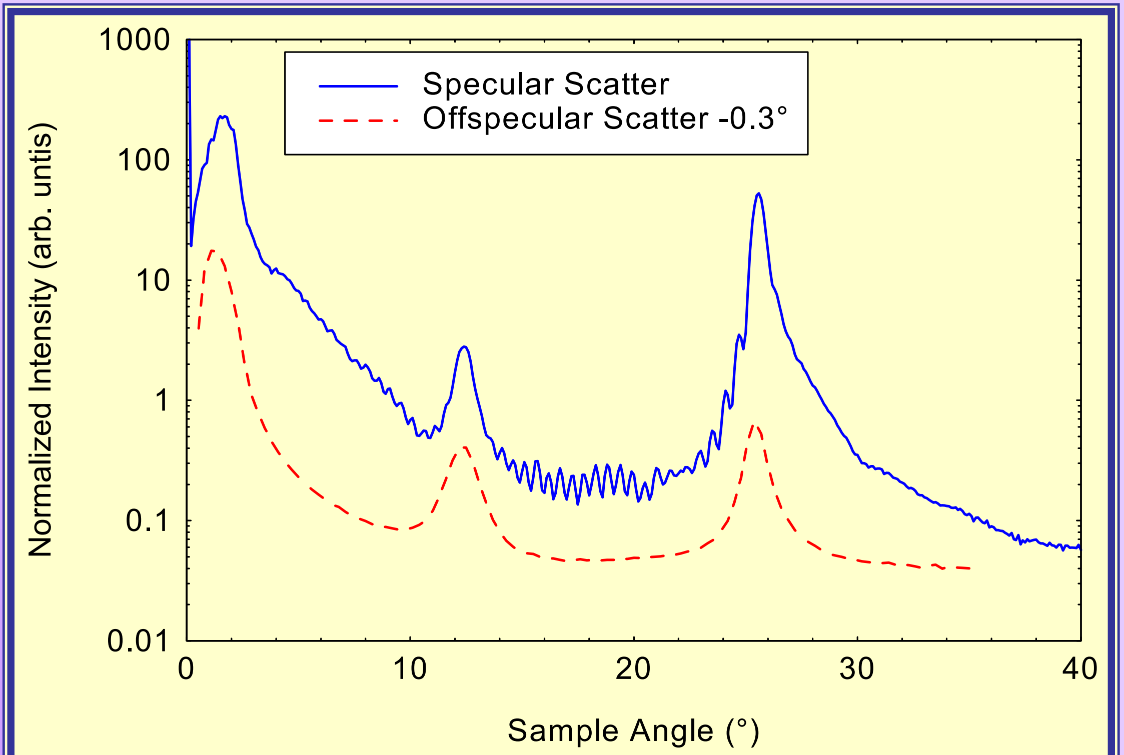
Cu/Co Multilayers grown at 1st AF coupling peak



❖ Pure magnetic Bragg peaks were observed for all samples at q/2 when the incident energy was tuned to the Co L3 edge.

❖ No resonance was observed at the Cu edge suggesting that there is no significant magnetic moment penetrating the copper spacer layer.

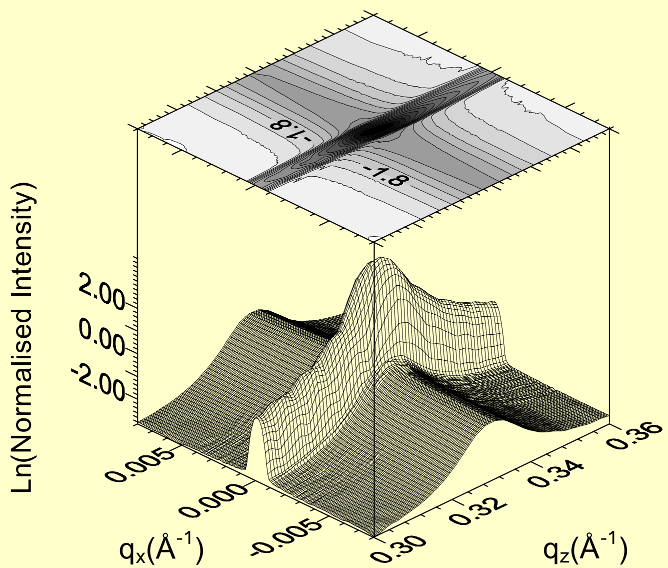
Longitudinal Diffuse scans



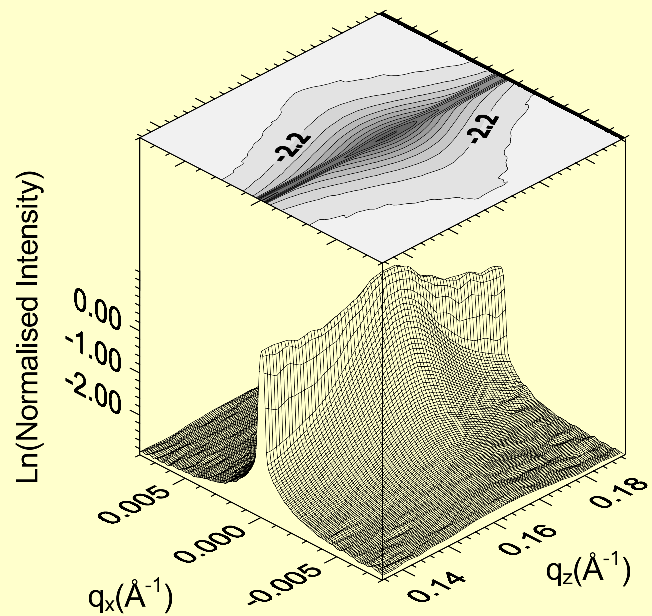
For all samples studied, both the magnetic and structural disorder was conformal out of the plane.

AF Cu/Co Samples

Charge and Magnetic information in transverse diffuse scans at different q_z due to magnetic propagation vectors



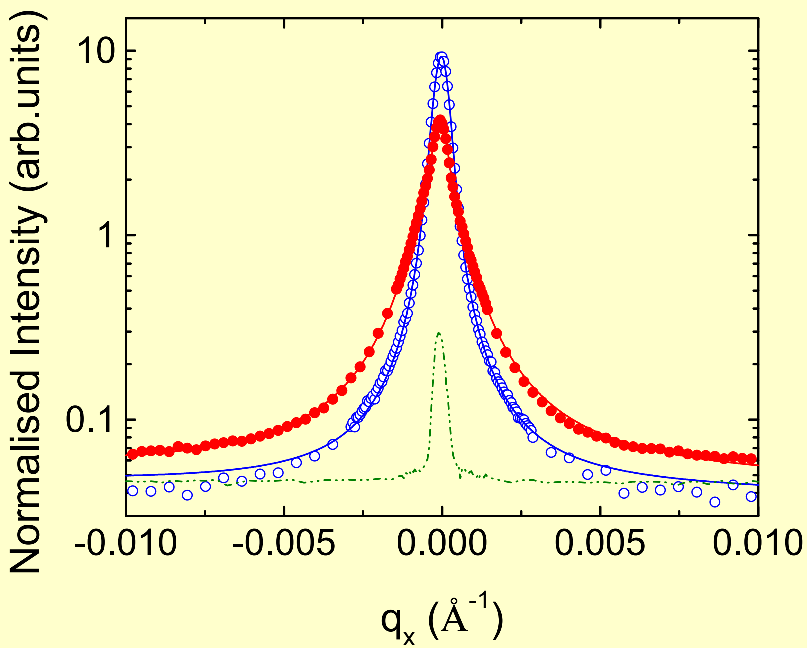
Cu/Co at 1st AF coupling peak

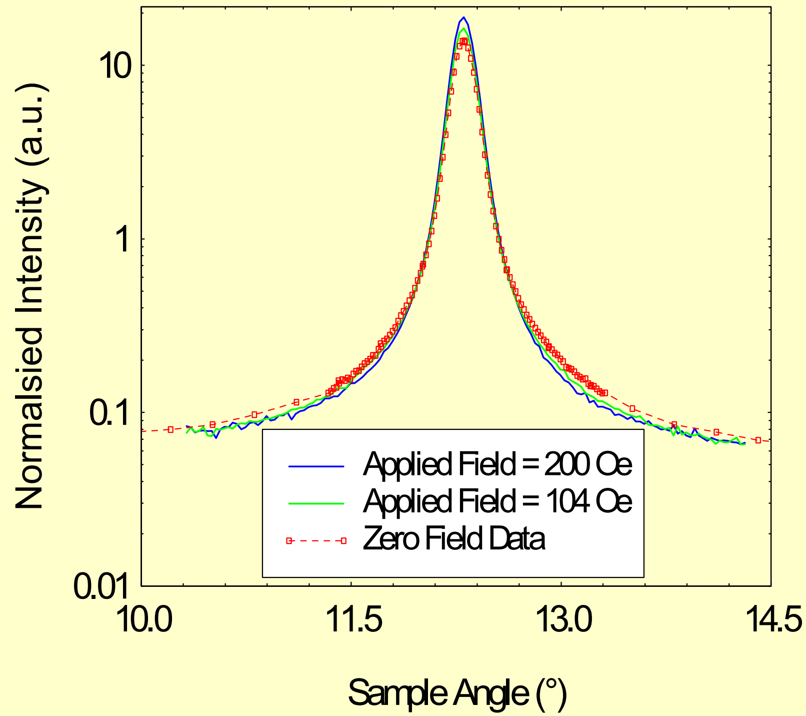


Roughness: σ_s (struc. Bragg Peak) = 2.8 ± 0.5Å

σ_m (easy axis) = 3.1 ± 1.0Å, σ_m (hard axis) = 5.8 ± 1.0Å

Correlation Lengths

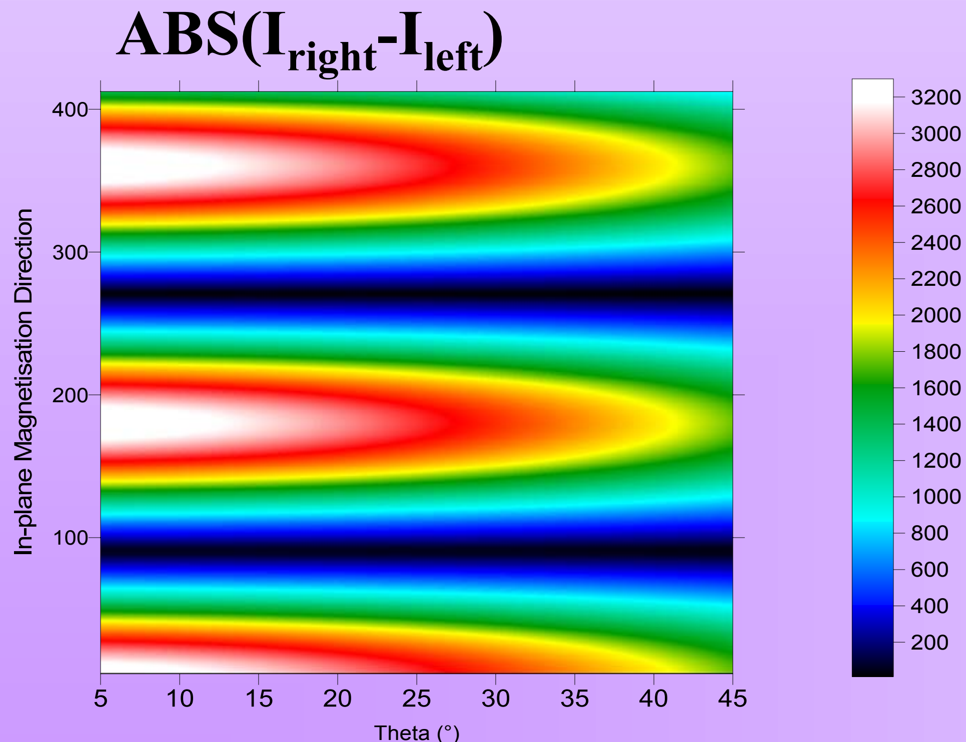


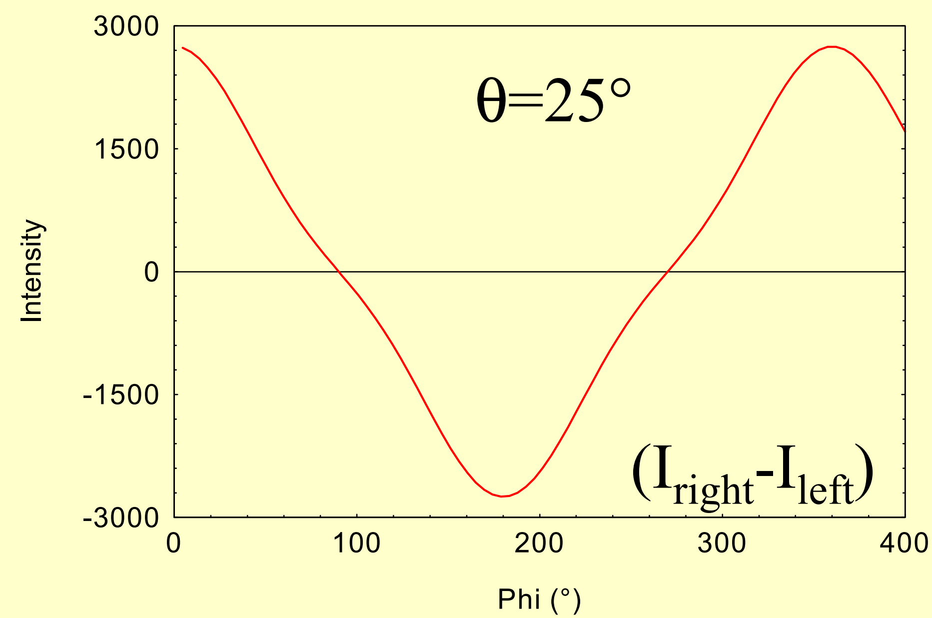


The correlation length, was 9,800 ± 250Å when magnetised perpendicular and 4,600 ± 250Å for magnetisation parallel to the scattering plane.

Circular Polarisation

Dichroic Signal – Magnetic information obtained by subtracting data recorded with light of opposite helicity



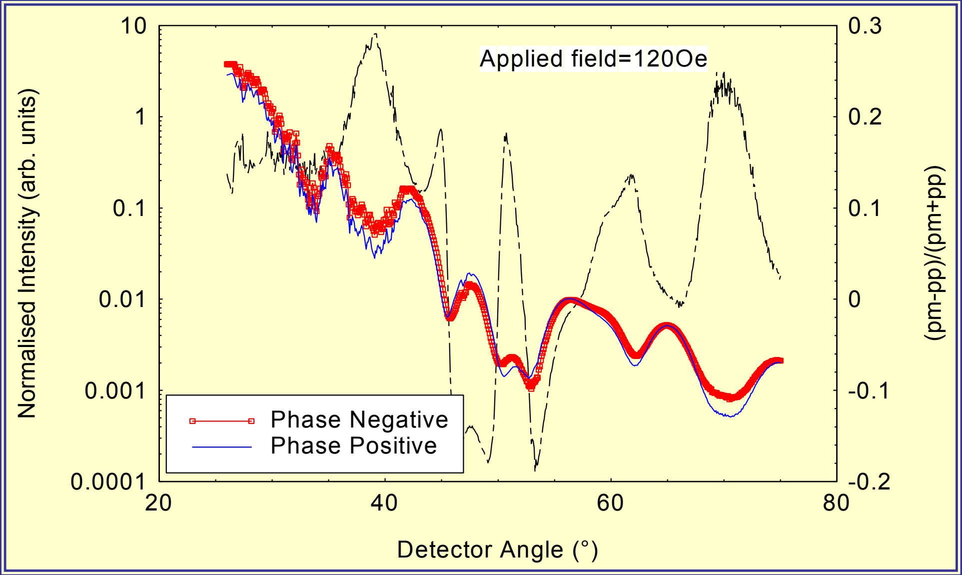


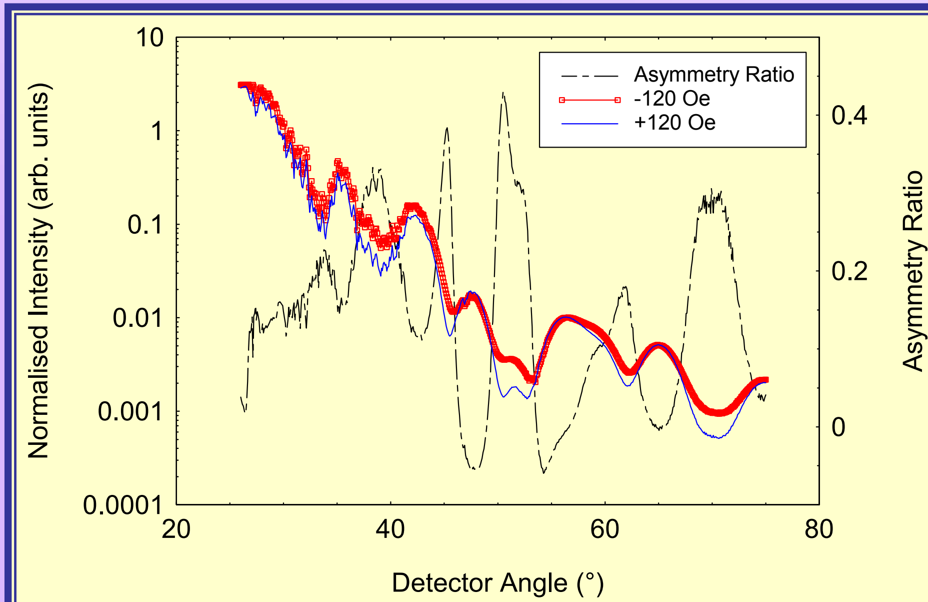
Again x-ray scattering experiments sensitive to $\pm M_x$

Spin Valves

Si:Ta/NiFe/Cu/Co/IrMn/Ta

No unique momentum transfer for magnetic scatter

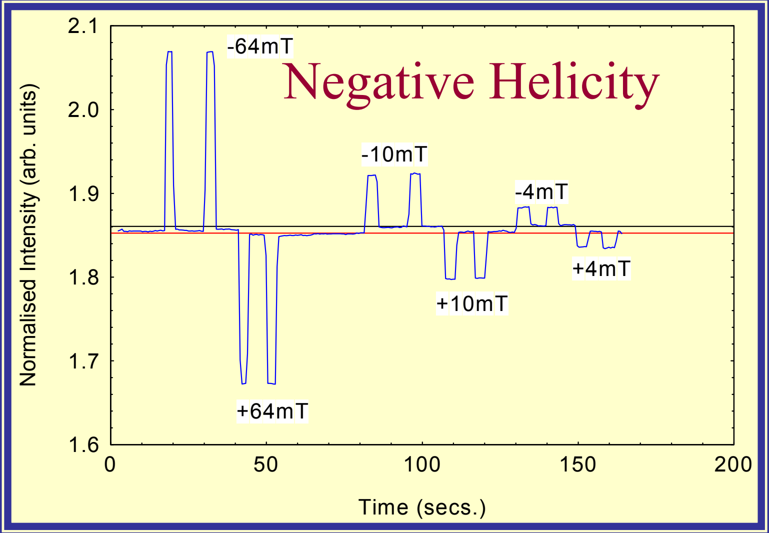




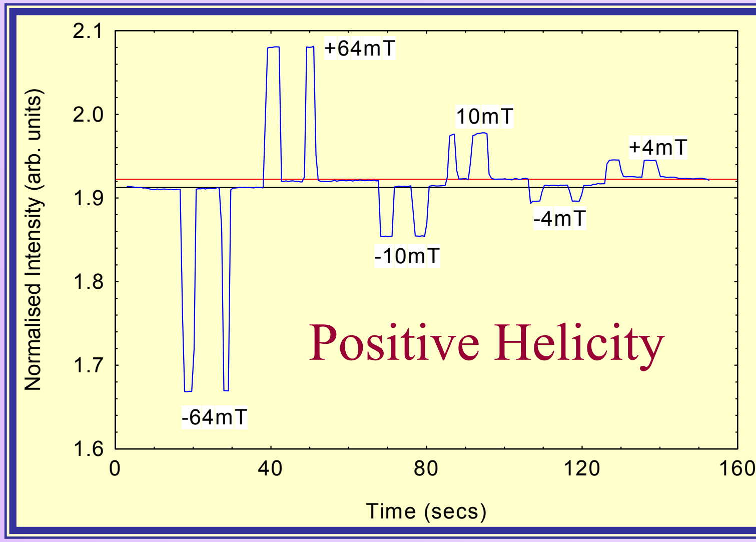
Need to use circular polarised x-rays and measure the difference in intensity between positive and negative helicity…

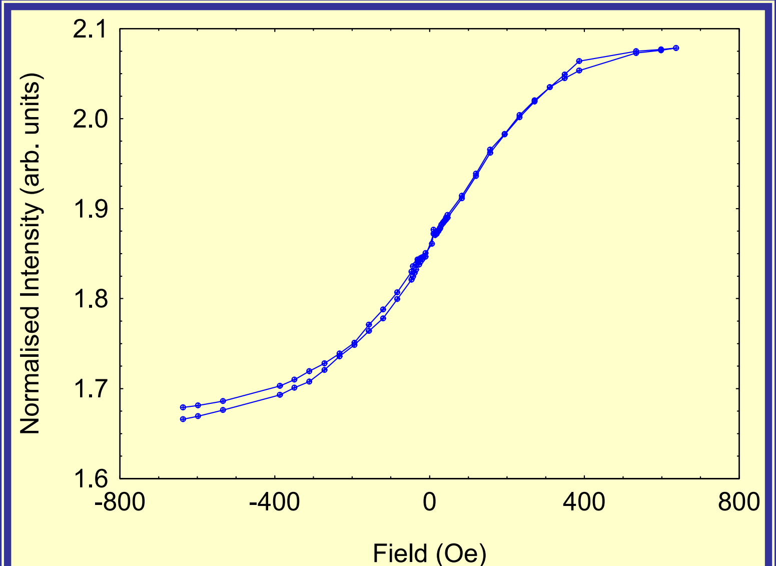
…or difference between positive and negative fields.

Magnetisation Loops



No evidence for time dependence on field application

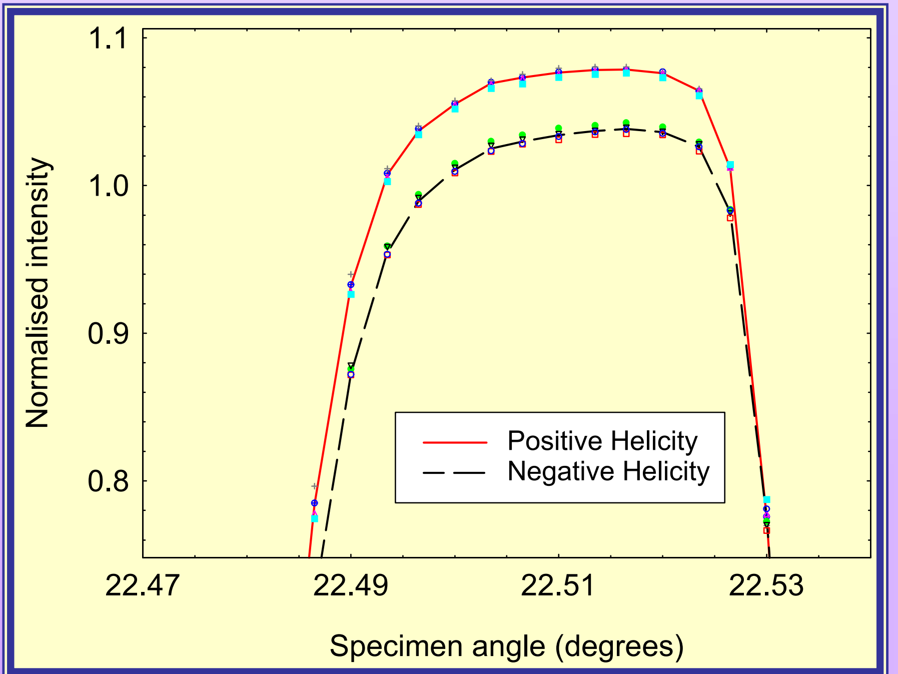


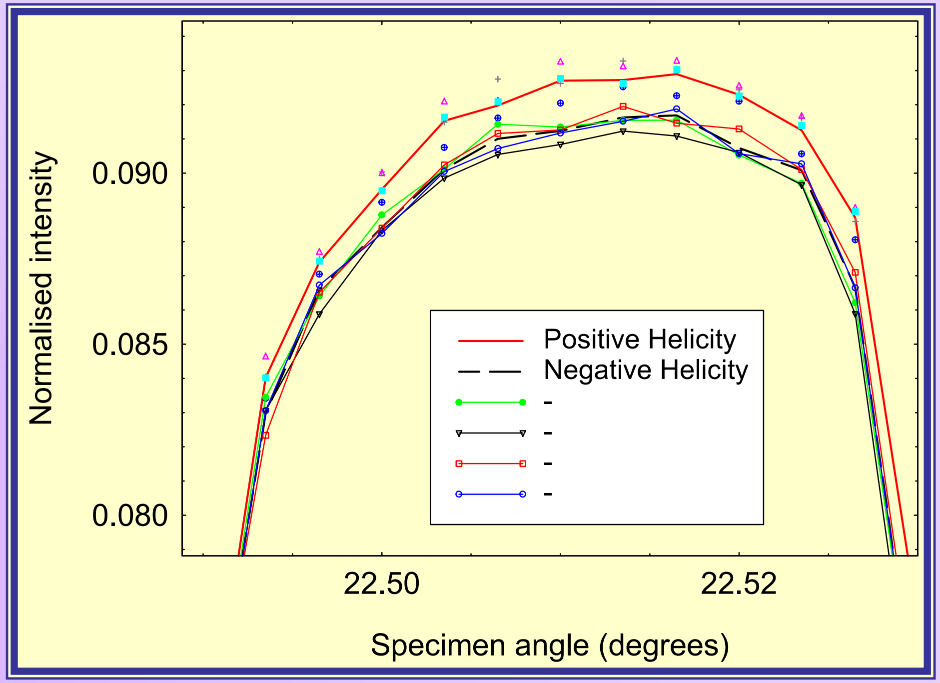


Fix momentum transfer and monitor the intensity as a function of field.

Hard axis Magnetisation loop for 20Å Co

Mn L_3 Edge





Near Mn L_3 Edge

20eV below Mn L_3 Edge

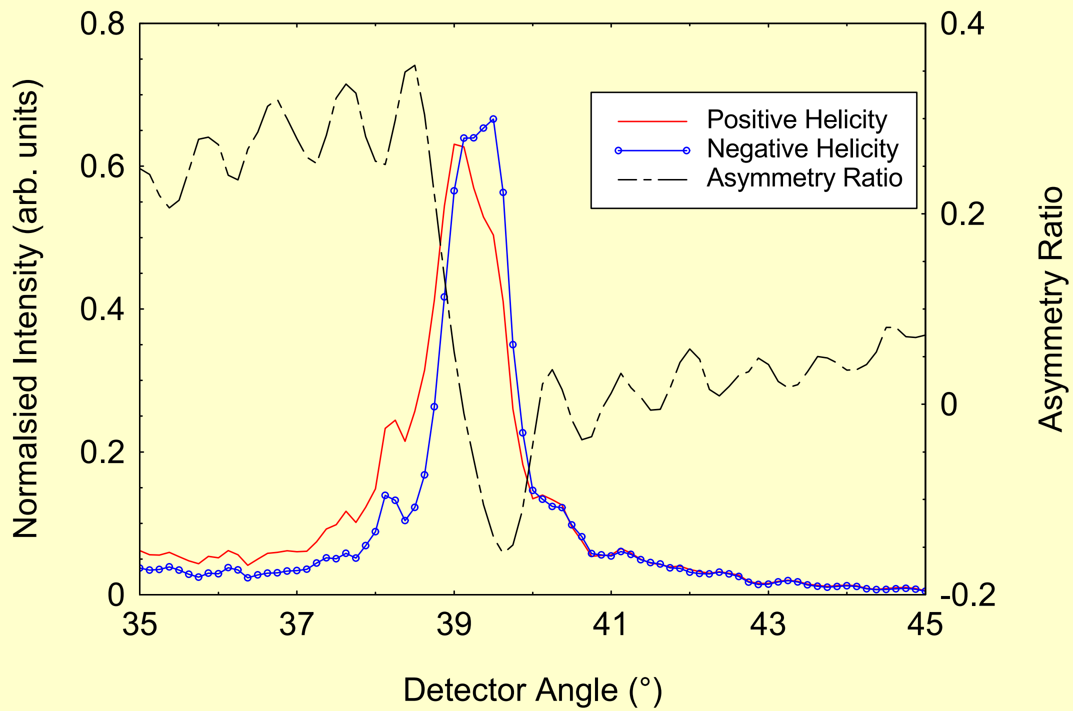
Helicity dependence of the specular intensity on resonance

Ferromagnetic component in the AF pinning layer

Specular Scatter

Circular polarised light and measure dichroic signal

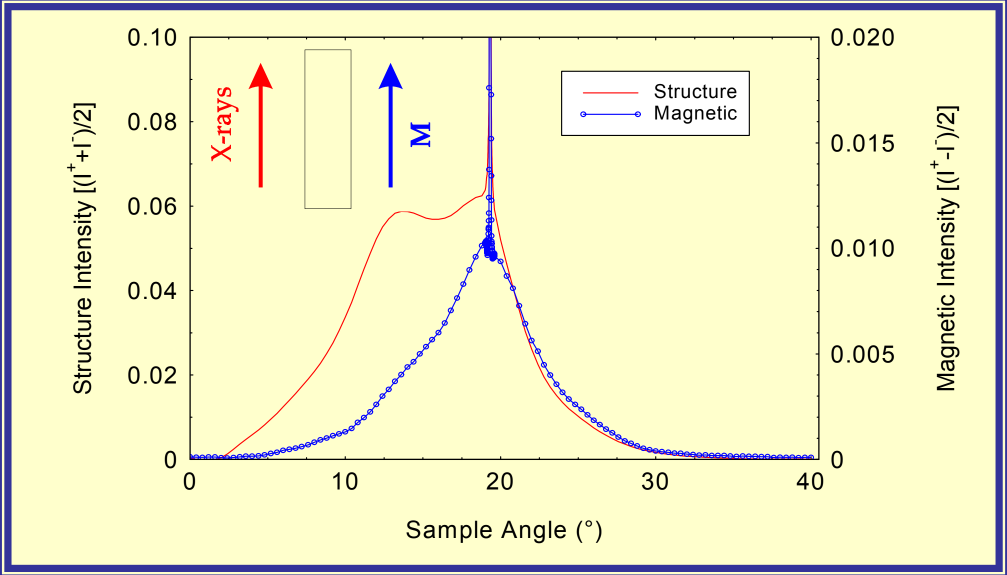
Ferromagnetically coupled Co/Cu Multilayer

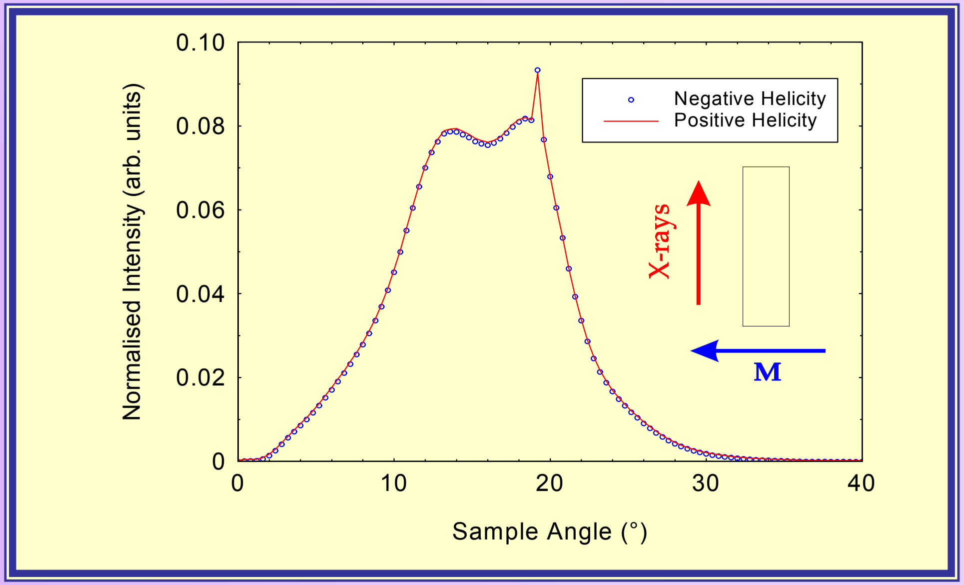


Small change seen in specular scatter for the two helicities, larger difference observed in the diffuse scatter.

Ferromagnetic Samples

Circular polarised light and measure dichroic signal





Magnetic diffuse only observed when M lies in the scattering plane

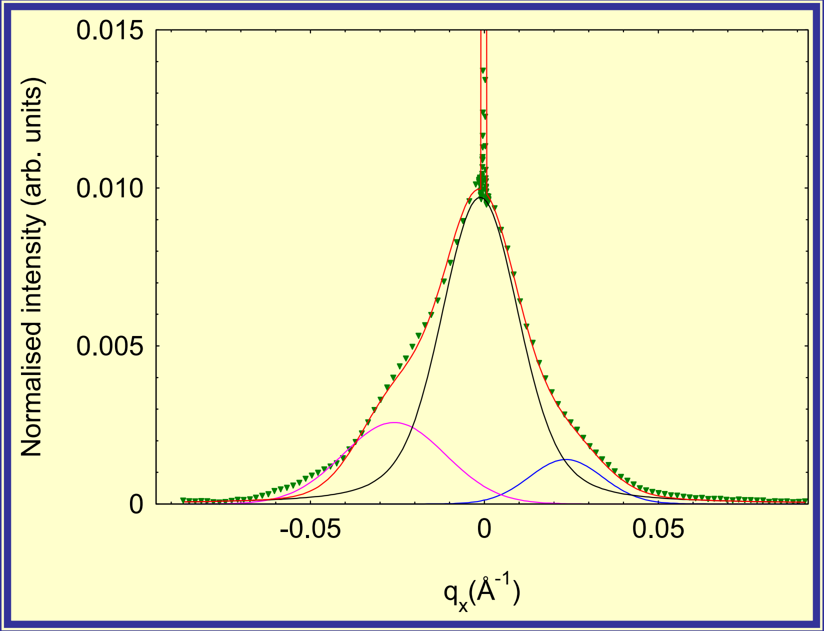
ξ in Ferromagnetic Samples

The difference spectra is not purely magnetic in origin but is an interference between the pure magnetic and charge surfaces.

$\sigma_{sm}=4\pm0.5$Å
$\xi_{sm}=375 \pm 20$Å

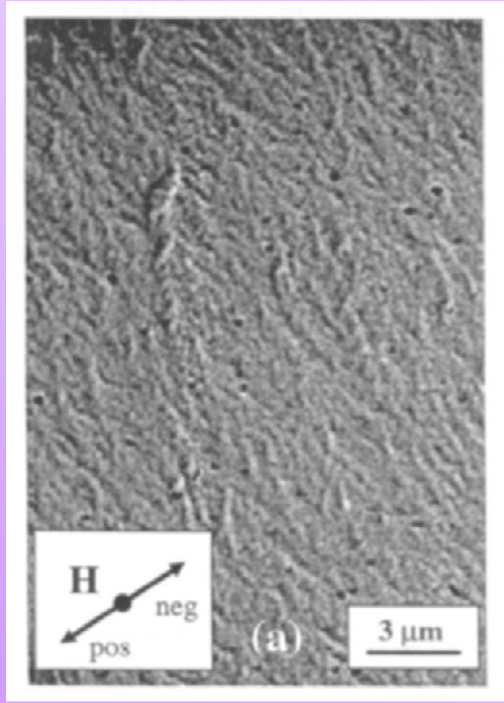
$\sigma_s=3\pm0.5$Å
$\xi_s=236 \pm 20$Å

'Magnetic' correlation length & roughness only slightly larger than that for the structural interface



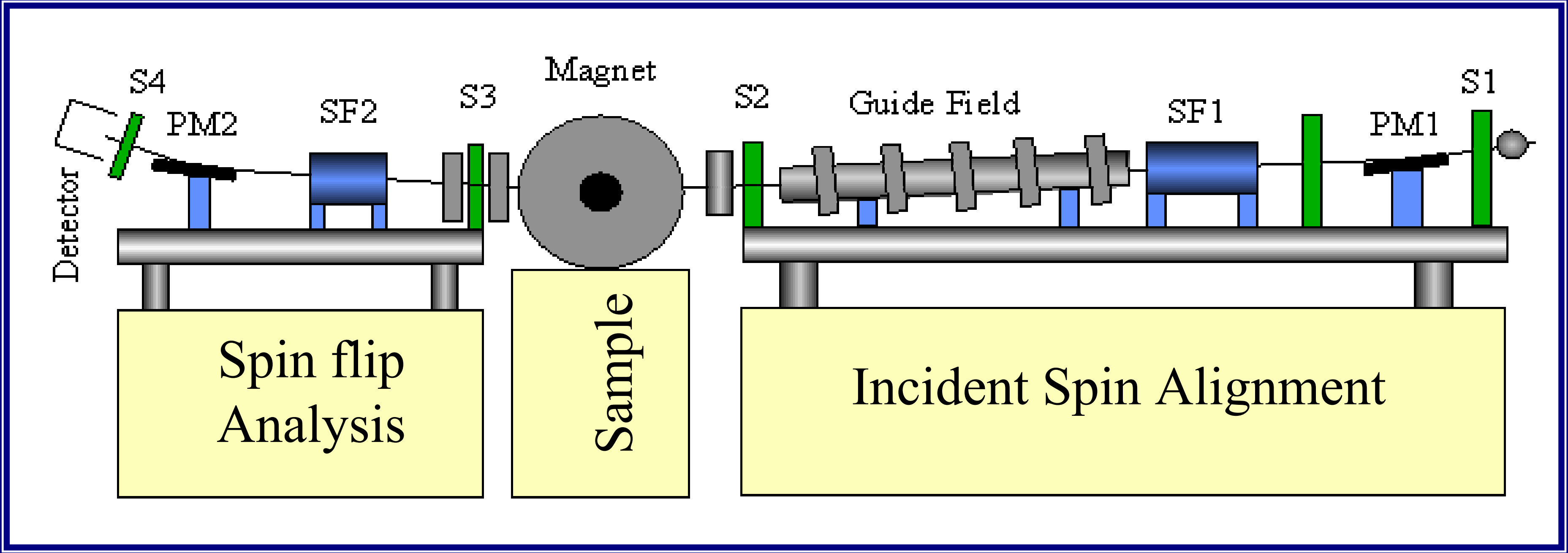
Both scans show peaks associated with a blazed grating on the substrate, with $\xi_{bg}=262\pm20$Å

What are we Measuring?



Length scales are similar to the Magnetic ripple observed in Lorentz TEM studies

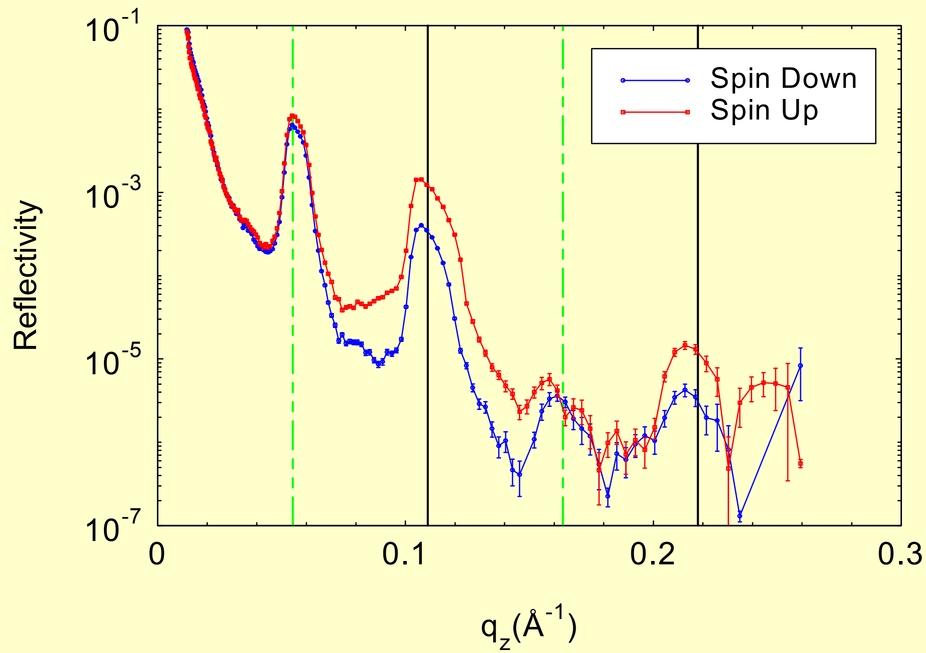
Polarised Neutron Reflectometry - CRISP

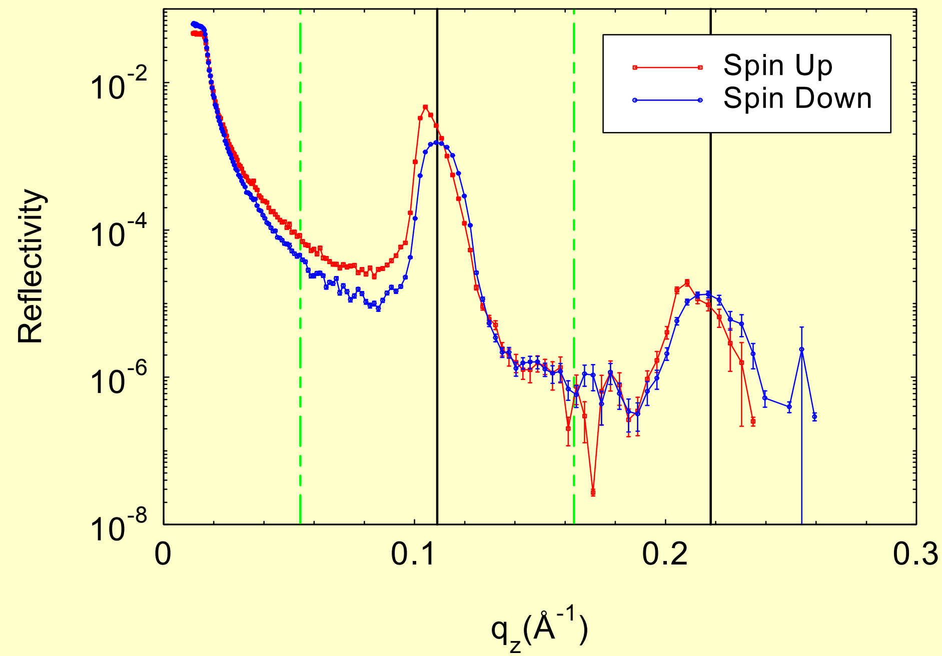


The neutron interacts with both the nucleus of atoms as well as any magnetic moment through its spin.

Spin analysis gives important information about the moment orientations within the plane of the sample

Co/Ru: PNR



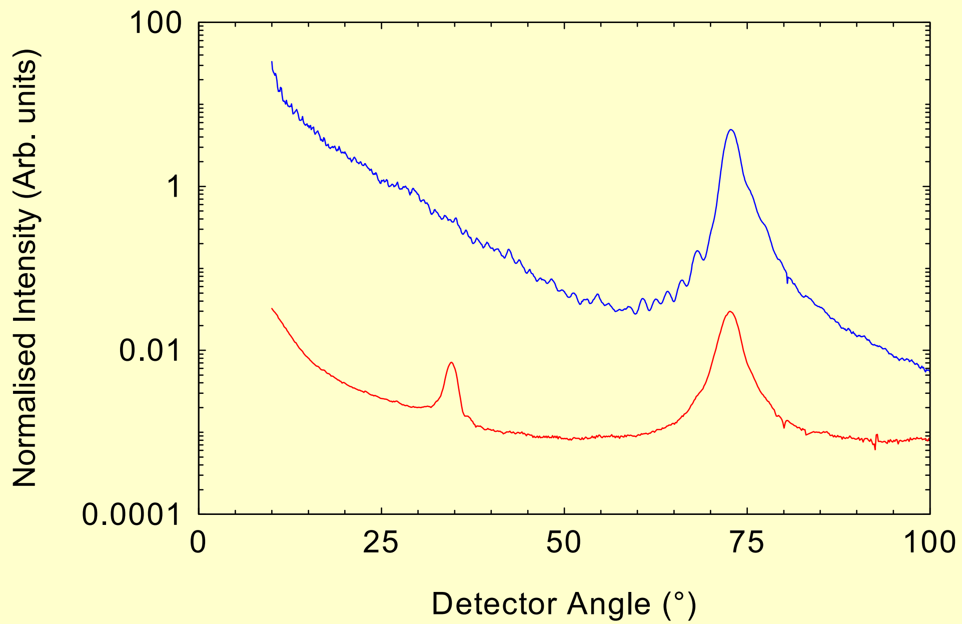


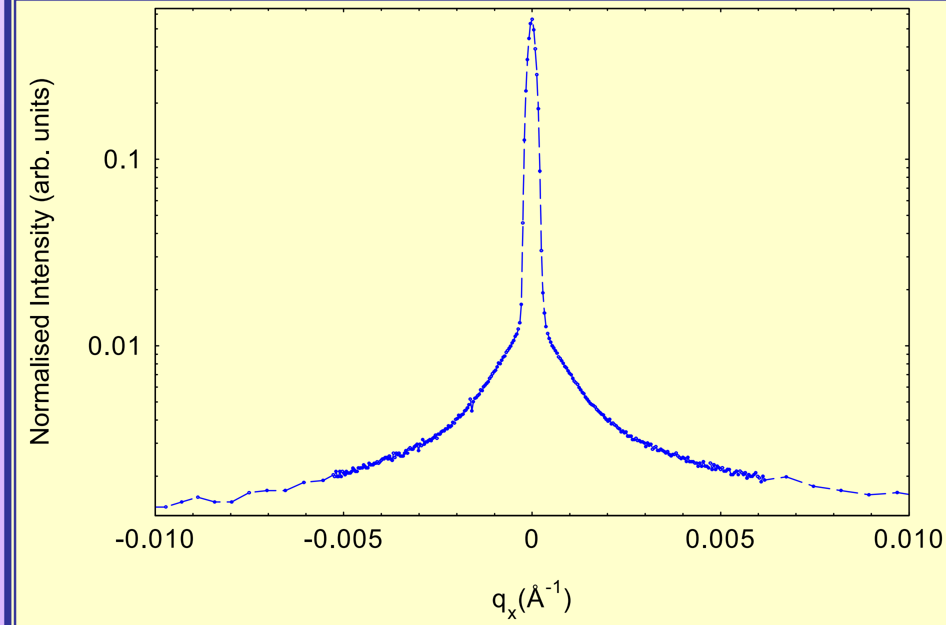
200 Oe, AF Coupled

2.6 kOe, F Coupled

Strong Bragg peaks arising from both the nuclear and magnetic superstructures

Co/Ru - SoXMaS



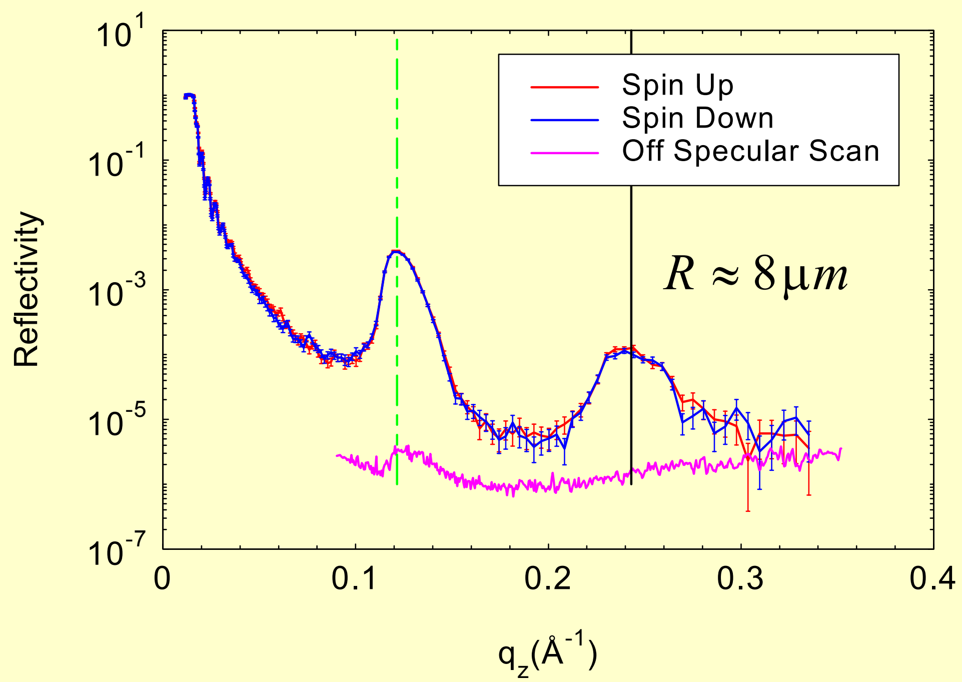


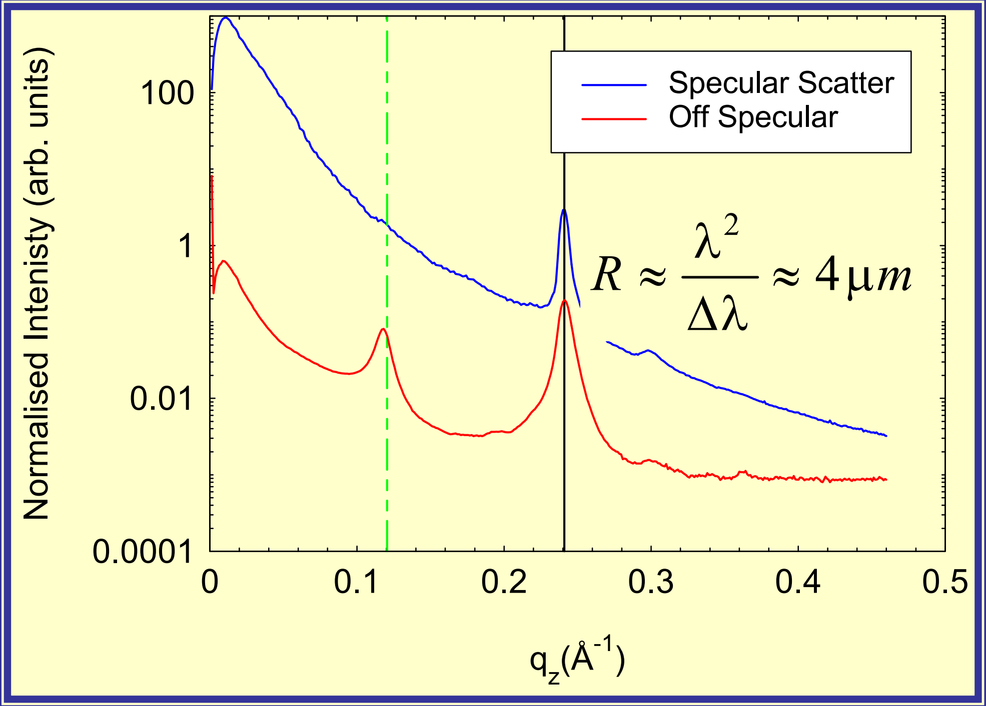
No magnetic specular peak observed, although we do see conformal, magnetic and structural disorder which have different in-plane correlation lengths

PNR

Fe/Cr

SoXMaS

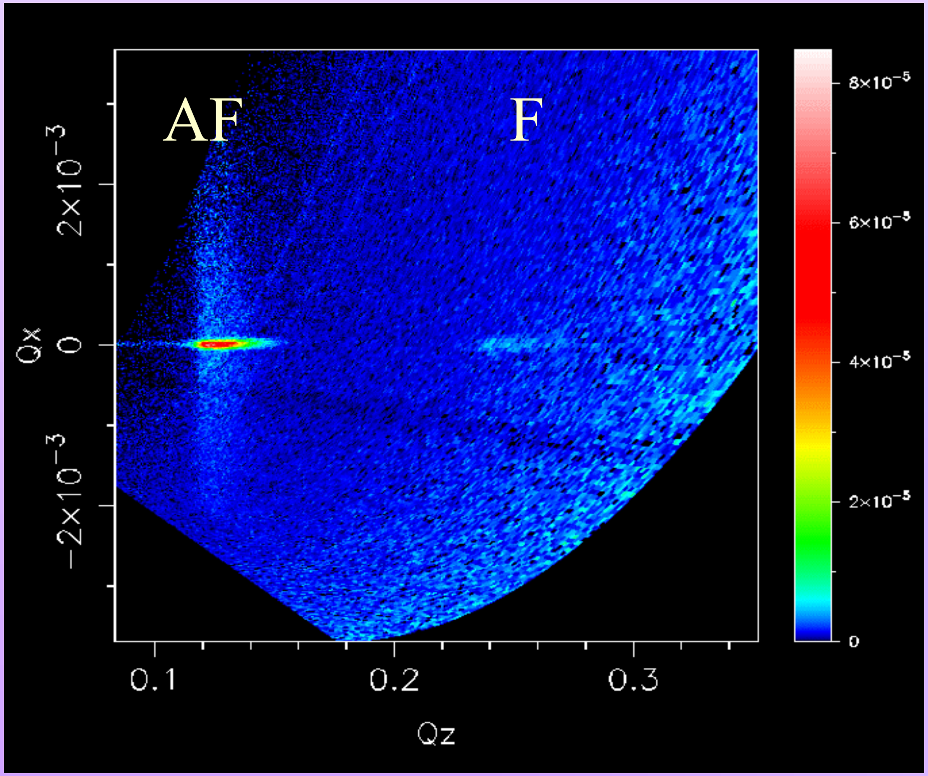


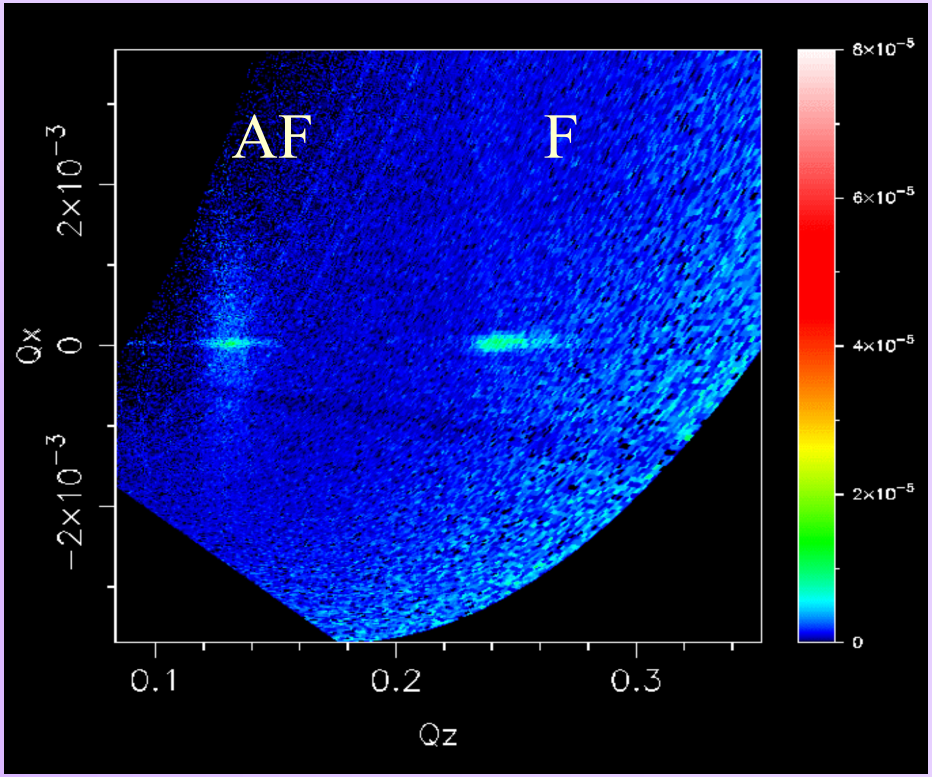


- Strong Specular AF and Nuclear peaks
- Weak diffuse scatter

- Strong Specular Charge peak, no AF peak
- Strong AF and Charge peaks in diffuse scatter

Off-specular Fe/Cr: PNR





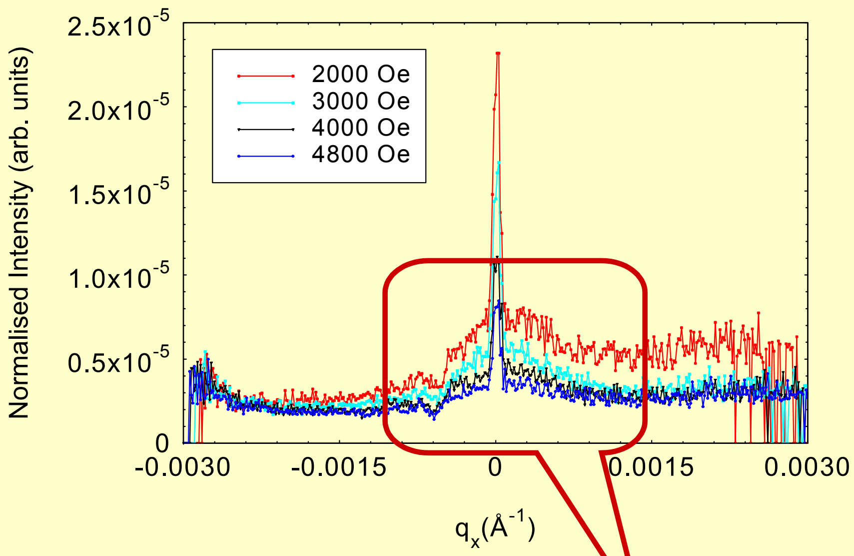
200 Oe, AF Coupled

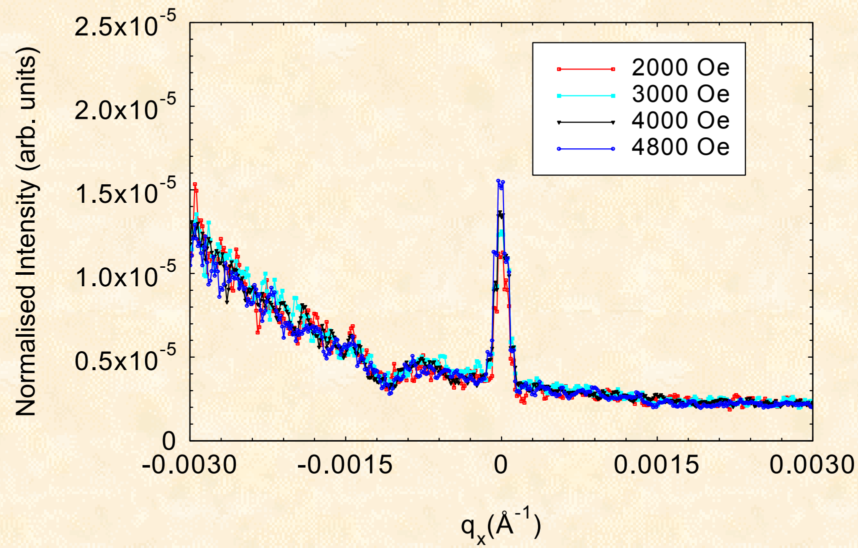
4000 Oe, Nearing Saturation

Strong diffuse scatter at the AF peak,

No evidence of structural roughness in the diffuse scans

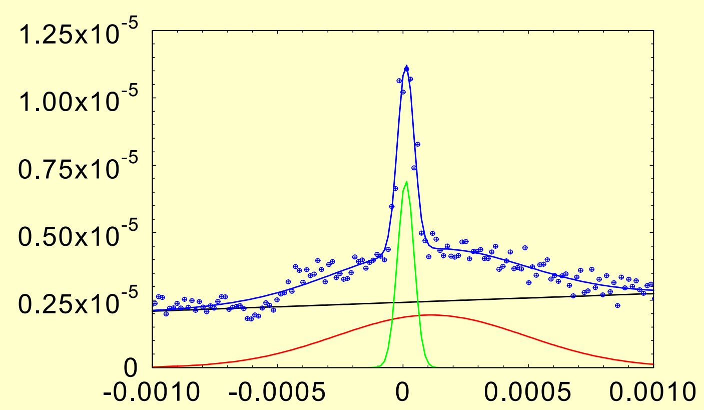
Extracted Line Scans





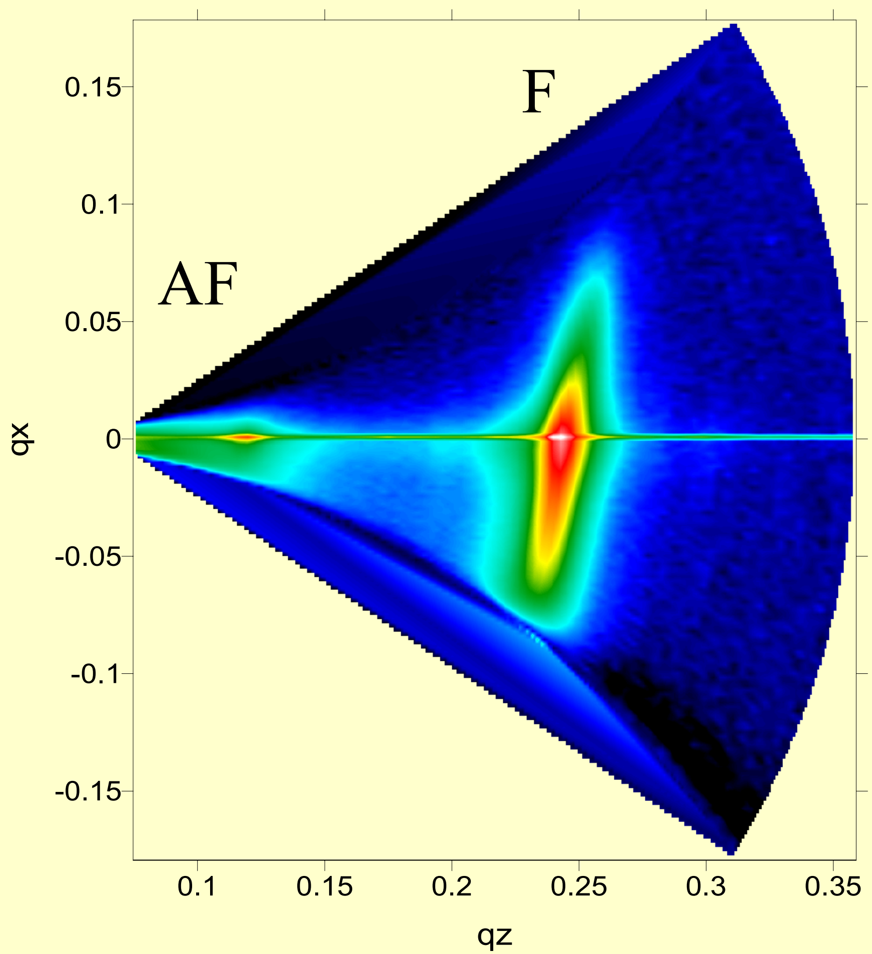
MAGNETIC

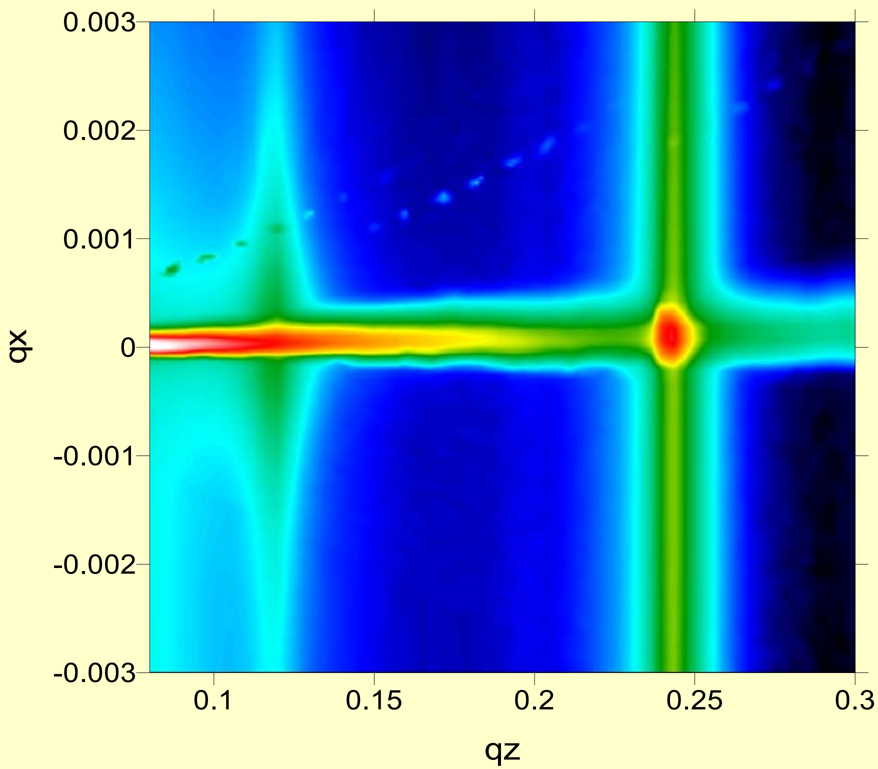
$\xi = 7300 \pm 500$Å



STRUCTURE

Off-Specular SoXMaS



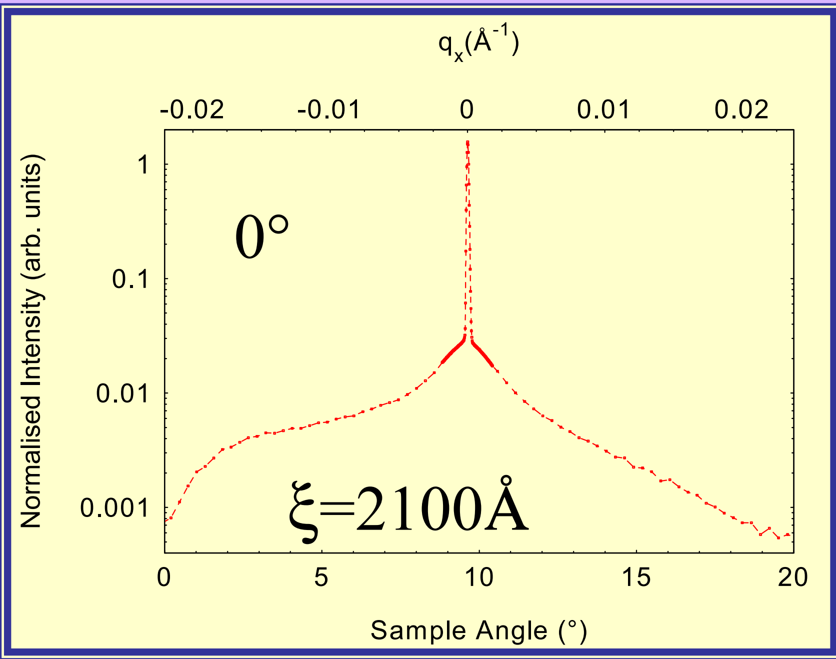


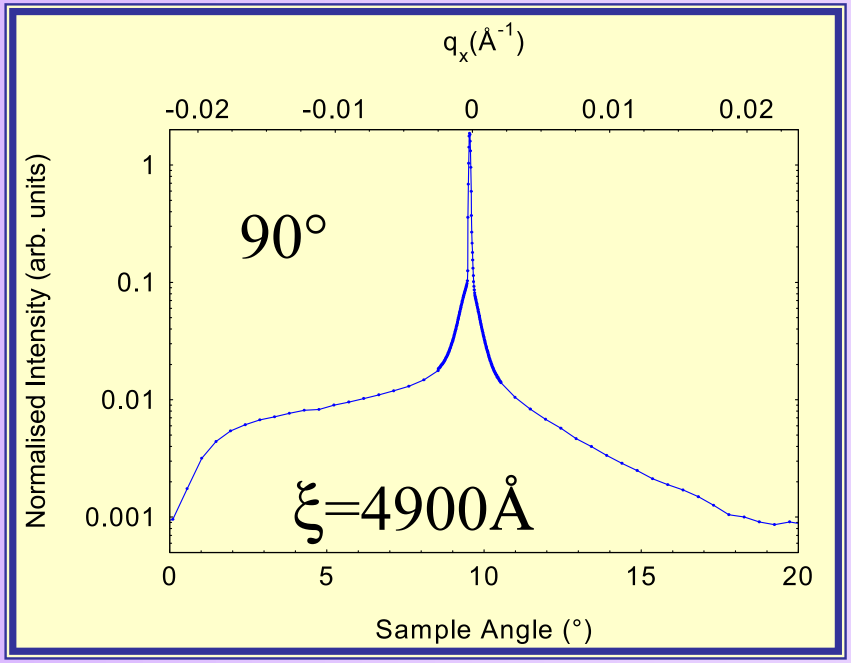
Strong diffuse scatter around both the charge and magnetic peaks.

Transverse Scans

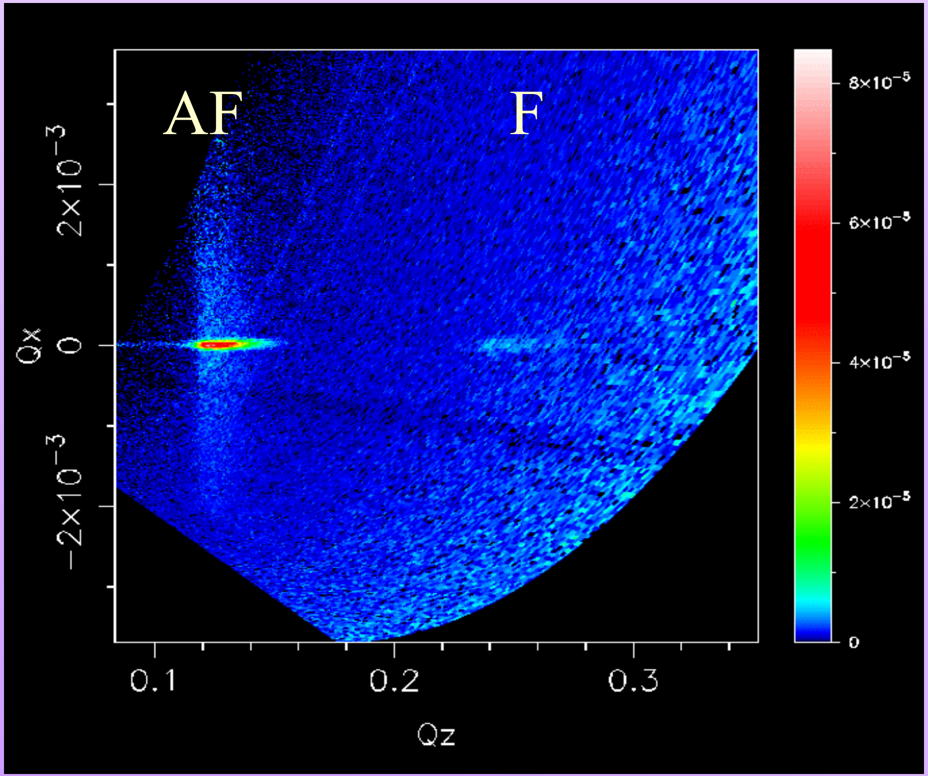
Magnetic Scatter observed for $\phi=0°$ and 90° but with different in-plane length scales.

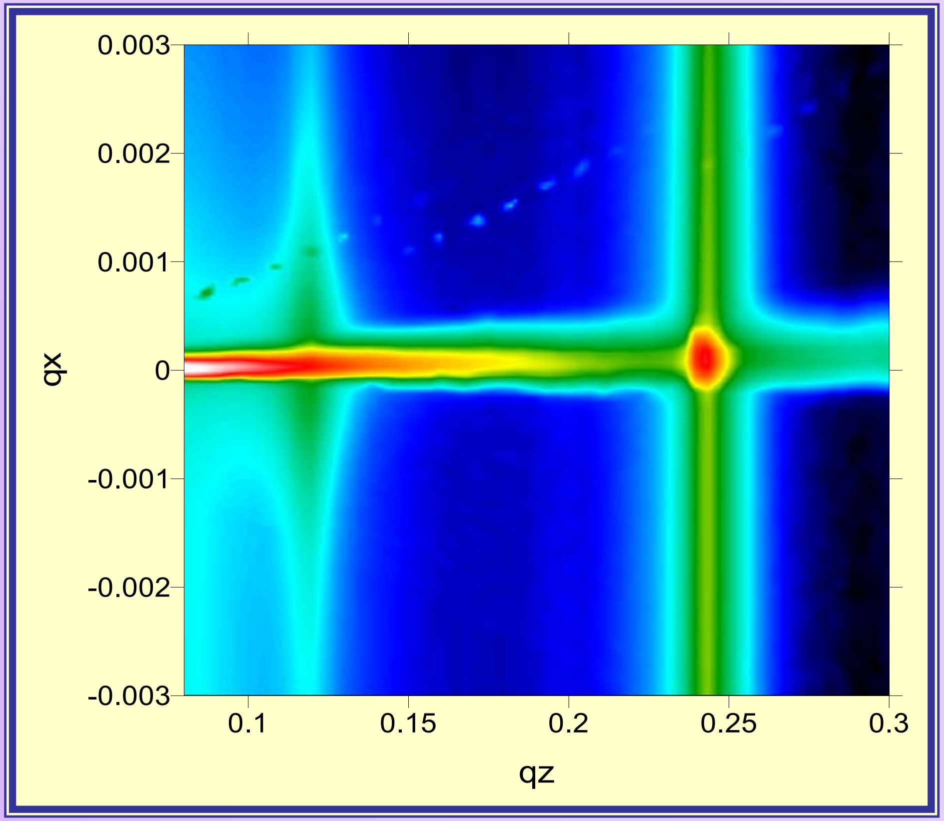
At remanence, no in-plane order to **M**





PNR vs. SoXMaS





Models?

All PNR data show strong AF Bragg peaks in both the specular and off-specular scatter

Neutron data has typically assumed a domain model to explain both the specular and diffuse scatter.

In this model, the magnetic roughness is caused directly by domain disorder at the interface

The low level of diffuse scatter around the Structural Bragg peak implies a low sensitivity to true, interface roughness.

The lack of diffuse scatter around the ferromagnetic peak on application of large fields is often cited as evidence for such a model

X-ray Model

The x-ray and neutron data observe different interface morphologies

The lack of specular Bragg peaks suggest a very rough, conformal magnetic interface

There is little difference between the samples in the magnitude and of the roughness, or the in-plane magnetic correlation length

Strong diffuse scatter at Structural peak shows high sensitivity to the interface roughness

There is a striking difference between the in-plane correlation length in AF and F coupled samples

Magnetic roughness at the interface seems to be a more dominant scattering mechanism for x-rays than the domain structure of the layers

Conclusions

Both PNR & SoXMaS can be used to measure the magnetic super structure in transition metal films

SoXMaS has the advantage of high flux and the ability to measure magnetisation reversal in real time

BUT

Differences between PNR and SoXMaS results from the same sample

&

Difficult to use PNR data to obtain exact cross sections for SoXMaS

Need to define *Magnetic Roughness* and assess the sensitivity of PNR and SoXMaS to domains and magnetic disorder.

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