MAGNETIC SPECKLES WITH SOFT X-RAYS

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Soft X-rays are rare at the ESRF. Nevertheless, the ESRF's soft X-ray user community has a clear impact on synchrotron radiation research due to the capabilities of the source. In this article we want to highlight new developments in magnetic soft X-ray scattering.

Traditionally, soft X-rays are applied in biology, chemistry and physics in various forms of high-energy spectroscopies and microscopy. While these techniques are still important, there is a growing attention for soft X-ray scattering. This may seem surprising, since the wavelengths in question, 5 Å and longer, are too large to fit interatomic distances. However, they do fit the length scales involved in the blooming field of 'nanoscience', as well as the correlation lengths occurring in many solids, such as superconductors and magnetic materials. Usually this size range is addressed by small-angle scattering (SAX) at hard X-ray energies (E > 5 keV). Because of the very high absorption coefficients at longer wavelengths, soft X-ray scattering is a technical challenge, requiring complicated vacuum beamlines, vacuum diffractometers, and thin samples.

WHENCE THEN THE ATTENTION FOR SOFT X-RAY SCATTERING?

The answer is found precisely in those strong absorption effects. By tuning the X-ray energy to an absorption resonance of a *specific* element, one can obtain a large increase in the sensitivity to that element. Furthermore, magnetic or crystal field effects that break the spherical symmetry of the atom give rise to *polarisation*-dependent scattering effects. Resonant scattering experiments are possible at the absorption edges down to the K levels of the light elements C, O, and N, important in biology and chemistry. However, at the moment the magnetism community is most active in exploiting resonant effects. These basically arise from magnetic dichroism: the dependence of the absorption coefficient on the magnetisation in the material and the polarisation of the light.

The first soft X-ray magnetic scattering experiments have been performed on artificially ordered magnetic structures in the form of magnetic bi- and multilayers. Last year, it was shown that it is also possible to obtain information on magnetic domain structures in thin films. In this experiment [1], polarised X-rays were scattered off FePd thin films in which the magnetisation self-organises in so-called magnetic stripe domains (see inset). These structures act as a magnetic grating that produces well-defined satellites around the specular reflected beam. By varying the angle of incidence, it was shown that one can also obtain information on the domain structure *below* the surface, which is very important since most domain imaging techniques only probe the magnetic profile of the fringe fields just outside the sample surface.

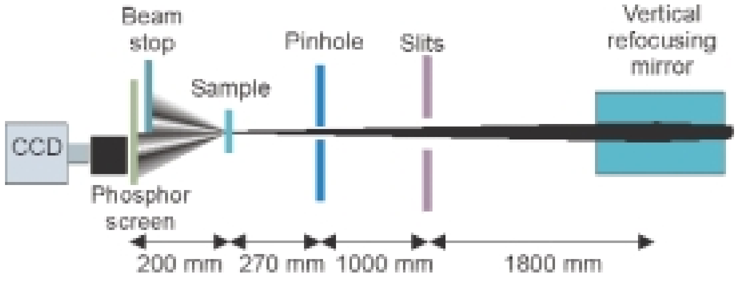

Fig. 1: Experimental layout. Note that the whole optical path from front end to scintillation screen is under ultra-high vacuum.

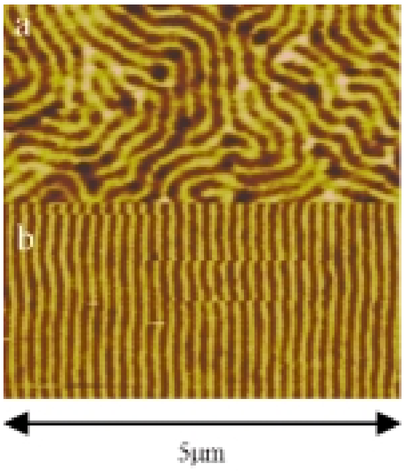

Fig. 2: (a) Magnetic force microscopy (MFM) image of the meandering magnetic stripe domains in a 35 nm thick film of GdFe$_2$. The width of the domains is 110 nm. (b) Parallel stripe domains obtained after saturation of a sample in an in-plane magnetic field applied along the stripe direction.

Recently, in a variant of these experiments on **ID12B** we have used a SAX-type transmission geometry, as shown in Figure 1. A 15 μm diameter beam was incident normally on a 35 nm thick film of amorphous GdFe$_2$ showing a pattern of 110 nm wide meandering magnetic stripe domains (Figure 2a.). Off-resonance, only the transmitted beam is observed. This changes radically when the energy of the beam is tuned to the Gd M$_5$ resonance ($\lambda = 1.1$ nm). Here the magnetic scattering cross-section is enhanced by orders of magnitude [2] and a clear first order and a much weaker third order (not shown) magnetic

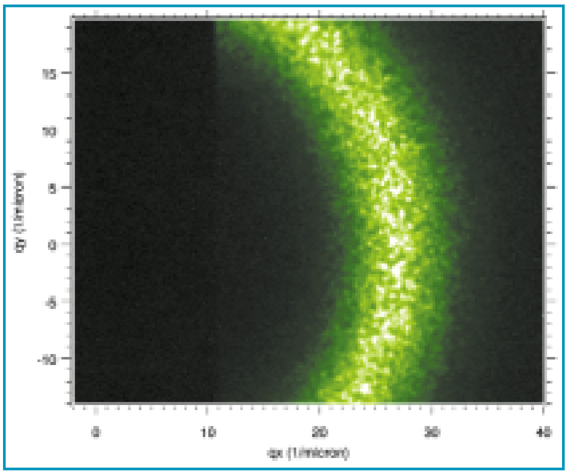

Fig. 3: Magnetic speckle observed on the first order magnetic diffraction ring in transmission from the sample described in Fig. 2a, illuminated by a 15 µm diameter beam of circularly polarised X-rays tuned to the Gd M_5 resonance at 1183.6 eV. A beam stop blocked the direct transmitted beam. The radius of the ring corresponds to a ~115 nm domain width.

diffraction ring appears (Figure 3). The total scattered intensity in the ring is 1.5 x 10^6 photons/s.

A closer look at Figure 3 reveals that the intensity in the ring has strong spatial fluctuations. These are static magnetic speckles, a result of the disordered magnetic structure in the scattering volume. Prior to this observation, magnetic speckles were reported on a Bragg diffracted peak of UAs [3]. Even though Figure 3 was recorded with non-optimised conditions, the speckle contrast is ~30%, indicating partial coherence with a coherence length of 5 μm. That one can do better is shown in Figure 4, which represents the Fraunhofer pattern of a 10 μm-diameter laser pinhole. It shows extremely regular diffraction rings up to the 24th order, implying nearly complete coherence. It was produced from the vertically convergent beam behind the vertical focusing mirror by collimating the beam with 300 x 500 μm slits, 1 m upstream from the pinhole (Figure 1). The total flux in this pattern is estimated at 1.3 x 10^7 photons/s.

As mentioned previously by Yakhou *et al.* [3], magnetic X-ray intensity fluctuation spectroscopy may be made possible by using such high fluxes. Probably the best chances for achieving this lie in the soft X-ray range, due to the inherently higher coherence length of soft X-ray undulators and the larger magnetic contributions to the scattering cross section. That being said, a large number of problems have to be surmounted. Primary concerns are the flux and the stability of the beamline. Hopefully the move of beamline ID12B to straight section ID8 will overcome these problems because it will then have a full length undulator with an estimated 10 times higher flux and a more stable optics layout. ■

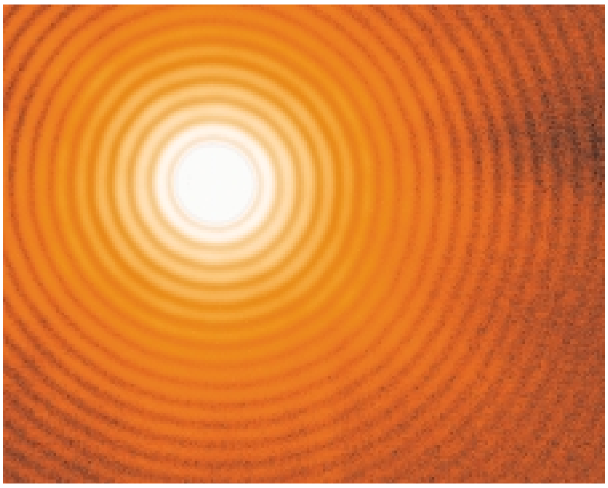

Fig. 4: Fraunhofer diffraction pattern from a 10 µm pinhole illuminated by a coherent beam of 1183.6 eV X-rays at ID12B. The total flux in this image is 1.3 10^7 photons/s with a 80 mA 16 bunch beam.

MAGNETIC DOMAINS IN THIN FILMS WITH A PERPENDICULAR MAGNETIC ANISOTROPY

Domains in magnetic thin films with a perpendicular magnetic anisotropy are the result of the competition between the magneto-static energy, which, to minimise the stray field, tends to an in-plane magnetised film (**Figure 5**a), and the perpendicular anisotropy, favouring an out-of-plane magnetisation (Figure 5b).

A configuration with alternating up and down domains (Figure 5c), reduces the stray field of the sample while most of the sample is perpendicularly magnetised, lowering the perpendicular anisotropy energy at the cost of creating domains walls [4]. Many different domain patterns are possible for the alternating up-down profile, for example the maze-like domain pattern and the perfect parallel stripes shown in Figure 2.

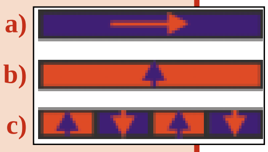

Fig. 5: Magnetisation profiles in a thin film, (a) uniform in-plane magnetisation, (b) uniform perpendicular magnetisation, (c) alternating up and down domains.

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