ESRF	**Experiment title:** **Layer-resolved imaging of the magne tisation reversal in exchange bias systems using soft x-ray holography**	**Experiment number**: HE-2840
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Report:

We proposed to study the microscopic magnetisation reversal of a perpendicular exchange bias system by using soft x-ray holography. We wanted to take advantage of the method's element selectivity to probe different magnetic layers in a layered sample structure. Our aim was to record layer-resolved magnetic domain images at different stages of the magnetisation reversal in ferromagnetic $[Pt/Co]_n$ multilayers exchange-coupled to an antiferromagnetic IrMn or FeMn layer.

In this beam time our group successfully performed for the first time soft x-ray holography measurements. We applied this technique to image the magnetic domain structure in a $[1.8\ nm\ Pt/0.6\ nm\ Co]_8/5\ nm\ Ir_{20}Mn_{80}$ system. Element selective images were recorded in zero and in an applied magnetic field to image the magnetic domains in the ferromagnetic (FM) $[Pt/Co]_n$ multilayer during the magnetisation reversal. Spectroscopic measurements were successfully used to detect uncompensated moments in the antiferromagnetic (AFM) IrMn layer. These moments are localised close to the interface and govern the exchange bias effect. We could show their existence and localisation by comparison of absorption spectra recorded by total electron yield (TEY) and transmission measurements. However, owing to their small signal we could not image them in the [Pt/Co]/IrMn system

For this experiment we used a setup that allows both holography and spectroscopy measurements. The latter was done either by recording the sample current or by detecting the transmitted beam intensity via a photo diode. Fig. 1 shows a sketch of the setup and the cross-section of the sample. The sample was mounted such that the magnetic layers were facing the beam. This configuration assured that the buried AFM/FM interface could be probed spectroscopically by TEY measurements. The depth sensitivity is ruled by the electron escape depth which is ~2nm at the L_3 resonances of the 3d elements.
Fig. 2 compares the TEY measurements with the transmission measurements. The main result here is that the uncompensated Mn moments lead to an XMCD signal that can only be seen by TEY detection. This is a

proof for their localisation close to the interface. A homogeneous distribution along the layer sequence would give rise to a transmission XMCD signal as well. From the sign of the XMCD signals and element selective hysteresis loops (not shown) we could conclude that the unpinned moments align parallel to the Co magnetisation. This graph shows also that the absorption minima the in transmission channel are less pronounced in comparison to the absorption peaks in the TEY channel. This results from the beam intensity passing the reference holes. This unpertubated beam intensity gives rise to a large and featureless background in the spectra. We have learned from this experiment that IrMn-based exchange bias samples are not well suited for imaging. The absent Mn XMCD signal in the transmission data impedes imaging the uncompensated moments in the IrMn layer. However, the strong Co XMCD signal (transmission) can indeed be exploited for magnetic domain imaging by soft x-ray holography.

Our first successfully reconstructed magnetic hologram is shown in Fig 3. The image shows the magnetic domain configuration of the Co layers in the remanent state of a [1.8 nm Pt/0.6 nm Co]$_8$/5 nm $Ir_{20}Mn_{80}$ sample. The two grey scales correspond to magnetic domains with opposite out-of-plane magnetisation. The image contrast is large enough to clearly distinguish several domains in the image. However, the spatial resolution of ~170nm is rather poor in comparison to the domain size and the field-of-view. This is owing to a relatively large reference hole diameter in the [Au/Cr] mask (c.p. Fig 1 b). During the course and preparation of this experiment we could improve our fabrication procedures for high-aspect-ratio reference holes. We will use this experience in the future to achieve smaller reference holes for an improved image resolution down to ~50nm. This will allow us to better resolve the nucleation of domain.

To study the magnetisation reversal in this perpendicular exchange bias system, we took Co domain images in an applied magnetic field along the hysteresis loop. A series of images together with a hysteresis loop is given in Fig 4. Here we used ability of this technique to image in an applied magnetic field. The image series shows (i) that the nucleation sites are not the same in both branches and (ii) that the nucleation fields is different in both branches, as suggested by the hysteresis loop which is shifted to negative fields. The series shows also that within the exposure time (~ 1 min) our setup is mechanically stable enough to allow an image resolution similar to the images taken in zero fields. Thermal drifts as a result of a possible heat load by the water-cooled electromagnet were not detected.

Unfortunately, as mentioned above, we could not image the uncompensated moments in the IrMn layer that we detected by TEY measurements (c.p. Fig 2). However, in a FeMn-bases system we found indeed a small signal from these moments at the Fe L_3 absorption edge. In the future we will use this signal to image the AFM layer during the reversal. We aim to detect spectroscopically and to image moments that are pinned and moments that rotate during the reversal. This microscopy study will hopefully improve the current understanding of exchange bias systems.

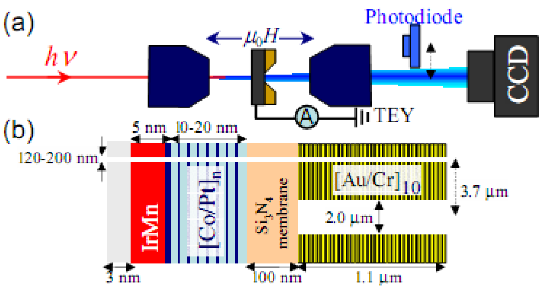

Fig 1(a) Scheme of the experimental set-up for absorption and soft x-ray holography measurements. (b) Cross section of the sample-mask structure showing the aperture for the field-of-view and one aperture for the reference beam in the opaque [Au/Cr]$_n$ mask.

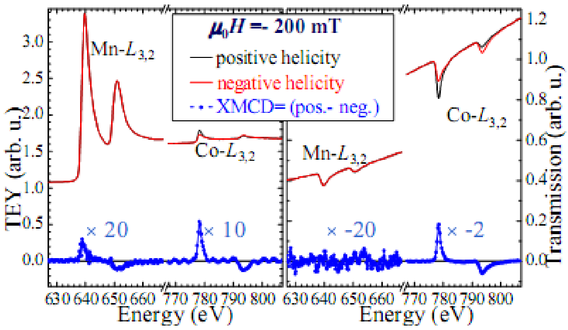

Fig 2 Absorption (red and black line) and XMCD (blue line) spectra at the Mn-L and Co-L edges of the sample [1.8 nm Pt/0.6 nm Co]$_8$/5 nm $Ir_{20}Mn_{80}$ recorded by detecting the TEY signal (left) and the transmitted photon intensity (right) in a saturating external magnetic field of 200 mT. The spectral differences in both detection channels result from different probing depth and different background contributions. Note that the small dichroism signal at the Mn-L edges is only seen by TEY detection

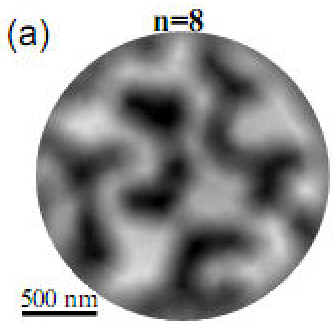

Fig 3 Magnetic domain imaged of the demagnetized state of the [1.8 nm Pt/0.6 nm Co]$_8$/5 nm $Ir_{20}Mn_{80}$ sample. The images are obtained from the Fourier transform of magnetic holograms acquired at the Co L3 absorption edge. The two prominent gray scale values in the images correspond to Co domains with opposite out-of-plane magnetization. The spatial resolution is 170 nm.

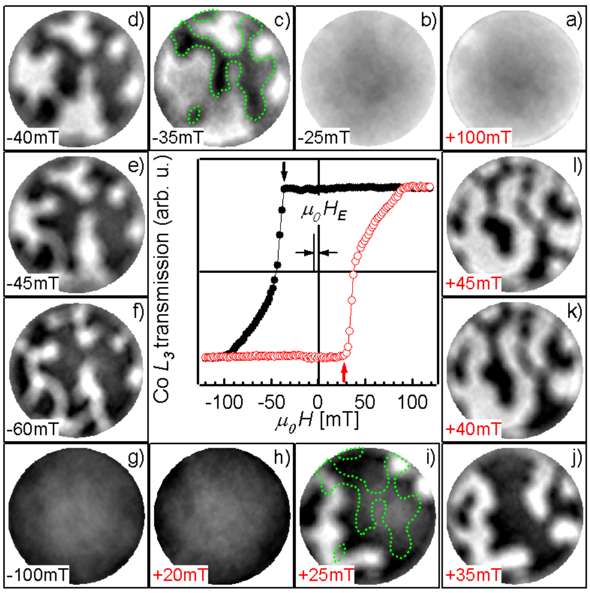

Fig 4 Evolution of the magnetic domain structure of the FM layer along the hysteresis loop in the [1.8 nm Pt/0.6 nm Co]$_8$/5 nm $Ir_{20}Mn_{80}$. The images were recorded at the Co-L_3 edge. Center: element selective hysteresis loop recorded in transmission at the Co L3 edge. The exchange bias field and the nucleation fields (arrows) in both branches are indicated in the hysteresis loop. The domain structure close to the nucleation point of the descending branch (c) is superimposed on the image recorded close to nucleation field of the ascending branch (i).