

# Degree of circular polarization of soft X-rays emitted from a multi-polarization-mode undulator characterized by means of magnetic circular dichroism measurements

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The degree of circular polarization of soft X-rays emitted from the multi-polarization-mode undulator of BL17SU at SPring-8 has been deduced by means of magnetic circular dichroism in core-level X-ray absorption spectroscopy for a ferrimagnetic Gd–Fe–Co amorphous thin film. The results of reference measurements performed using well characterized undulator radiation of BL25SU at SPring-8 have also been utilized. The degrees of circular polarization were presumed for all the available operational modes and were compared with simple theoretical calculations. It was found that the calculated degrees of circular polarization were validated by the measurements reasonably well and will be useful in further experiments at BL17SU.

**Keywords:** multi-polarization-mode undulator; degree of circular polarization; X-ray absorption spectroscopy; magnetic circular dichroism.

## 1. Introduction

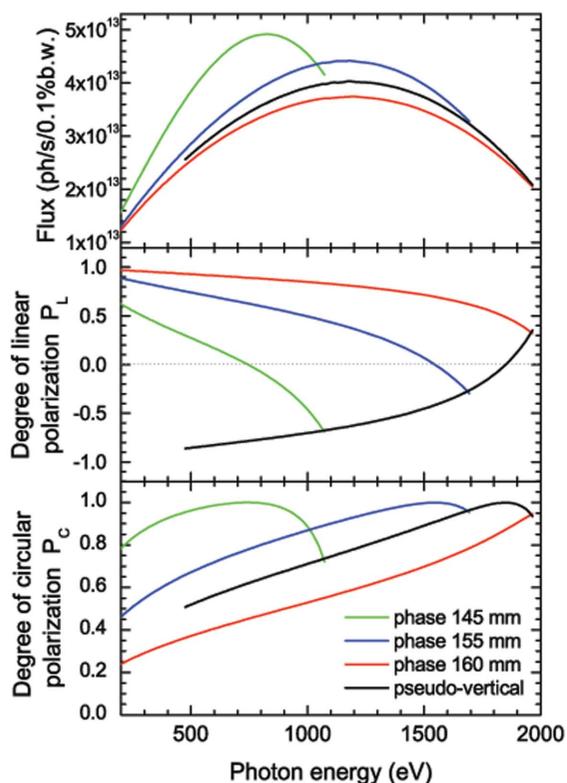
Synchrotron radiation in the soft X-ray region is a powerful light source for investigating the electronic structure of materials by means of X-ray absorption spectroscopy (XAS), photoemission spectroscopy (PES) and soft X-ray emission spectroscopy (SXES). Recently, soft X-ray magnetic circular dichroism (SXMCD) of XAS measurements has become a powerful technique for studying the magnetic properties of materials (Chen *et al.*, 1990). Magnetic linear dichroism is also a very unique means of observing antiferromagnetic domains (Arenholz *et al.*, 2006, and references therein). The difference in spectroscopic behaviors of SXES between the polarized and depolarized geometries using linearly polarized soft X-rays provides essential information for interpreting the orbital anisotropy of electrons in solids (Kotani & Shin, 2001). Thus, the wider tunabilities of both energy and polarization have become important more and more as such spectroscopies develop. Moreover, characterizing the degree of polarization is especially important for quantitative analysis, *e.g.* the magneto-optical sum rule for XMCD (Thole *et al.*, 1992; Carra *et al.*, 1993).

In order to advance such spectroscopic studies in materials science using high-brilliant soft X-ray radiation, we have constructed the highly stabilized and high-resolution undu-

lator beamline BL17SU at SPring-8 (Shin *et al.*, 2001, 2006; Ohashi *et al.*, 2004, 2006; Senba *et al.*, 2006). A novel insertion device, ID17, called a multi-polarization-mode undulator, has been developed for the beamline (Tanaka *et al.*, 2002; Shirasawa, Tanaka *et al.*, 2004; Shirasawa, Hiraya *et al.*, 2004). ID17 consists of electromagnets and permanent magnets applying vertical and horizontal magnetic fields, respectively. The vertical magnetic field ( $B_y$ ) is adjustable by changing the coil current of the electromagnets; on the other hand, the horizontal magnetic field ( $B_x$ ) is adjustable by phasing the arrays of the permanent magnets. It is well known that the peak values  $B_{x_0,y_0}$  and the periodic lengths  $\lambda_{ux,uy}$  of these magnetic fields  $B_{x,y}$  are related to useful dimensionless parameters  $K_{x,y}$ , called deflection parameters, which determine the characteristic features of undulator radiation. Usually these are simply described as  $K_{x,y} = 0.934\lambda_{ux,uy}[\text{cm}]B_{x_0,y_0}[\text{T}]$ . At present, ID17 is operated with the condition  $\lambda_{uy} = \lambda_{ux}$ . If we adjust the electromagnets, however, the condition  $\lambda_{uy} = (1/2)\lambda_{ux}$  is available for the figure-8 undulator mode (Tanaka *et al.*, 2002; Shirasawa, Tanaka *et al.*, 2004). By adjusting these magnetic fields to the specific operational mode, ID17 will be operated as a helical ( $K_x \simeq K_y$ ), elliptical, pseudo-linear ( $K_x \ll K_y$ ) or pseudo-vertical ( $K_x \gg K_y$ ) undulator, and also have a polarization switching capability. The intense synchrotron radiation beam of circularly/linearly polarized

light or the mixed polarization state of the beam can thus be obtained by changing the operational mode of ID17, and this advantage enables us to perform advanced soft X-ray spectroscopy with the aid of the polarization tunability.

There is, however, a problem in that the high-quality synchrotron radiation beam with high degree of polarization is restricted to specific operational conditions at present. The main reason is attributable to the following: the operational condition for ID17 is somewhat limited so as to warrant an independent tuning of ID17 during the storage-ring operation. Thus the resultant degree of circular polarization for ID17 in the helical/elliptical undulator mode shows energy dependence and is calculated as shown in Fig. 1. In Fig. 1, curves for phase  $X$  mm ( $X = 145, 155$  or  $160$ ) represent the energy-dependent characteristics of undulator radiation in the case of a fixed horizontal magnetic field, *e.g.* phase 145 mm ( $K_x = 1.45$ ), and variable vertical magnetic field, *i.e.* coil current 0–80 A ( $K_y = 0.0$ – $4.82$ ). Curves for the pseudo-vertical, on the other hand, show characteristics of the case of a fixed vertical magnetic field, *i.e.* coil current 10 A ( $K_y = 0.51$ ), and variable horizontal magnetic field, *i.e.* phase 160–120 mm ( $K_x = 0.35$ – $2.75$ ). As can be seen in Fig. 1, the calculations have predicted that ID17 produces circularly polarized light with a high degree of circular polarization in the energy ranges 700–800 eV for phase 145 mm, 1500–1600 eV for phase 155 mm ( $K_x = 0.71$ ) and so forth. We should note, however, that we can extend the energy range having a high degree of circular polarization in the future by accomplishing the completion of



**Figure 1**  
Calculated characteristic features of the soft X-rays emitted from ID17.

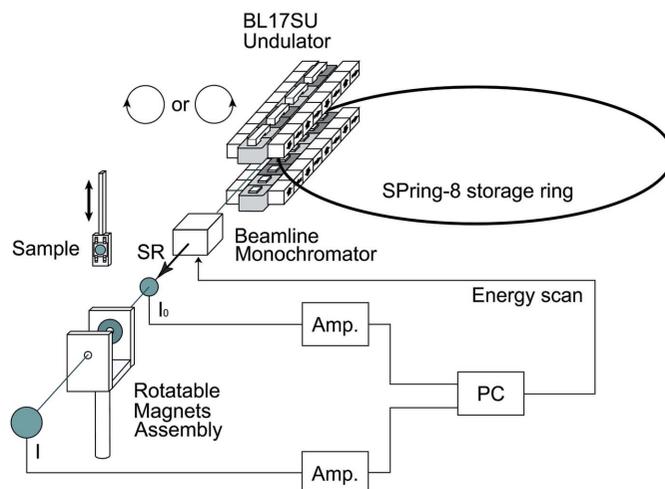
the operational conditions of ID17, *e.g.* phase 130 mm ( $K_x = 2.40$ ) or 150 mm ( $K_x = 1.08$ ).

In the present study, we report on the characterization of the degree of circular polarization of soft X-rays emitted from multi-polarization-mode undulator ID17 by means of SXMCD measurements. The results will be compared with theoretical calculations.

## 2. Equipment and experimental set-up for SXMCD measurements

A compact apparatus was newly designed for the present SXMCD measurements. The apparatus consists of a Nd–Fe–B permanent-magnets assembly and a sample holder housed in the vacuum chamber. The permanent-magnets assembly is mounted on the rotary drive; then the direction of the magnetic field can be easily rotated around the sample to be measured. The magnetic field at the sample position was roughly measured to be about 0.17 T by using a handy gauss meter (LakeShore 421). Up to two or three samples can be mounted on the sample holder. In advance of measurements at BL17SU, the apparatus was installed at BL25SU (Saitoh *et al.*, 2000) in order to obtain the reference SXMCD spectra. BL25SU employs a twin-helical undulator having the helicity switching capability of circularly polarized radiation (Hara *et al.*, 2003; Muro *et al.*, 2005).

A schematic diagram of the SXMCD measurement system for the transmission geometry is shown in Fig. 2. By recording the primary and the transmitted intensities of the soft X-ray beam, we can measure the absorption intensity. Both the absorption intensities  $I_+$  and  $I_-$ , where  $I_+$  and  $I_-$  denote the absorption intensities with the photon spin parallel and anti-parallel to the direction of the applied magnetic field, can be acquired by switching the helicity of the undulator radiation with fixed magnetic field direction or rotating the permanent-magnets assembly of the compact SXMCD apparatus with the fixed helicity. Finally we can measure the SXMCD spectrum,



**Figure 2**  
Schematic diagram of the SXMCD measurement system.

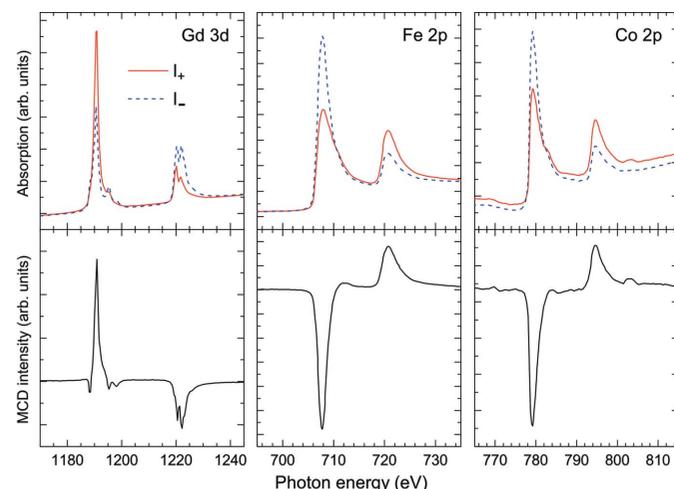
i.e.  $I_{\text{MCD}}(E) = I_+(E) - I_-(E)$ , by scanning the beamline monochromator.

In the present SXMCD measurement, a ferrimagnetic  $\text{Gd}_{0.27}\text{Fe}_{0.605}\text{Co}_{0.125}$  amorphous thin film (30 nm thick) was used for the standard sample in the transmission geometry. The sample has buffer layers of Rh (4 nm thick) and  $\text{Si}_3\text{N}_x$  (100 nm thick) and also has a capping layer of Rh (4 nm thick) on a top surface to prevent oxidation. The Gd–Fe–Co amorphous thin film shows perpendicular magnetic anisotropy; therefore, the sample was mounted so that the sample surface was perpendicular to the magnetic field.

### 3. Experimental results and discussion

The soft X-ray radiation from the twin-helical undulator of BL25SU was well characterized by using the versatile apparatus for polarimetry and ellipsometry (Kimura *et al.*, 2004), and the absolute degree of right-handed (left-handed) circular polarization  $P_C$  at 398.2 eV was reported as  $0.96 \pm 0.03$  ( $-0.97 \pm 0.03$ ) (Hirono *et al.*, 2005). In the present experiment, the incident soft X-ray beam was monochromated using the varied-line-spacing plane grating with groove density of 600 lines  $\text{mm}^{-1}$ . During the SXMCD measurements, the resolving power of the beamline monochromator was kept to about  $E/\Delta E \simeq 5000$ . The SXMCD spectra were recorded at the Gd  $M_{4,5}$ -, Fe  $L_{2,3}$ - and Co  $L_{2,3}$ -edges at room temperature.

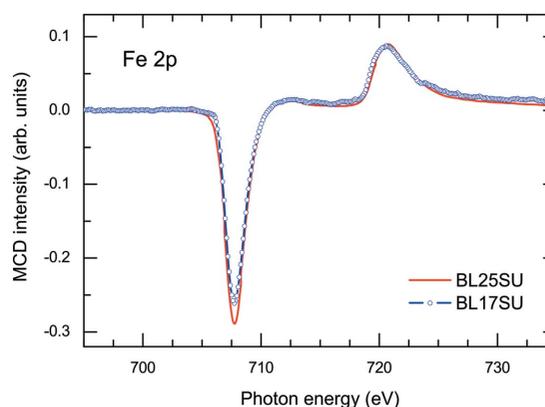
Fig. 3 shows the absorption and SXMCD spectra of a Gd–Fe–Co sample measured at BL25SU. In the upper part of Fig. 3, red solid lines show the absorption intensities measured with the photon spin parallel to the direction of the applied magnetic field, and blue dashed lines indicate those measured in the antiparallel case. The lower part of Fig. 3 represents the SXMCD spectra deduced from the absorption spectra. These SXMCD spectra were excited and recorded using the well characterized undulator radiation (Hirono *et al.*, 2005) from



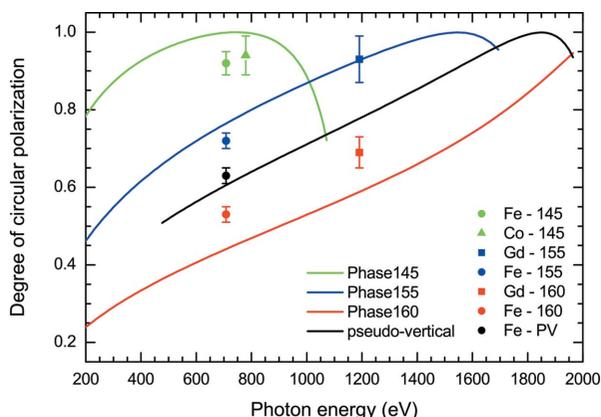
**Figure 3** Absorption and SXMCD spectra of a Gd–Fe–Co sample measured at BL25SU of SPring-8. Red solid lines show the absorption intensities measured with the photon spin parallel to the direction of the applied magnetic field; blue dashed lines, on the other hand, depict those for the antiparallel case.

the twin-helical undulator of BL25SU (Hara *et al.*, 2003; Muro *et al.*, 2005). Thus we utilize these SXMCD spectra as the reference data for characterizing the soft X-rays emitted from ID17. In the case of measurements at BL17SU, however, we recorded the SXMCD spectra with all the available operational modes of ID17, e.g. helical undulator mode, elliptical undulator mode and pseudo-vertical undulator mode, so that we can validate the simple theoretical calculations for undulator radiation, in which computer code *SPECTRA* (Tanaka & Kitamura, 2001) is used for the calculations. In the case of the helical/elliptical undulator mode, we utilized the sinusoidal field for the vertical magnetic field to simplify the calculations. We refer to such calculations as simple theoretical calculations.

We installed the compact SXMCD apparatus into BL17SU and performed a similar experiment to measure the SXMCD spectra of a Gd–Fe–Co sample at the Gd  $M_{4,5}$ -, Fe  $L_{2,3}$ - and Co  $L_{2,3}$ -edges at room temperature. The beamline monochromator was set to be almost the same as the case for reference measurements at BL25SU. Fig. 4 shows a typical example of a comparison of SXMCD spectra from BL17SU and BL25SU measured around the Fe  $2p$  absorption edges. The red solid line indicates the SXMCD spectrum measured at BL25SU, and the blue open circles with line represent the corresponding one recorded at BL17SU. It is immediately noticeable that the measured SXMCD spectra look quite comparable. This indicates that ID17 emits the soft X-ray beam with a high degree of circular polarization in the region of the Fe  $2p$  absorption edge. From the measured SXMCD spectra, we can deduce the degree of circular polarization of soft X-rays emitted from ID17 by normalizing the results obtained at BL17SU to the reference data obtained at BL25SU according to the fact that the MCD intensity is proportional to the degree of circular polarization,  $P_C$ . Thus we could plot the resultant degrees of circular polarization data and compare them with the simple theoretical calculations as shown in Fig. 5. In Fig. 5, closed circles represent the results for the Fe  $2p$  region, the closed triangle for the Co  $2p$  region, and closed squares for the Gd  $3d$  region. As can be



**Figure 4** Comparison of the SXMCD spectra of a Gd–Fe–Co sample in the region of the Fe  $2p$  absorption edge measured at BL25SU (red solid line) and BL17SU (blue open circles with line).



**Figure 5**  
Comparison between the measured data of degree of circular polarization and those calculated theoretically. Closed circles are the results for the Fe 2*p* region, the closed triangle for the Co 2*p* region, and closed squares for the Gd 3*d* region. Curves in the figure represent the calculated results for various operational modes.

seen in the figure, the measurements were made with various operational modes of ID17, *e.g.* helical undulator mode, elliptical undulator mode, pseudo-vertical undulator mode and so forth. We notice a tendency of correspondence between measurements and the simple theoretical calculations. Calculated energy dependences of the degree of circular polarization of soft X-rays emitted from ID17 are validated by the present measurements. These facts indicate that the simple theoretical calculations are good enough for inferring the degree of circular polarization and will be useful in further experiments at BL17SU.

#### 4. Summary

We have measured the SXMCD spectra of a ferrimagnetic Gd–Fe–Co thin film to deduce the degree of circular polarization of soft X-rays emitted from a multi-polarization-mode undulator of BL17SU at SPring-8. Reference measurements were also made at BL25SU of SPring-8, in which a well characterized twin-helical undulator was used as the light source. The deduced data of the degree of circular polarization for all the available operational modes were compared with simple theoretical calculations. We could confirm that the calculated degrees of circular polarization are validated reasonably well by the present measurements, and the simple

calculations are confirmed to be useful in further experiments at BL17SU.

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