A microfocused circularly polarized x-ray probe for energies between 5 and 10 keV

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Introduction

The magnetic contribution to the cross section for scattering of x-rays by matter is of significant scientific interest because of its capability to reveal information about the angular and spin momentum distribution in the scattering medium [1]. We report on a setup that combines microfocusing x-ray optics with Bragg-diffracting phase retarders for producing a circularly polarized x-ray microprobe in the energy range from 5 to 10 keV. Circularly polarized x-rays are of particular interest since they couple linearly to the magnetic moments. A microfocused x-ray beam will enable a wide variety of spatially resolved magnetic scattering experiments, yielding results in applied fields like modern magnetic materials and superconducting compounds, as well as in more basic physics. An important advantage of x-rays in the energy range from 5 to 10 keV is their relatively high penetration power, allowing real bulk measurements of magnetic samples and penetration through nonmagnetic surface layers. Unlike neutrons, x-rays can be used to probe for element-specific properties by working at an x-ray resonance.

For the energy range between 5 and 10 keV, Bragg-transmission phase retarders have proven to be the most practical approach for the production of a circularly polarized x-ray beam from a linearly polarized synchrotron beam [2]. Such phase retarders utilize the fact that, according to the dynamical theory of x-ray diffraction, the wave fields inside a crystal belonging to different linear polarizations propagate with different phase velocities close to a Bragg reflection. The phase difference thus induced is a linear function of the deviation of the angle of incidence from the exact Bragg condition [3]. Switching the beam helicity requires only minimal rotations of the phase retarder, which can be done even during the course of a measurement, thereby reducing systematic errors. Due to their low absorption, diamond crystals are exceptionally well suited for this application, with only a few crystals of different thickness required to cover the whole energy range between 3 and 12 keV.

To produce x-ray beams with submicron cross section, microzone plates are a well-established tool [4]. They can be understood as circular diffractive gratings with radially increasing line density, whose operation principle is based on Fresnel's theory of diffracting zones [5]. In the nondiffraction-limited regime, zone plates focus the beam simply by demagnifying the x-ray source. Since the different diffraction orders of a zone plate correspond to distinct focal lengths, a microfocusing experimental setup typically includes an order-sorting aperture (OSA) (e.g., a pinhole, to reduce unwanted diffraction orders).

Methods

The polarized microprobe was set up at the 1-ID insertion device beamline at the Advanced Photon Source (APS). Figure 1 shows the setup schematically. The undulator beam was collimated using white-beam tungsten slits close to the source. The radiation was then monochromatized using a standard liquid-nitrogen-cooled double-crystal Si(111) monochromator. An additional set of slits downstream of the monochromator was used to further define the beam to a size of 0.5×0.5 mm^2 at 60 m from the source. This beam was incident on the phase-retarding optics. As the phase retarder, a 400 μm-thick diamond in (111) reflection

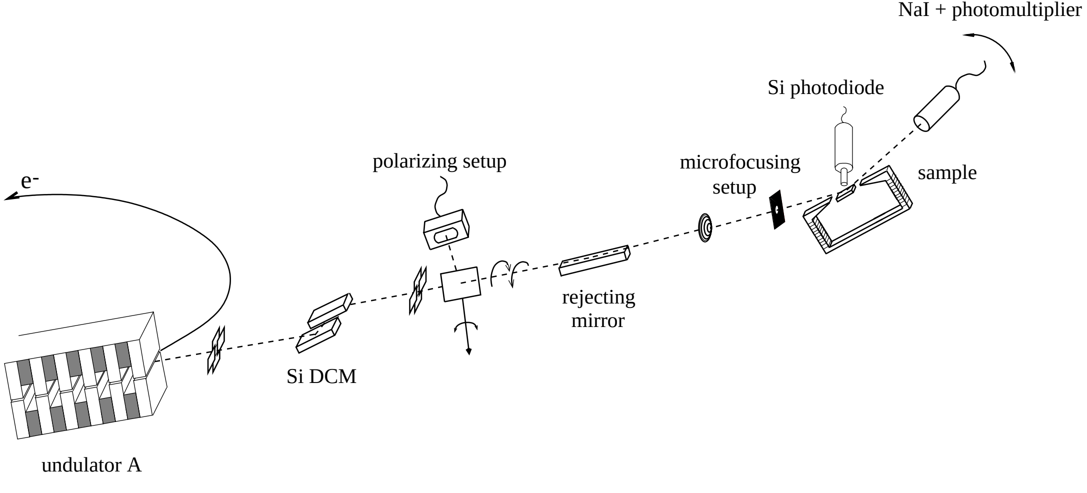

Figure 1: The experimental setup at the APS beamline 1-ID.

geometry was chosen. For an x-ray energy of 8 keV, the incident flux on the diamond was measured to be $\approx 2 \times 10^{12}$ photons per second, and the transmitted circularly polarized flux was 4×10^{11} photons per second. The transmitted radiation had a degree of circular polarization of about 0.99. To suppress higher harmonics, the beam was reflected by a Pd mirror placed behind the phase retarder. The beam path was enclosed in evacuated beam pipes to reduce the intensity loss due to air scattering. The microfocusing setup following the diamond consisted of two parts: the zone plate and the OSA. The zone plate had a diameter of 250 μm and a focal length of about 40 cm at 8 keV. It was mounted on a three-axis motorized stage to allow the focused beam to be positioned on the sample. Pinholes of various sizes from 20 to 50 μm were used as order-sorting apertures. The sample was likewise mounted on a three-axis motorized stage in the center of a standard eight-circle diffractometer. An electromagnetic field of up to 0.8 T could be applied to the sample parallel to the beam. Two different kinds of detectors were employed to monitor both the fluorescence yield and the Bragg-scattered intensity as a function of the position of the sample in the microfocused beam. To align the different components of the setup (zone plate, OSA, and sample), we used optical microscopes with and without x-ray scintillators, as well as standard x-ray-utilizing alignment techniques.

Results

The size of the microfocused beam was measured by scanning a Cr-coated knife edge horizontally and vertically through the beam. The knife edge was mounted on a precision three-axis motorized linear stage with an absolute accuracy better than 0.5 μm and a relative accuracy of $\approx 10^{-4}$. We measured the Cr K-fluorescence of the knife edge as a function of its position in the focused beam. The optimum focus size that could be reached was $4.0 \times 2.3\ \mu\text{m}^2$ (horizontally × vertically). Horizontally, the measured focus size agrees very well with the value calculated from the demagnification of the source. The vertical size was significantly larger than the calculated value. By temporarily clamping the knife-edge holder on the diffractometer to the zone-plate mounting, it could be shown that this difference is mainly due to vibrations of the knife edge relative to the zone plate. For the mentioned focal size, we measured a flux on the order of 10^8 photons per second. The flux depends slightly (up to a factor of 1.5) on the chosen energy because of the changing transmission of the diamond phase retarder.

As a demonstration experiment, we used the microprobe to image magnetic domains in a $HoFe_2$ crystal at the Ho L-III edge. Observing the (400) Bragg reflection of the crystal, two-dimensional scans were performed while reversing the helicity of the incident beam to obtain the flipping ratio for each point on the sample. Clearly, different magnetic domains could be identified, whose size matched well previous results obtained with magnetic force microscopy [6].

Summary

We built a circularly polarized x-ray microprobe with a high degree of polarization and small beam cross section. The beam was polarized by means of a diamond phase retarder. The obtained degree of polarization was up to 99%. The polarized beam was focused using a microzone plate. The useful beam spot had a size of about 4×2 μm. The setup can be used to perform magnetic domain mapping measurements on materials like spring magnets or magnetic multilayers. To improve the spatial resolution, the use of a microzone plate with smaller zone structure is planned.

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References

[1] M. Blume and D. Gibbs, *Phys. Rev. B* **37**, 1779 (1988).

[2] K. Hirano, K. Izumi, T. Ishikawa, S, Annaka, and S. Kikuta, *Jpn. J. Appl. Phys.* **30**, L407 (1991).

[3] J.C. Lang and G. Srajer, *Rev. Sci. Instrum.* **66**, 1540 (1995).

[4] J. Thieme, G. Schmahl, D. Rudolph, and E. Umbact (eds.), *X-ray Microscopy and Spectromicroscopy*, (Springer-Verlag, Berlin Heidelberg, 1998).

[5] M. Born and E. Wolf, *Principles of Optics*, (Cambridge University Press, Cambridge, UK, 1980).

[6] G. Srajer *et al.*, to be published.