A high-energy phase retarder for the simultaneous production of right- and left-handed circularly polarized x-rays

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Introduction

The availability of new high-energy synchrotron radiation sources, such as the Advanced Photon Source (APS), have made measurements of the spin-dependent momentum distribution of electrons much easier. Making these experiments feasible, however, requires high-energy x-rays (E > 30 keV) with not only a high flux density but also a high degree of circular polarization. Circularly polarized (CP) x-rays have until now been produced essentially in three ways: (i) use of perfect crystal x-ray phase retarders (XPR), (ii) selection of synchrotron radiation off-axis to the orbital plane, and (iii) specialized insertion devices, such as elliptical multipole wiggler (EMW). While each technique has its specific benefits, high-energy phase retarders coupled with a planar undulator have proved to be versatile, simple to operate, economical to fabricate, and extremely successful at energies below 100 keV. Although they may not match a focused EMW beam in throughput flux at these higher energies [1], they do provide other distinct advantages. Because they are the last optical element prior to the sample, the final photon polarization state is well defined and not subject to the instabilities of the particle orbit. Helicity switching can be incorporated thus reducing beam-related errors in the low count-rate signal.

Previous XPRs used to produce high-energy (>20 keV) CP x-rays have utilized both reflection and transmission Laue geometries [2, 3]. In this report we describe a monolithic XPR design using both Bragg and Laue reflections to monochromatize and polarize the x-ray beam. It is an upgrade from our previous design in that both the left- and right-handed beams are simultaneously excited [3]. The two emerging CP beams are spatially separated by a few mm and are parallel to the incident beam. This provides good dispersive matching between the Bragg and Laue reflections thereby enhancing the throughput.

Methods and Materials

The principle behind an XPR is the four-refringent property of a perfect single crystal in a transmission geometry as described by dynamical diffraction theory. The two polarization states, σ and π, perpendicular and parallel to the diffraction plane, respectively, propagate through the crystal with different phase velocities. The relative phase difference between the two polarization states at the Bragg condition, at the exit face of a crystal of thickness t, is given by equation (1)

$$\phi = \frac{t r_e \lambda |F_H| \left(1 - |\cos 2\theta_B|\right)}{V \cos\theta_B}, \qquad (1)$$

where r_e is the classical electron radius, λ is the incident x-ray wavelength, V is the unit cell volume, F_H is the structure factor specific to the reflection, and θ_B is the Bragg angle. When the amplitudes of the two components are equal and their phase shift is ± (2n+1)π/2, they combine to produce circularly polarized x-rays.

In the current design, the Bragg-Laue XPR is a germanium monolith cut from an oriented Ge (100) single-crystal boule. It comprises a Bragg section with a [100] surface normal and a Laue section where symmetric (220) planes polarize the beam in a transmission geometry (Fig. 1). The asymmetry angle for this scattering geometry for the (220) planes is 0.35 degrees in the diffraction plane. This arises from a 1.7 degree miscut of the crystal surface with respect to the [001] direction and is provided so that the Bragg-reflected beam can exit the crystal surface.

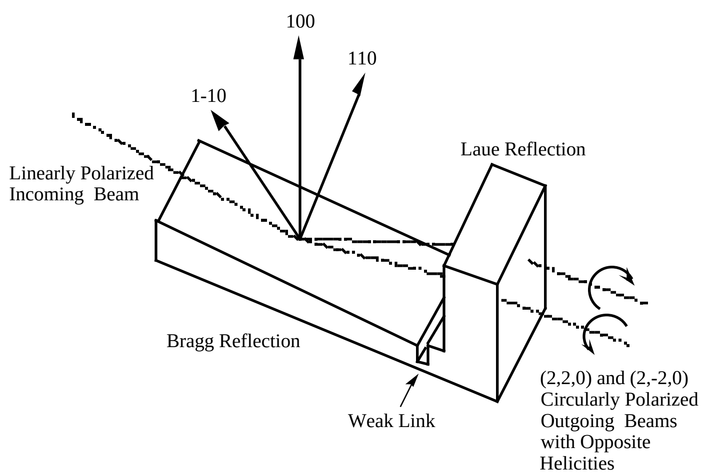

Figure 1: The high-energy x-ray phase retarder.

This design is a modification of previous Bragg-Laue monolithic XPRs [2, 3], which had the surface normal of the Bragg portion of the crystal oriented along the [110] direction. To obtain CP x-rays, the phase retarder plane of diffraction had to be oriented at ± π/4 with respect to the synchrotron orbital plane. To obtain helicity reversal, the whole XPR had to be rotated by 90˚ about the incident beam, which was cumbersome and could not be done rapidly. This XPR overcomes this problem by producing beams of both helicities simultaneously. The whole optical element is 79 mm long, which results in a 5 mm separation of the (220) and (2-20) beams at the exit face. The thickness of the Laue portion is 14.81 mm, which is optimal for the designed operating energy of 86 keV. The XPR is, however, capable of producing CP x-rays with a lower degree of circular polarization over a range of energies from 50 to 100 keV.

The linearly polarized incident white beam undergoes successive Bragg and Laue (220) reflections. The length of the Bragg portion is determined by the resulting footprint at grazing incidence. By spreading out the beam over a wide area and providing contact cooling, the heat load on the crystal is reduced. In this orientation, the (220) planes are at $\pm\ \pi/4$ degrees to the orbital plane. The two beams pass though the Laue portion of the XPR and emerge from the exit face circularly polarized with opposite helicities and parallel to each other and to the incident beam. In this manner, dispersion matching is achieved. The Laue and Bragg diffraction conditions differ by less than an arcsecond in angle due to differing indices of refraction for the two geometries. To compensate for this, a weak link is cut between the two parts so that the Laue portion can be rotated with respect to the Bragg.

The performance of the XPR was determined by measuring the magnetic Compton profile of Fe. Because the magnetic moment of Fe is well known, one can use the measured magnetic Compton cross section to extract the degree of circular polarization, P_c. Both SRI-CAT beamlines 1-ID and 1-BM were used to characterize the XPR in terms of P_c and throughput efficiency. Aluminum and copper filters were placed in the incident beam to absorb the low-energy radiation. This served the dual purpose of reducing the scattered background and reducing the heat load on the crystal. White-beam slits far upstream of the XPR served to collimate the incident beam. A second set of tungsten white-beam slits placed just before the XPR further defined the incident beam and reduced the scatter around the XPR. The XPR was mounted on a Huber double-arc goniometer to provide rotations about a horizontal axis perpendicular to the incident beam, which defines the Bragg angle, and about the beam direction. These arcs were in turn mounted on a second goniometer to provide rotation about the vertical axis. This last rotation proved crucial in the alignment of the XPR so that both CP x-ray beams had the same energy. Upon exiting the XPR, a single helicity CP x-ray beam was selected by a slit mounted on a translation stage. The CP x-ray beam then passed through a sealed Ar ionization chamber that served as a beam monitor before the beam was incident on the sample.

Results

Magnetic Compton spectra were taken for a series of energies between 55 and 100 keV. The technique used to take the data is essentially the same as described by Yahnke, *et al.* [3] with a major improvement in data collection times. Figure 2 gives the experimentally determined P_C as a function of incident energy. While the performance of the XPR does not meet theoretical expectations at higher energies, it is still capable of producing above 65% CP x-rays at 86 keV. In addition, both helicity beams yield the same value of P_C within the error bars making helicity-switching a viable alternative to magnetization reversal. The larger error bars at lower energies arise from poorer statistics due to shorter data collection times. At lower energies, the XPR has reduced flux throughput through the Laue portion due to the combination of dynamical and filtering effects. The difficulty in reducing statistical error is due to the inherently weak magnetic scattering cross section. For our initial characterization of the performance of the XPR, we were able to reduce the statistical error at 86 keV to less than 10% in about one hour of data collection.

The flux output from the XPR was characterized using the sector 1 APS bending magnet calculated to deliver 9.4 x 10^9 photons/s/0.1% BW at a ring current of 100 mA at 85 keV. The flux in the circularly polarized beam, after consecutive (220) Bragg and (220) Laue reflections, was measured to be approximately 2 x 10^7 photons/s. (For comparison, the flux on the undulator A beamline was approximately 2 x 10^9 photons/s.) This is an order of magnitude less than the theoretical flux expected from the XPR. The source of this loss is suspected to be strain within the Laue portion of the crystal. The intensities of (400) Bragg and Laue reflections, both measured using the Laue part of the XPR, were compared and the ratio found to be an order of magnitude less than predicted by theory. The crystal does not appear to be undergoing thermal strain as there was no observed rise in the temperature of the crystal with the white beam incident on it. The strain is likely inherent within the Ge single crystal, and the 14.1 mm Laue thickness would compound the loss of intensity arising from it. Mechanical strain due to the rotation of the Laue part through the weak link could also be a factor.

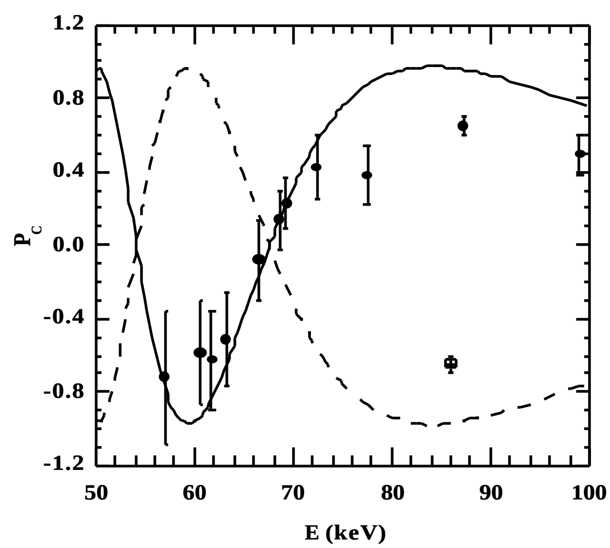

Figure 2: Comparison of experimental and theoretical P_C produced by the Ge XPR by the (220) reflections at 86.5 keV. The error bars are purely statistical. The two data points at 86 keV are acquired from the two opposite helicity CP x-ray beams.

Discussion

A monolithic Ge Bragg-Laue XPR has been fabricated and found to yield CP x-rays in good agreement with theoretical predictions at energies between 50 and 100 keV. The XPR has been characterized in terms of P_C of the CP x-rays and throughput efficiency. Using an undulator source at the APS, the data collection periods are extremely short. The simultaneous production of both helicities can be exploited to measure difference signals with a fixed applied magnetic field. Low-temperature studies of hard ferromagnets have indicated that helicity switching over magnetic field reversal is the preferred method of obtaining spin-dependent behavior of such systems. To obtain switching frequencies of the order of 1 Hz, a shutter mechanism will need to be incorporated into the current experimental setup. The XPR is currently being applied towards the measurement of spin-dependent momentum distributions of ferromagnetic systems.

Acknowledgments

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