High-precision X-ray polarimeter based on channel-cut crystals

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Date: 2024-02-07T00:00:00+00:00

Abstract

We report on using synthetic silicon for a high-precision X-ray polarimeter comprising a polarizer and an analyzer, each based on a monolithic channel-cut crystal used at multiple Brewster reflections with a Bragg angle very close to 45°. Experiments were performed at the BL09B bending magnet beamline of the Shanghai Synchrotron Radiation Facility using a Si(800) crystal at an X-ray energy of 12.914 keV. A polarization purity of 8.4$×$10-9 was measured. This result is encouraging, as the measured polarization purity is the best-reported value for the bending magnet source. Notably, this is the first systematic study on the hard X-ray polarimeter in China, which is crucial for exploring new physics, such as verifying vacuum birefringence.

Full Text

Preamble

High-precision X-ray polarimeter based on channel-cut crystals

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Abstract: We report on the development of a high-precision X-ray polarimeter using synthetic silicon, comprising a polarizer and an analyzer, each based on a monolithic channel-cut crystal operated at multiple Brewster reflections with a Bragg angle very close to 45°. Experiments were performed at the BL09B bending magnet beamline of the Shanghai Synchrotron Radiation Facility using a Si(800) crystal at an X-ray energy of 12.914 keV. A polarization purity of 9.8×10^{-10} was measured. This result is encouraging, as it represents the best-reported value for a bending magnet source. Notably, this is the first systematic study of a hard X-ray polarimeter in China, which is crucial for exploring new physics such as verifying vacuum birefringence.

Keywords: X-ray polarimeter, Vacuum birefringence, Synchrotron radiation, Channel-cut crystal

1 Introduction

Polarization is a fundamental characteristic of electromagnetic waves. The discovery of X-ray polarization by Barkla in 1904 [1] was decisive in establishing X-rays as electromagnetic waves, and polarized X-rays have since enabled numerous applications. Today, high-precision polarization modulation and measurement of X-rays are essential techniques in synchrotron radiation (SR) applications, particularly for resonant/non-resonant X-ray scattering [2-5] and nuclear resonant X-ray scattering experiments [6, 7], as they provide deep insights into material structure via X-ray dichroism [8, 9] and enable detection of novel physical phenomena such as vacuum birefringence [10-13], initially predicted in the early days of quantum electrodynamics (QED) [14]. The key to these experiments is obtaining X-rays with ultrahigh polarization purity, defined as the ratio of polarized components parallel and normal to the diffraction plane integrated over a certain angular and energy range [15].

The realization of the first X-ray diffraction experiments based on crystals [16] and the development of diffraction theory [17] laid the foundation for effectively modulating X-ray polarization. In 1961, Cole et al. utilized the Borrmann effect in perfect crystals to obtain linearly polarized X-rays and created the first crystal polarimeter [18]. However, the polarization purity achievable with the Borrmann effect is limited to the 1% level due to limitations in modulation efficiency and absorption [19], leading to a dearth of systematic studies on X-ray polarization for the subsequent 30 years.

Since the 1990s, high-precision X-ray polarimeters based on Bragg diffraction from perfect crystals have made tremendous strides, benefiting from advancements in SR sources and crystal processing technology. In 1990, an extinction ratio of 10^6 was achieved near the cobalt K-edge using a white SR beam from a bending magnet (BM) source [20]. In 1997, a polarization purity of 4×10^{-8} at 14.4 keV was achieved using an asymmetrically cut Si(840) crystal [21]. In 2011, B. Marx et al. employed four reflections from a channel-cut crystal with a Bragg angle close to 45° to reach a polarization purity of 9×10^{-9} at 12.914 keV

and 1.5×10^{-9} at 6.457 keV [22], and two years later, this was improved to the 10^{-10} level [23]. Currently, the best polarization purity for X-rays can approach 8×10^{-11}, attained at an X-ray free-electron laser (XFEL) [24], which has met the demands for exploring new physics such as the experimental verification of vacuum birefringence [13].

Recent progress in accelerator [25-28] and laser technology [29-31] has produced new-generation accelerator light sources with ultrahigh brightness and ultra-intense lasers with ultrashort pulses, establishing a solid foundation for future exploration of new physics. However, research on X-ray polarimeters—a key technology in pump-probe experiments—is almost absent in China. Therefore, developing a high-precision X-ray polarimeter for such experiments is highly desirable. A high-quality accelerator light source is essential for developing high-precision X-ray polarimeters. The Shanghai Synchrotron Radiation Facility (SSRF) is the only third-generation accelerator light source in China, and its X-ray test beamline, a BM radiation source [32] with a broad X-ray spectrum, large experimental space, and high experimental flexibility, is an excellent platform for China' s first X-ray polarimeter research.

In this study, we designed and built a high-precision X-ray polarimeter consisting mainly of two channel-cut crystals used as a polarizer and analyzer, a high-precision motion-control mechanism, and a high-sensitivity detection system. With precise electron orbit alignment and photon energy calibration technology, a polarization purity of 9.8×10^{-10} was achieved at an X-ray energy of 12.914 keV, establishing the foundation for vacuum birefringence experiments in China based on a free-electron laser (FEL) [33] and 100 PW lasers [34].

2 Theory

The polarization direction can be defined for the electric radiation field. For a general BM source, the electric field is parallel to the plane of the electron orbit within the orbit plane, producing horizontal polarization, or σ-mode. Above and below this plane, the electric field has a component perpendicular to the orbit plane, producing vertical polarization, or π-mode. The angular distribution of the different polarized photon fluxes follows the modified Bessel functions $K_{1/3}$ and $K_{2/3}$, and the intrinsic polarization purity of the SR is defined as the ratio of the polarized components parallel and normal to the diffraction plane [35]:

$$\frac{N_\sigma(\psi)}{N_\pi(\psi)} \propto \frac{K_{2/3}^2(\xi)}{K_{1/3}^2(\xi) + \frac{\psi^2}{\gamma^2} K_{2/3}^2(\xi)} \quad \text{where} \quad \xi = \frac{\omega}{2\omega_c}(1+\gamma^2\psi^2)^{3/2}$$

where ω and ω_c are the photon frequency and critical photon frequency, respectively, γ is the relativistic Lorentz factor of the electrons, and ψ is the vertical angle of the photons departing from the orbit plane. Fig. 1 Figure 1: see original paper shows the angular distribution of photon flux percentage in different polarization states from the BM source, where the horizontal axis

represents the vertical angle of photon departure from the electron orbit plane, the left vertical axis shows the photon flux percentage of σ-mode and π-mode polarization, and the right vertical axis shows the intrinsic polarization purity of the SR. Fig. 1(a) demonstrates that the spatial distribution of σ-polarized photons is directed mainly toward the orbital plane, with flux dropping rapidly off the plane. The flux percentage of σ-polarized photons exceeds 99% within a 10 rad departure from the orbital plane, then drops rapidly from 99% to 1% within 10 to 200 rad, and falls below 1% when the vertical angle exceeds this range. Therefore, precise alignment of the orbit plane is essential for maximizing σ-polarized photon flux and achieving optimal linear polarization purity. In contrast, the intrinsic polarization purity of the SR decreases even more rapidly off the orbital plane. To reach an intrinsic polarization purity of the 10^{-10} level, the vertical angle of photon departure from the orbital plane must be restricted to the order of nanoradians, which is nearly impossible for a BM source. Generally, the acceptance angle of a Si(111) monochromator is about 20 rad ($±$10 rad), and the corresponding polarization purity of the diffracted beam is only about 3‰. Therefore, obtaining SR with extremely high polarization purity using slits or ordinary monochromators is impossible.

The limit of polarization purity achievable through crystal diffraction is determined by the dynamic theory of X-ray diffraction [36], which can be expressed as:

$$\delta_{\pi\sigma}^{\lim} = \frac{|\chi_{\pi\pi}|}{|\chi_{\sigma\sigma}|} \approx \frac{|\gamma_h|}{|\gamma_0|} \tan^2\theta_B |\chi_{\delta\theta}|$$

where b is the asymmetry factor, χ is the dielectric susceptibility, and θ_B is the Bragg angle. At a Bragg angle of exactly 45°, the diffracted X-ray is totally σ-polarized, and this specific Bragg angle is called the polarization angle or Brewster angle. Fig. 1(b) shows the theoretical limit of polarization purity based on crystal-Bragg diffraction for different angular deviations from the Brewster angle, where both horizontal and vertical coordinates are logarithmic. The horizontal coordinate represents the angular deviation from the Brewster angle, and the vertical axis shows the theoretical limit of polarization purity for Si(800) diffraction in symmetric-Bragg configuration ($b = -1$). Fig. 1(b) demonstrates that the achievable polarization purity is highly sensitive to angular/energy deviation from the Brewster angle/energy. For example, the angular deviation must not exceed 0.0016° to ensure polarization purity better than the 10^{-10} level, and the corresponding energy deviation should not exceed 360 meV according to the differential form of Bragg' s equation, i.e., $\Delta E/E = \cot\theta_B \Delta\theta$, where θ_B and E are the Brewster angle/energy and $\Delta\theta$ and ΔE are the angular/energy deviations from the Brewster angle/energy. Therefore, high-precision angular/energy calibration is essential for improving the theoretical limit of polarization purity.

3 Experiments and Results

The experiments were conducted at the BL09B X-ray test beamline of the SSRF, a BM source with a critical energy of 10 keV [37]. The experiment comprised four parts: crystal quality characterization, electron orbit alignment, photon energy calibration, and polarization purity measurement.

3.1 Crystal Quality Characterization

Perfect polarization requires perfect channel-cut crystals. On one hand, channel-cut crystals enable multiple reflections without changing the beam direction, reducing the number of crystals required and the difficulty of crystal alignment. On the other hand, high reflectivity allows for high transmission efficiency of X-rays, even with multiple reflections. Therefore, characterizing the quality of the channel-cut crystals used as polarizers and analyzers is necessary.

The optical layout for crystal quality characterization is shown in Fig. 2 Figure 2: see original paper. Two grooves with different widths were cut into a monolithic crystal to facilitate adjustment and measurement, enabling 4-reflection, 6-reflection, and 8-reflection configurations. The channel-cut crystal was placed on a high-precision turntable (KOHZU, KTG-16W, 0.0025 arcsec/step) fixed on a high-load X-Z motorized stage (KOHZU, KHI-4SK, 1 m resolution and 100 mm stroke). At the end of the optical path, approximately 40 m from the source, two detectors recorded the experimental data. A photodiode detector (PD, Hamamatsu, S3584-08) with a noise floor of ~0.1 pA measured the rocking curves (RCs) of the 6- and 8-reflection beams, and reflectivity was calculated using the formula $R = I_8/I_6$, where I_6 and I_8 are the peak intensities of the 6- and 8-reflection RCs, respectively. Additionally, a CCD camera (XIMEA, MH160XC-KK-FA) with a resolution of 7.4 m/pixel recorded the position and shape of the diffraction spots. First, the X-ray photon energy was adjusted to 12.914 keV using Si(111) plane diffraction from a double-crystal monochromator (DCM). The incident beam size was adjusted to 5 mm × 1 mm through a slit upstream of the DCM to ensure sufficient area on the inner surfaces of the groove. Subsequently, the position of the channel-cut crystal along the Z-axis and the incident angle around the X-axis were adjusted to ensure full diffraction of the incident X-rays by the channel-cut crystal. The 6- and 8-reflection RCs were recorded by the PD, as shown in Fig. 2(b). Finally, the channel-cut crystal was rotated to the Bragg angle, and the 6- and 8-reflection diffraction spots were recorded using the CCD, as shown in Fig. 2(c).

Figs. 2(b) and 2(c) present the crystal quality characterization results. Fig. 2(b) shows the RCs of the Si(800) crystal for 6- and 8-reflections, where the horizontal coordinate represents angular deviation from the Bragg angle and the vertical axis shows the photocurrent intensity recorded by the PD. The peak intensities of the 6- and 8-reflection RCs are 16.3 nA and 13.6 nA, respectively, yielding a calculated reflectivity exceeding 90%. Each RC exhibits a distinct glitch derived from multiple-beam diffraction, which can be eliminated

by selecting an appropriate in-plane crystal angle. Fig. 2(c) shows the Si(800) diffraction spots for 6- and 8-reflections, where the horizontal and vertical coordinates represent the horizontal and vertical positions on the CCD, respectively. The imaging results in Fig. 2(c) indicate that the sizes and shapes of the two diffracted beams match those of the incident beam, demonstrating successful transmission of X-rays into the channel-cut crystal groove. Additionally, the beam position in Fig. 2(c) shows that the 6-reflection beam is higher than the 8-reflection beam due to the wider groove width for 6-reflections.

3.2 Electron Orbit Alignment

Considering the polarization characteristics of the BM source discussed in Section 2 and the narrow acceptance angle of the polarizer, precise alignment of the orbital plane is essential for optimal linear polarization purity.

The optical layout for electron orbit alignment is shown in Fig. 3 Figure 3: see original paper. The orbit analyzer was a flat Si(800) crystal placed on a turntable (KOHZU, RA10A-W01, 20-subdivision settings with 0.36" resolution) approximately 40 m downstream from the BM source. The diffraction plane of the orbit analyzer was perpendicular to that of the DCM. In this configuration, π-polarized photons can be fully reflected while σ-polarized photons are greatly suppressed. As described in Section 2, photons are σ-polarized in the electron orbit plane, while π-polarized photons are present above and below the orbital plane. Therefore, if the incident beam contains photons emitted from the electron orbit plane, a dark area must appear at the center of the diffraction spot. At the experiment' s start, two slits upstream and downstream of the DCM were fully opened to obtain maximum photon flux at 12.914 keV and maximize alignment efficiency. Next, the orbit analyzer was rotated to the Bragg angle, and the CCD camera at the optical path' s end recorded the diffraction spot of the orbit analyzer, as shown in Fig. 3(b). Finally, the vertical size of the slit downstream of the DCM was gradually narrowed to approximately 0.5 mm around the orbital plane based on the intensity distribution of the diffraction spot in the vertical direction, and the CCD camera recorded the diffraction spot of the orbit analyzer, as shown in Fig. 3(c).

The electron orbit alignment results are shown in Figs. 3(b) and 3(c). Fig. 3(b) shows that the diffracted spot size is approximately 30 mm $\times$ 4 mm, consistent with the incident beam size determined by the slit upstream of the DCM. Fig. 3(c) shows enlarged diffraction spots, including the dark central area marked by the red rectangle in Fig. 3(a). Fig. 3(d) shows the intensity distribution of the central dark area in the vertical direction, where the horizontal coordinate represents the vertical position of the spots on the CCD and the vertical axis represents photocurrent intensity expressed as gray value. Fig. 3(d) shows that the vertical size of the dark area—the distance between the two peaks—is approximately 0.5 mm. Considering the incident beam flux, angular divergence, and crystal bandwidth, the final incident beam size was limited to approximately 1 mm $\times$ 0.5 mm centered on the electron orbit plane, as shown in Fig. 3(c),

with corresponding angular divergence of 25 rad × 12.5 rad in the horizontal and vertical directions. The intrinsic linear polarization purity within the 0.5 mm range of the orbit plane is about 1‰ according to Equation 1; however, the theoretical limit of polarization purity restricted by angular divergence under these conditions can reach the 10^{-10} level, as demonstrated by $\delta \approx \sigma_H^2 + \sigma_V^2$ [38], where σ_H and σ_V are the horizontal and vertical divergence angles, respectively.

3.3 Photon Energy Calibration

Given the polarization characteristics of crystal diffraction discussed in Section 2, the achievable polarization purity limit is sensitive to angular/energy deviation from the Brewster angle/energy. Therefore, precise photon energy calibration is essential for maximum polarization purity.

The optical layout for photon-energy calibration is shown in Fig. 4 Figure 4: see original paper. The white beam generated by the BM was monochromatized to approximately 12.914 keV using Si(111) plane diffraction in the DCM. To achieve high-precision calibration, a V-shaped crystal with two orthogonal Si(800) and Si(080) planes having an equal Darwin width of about 0.72”was employed as the energy analyzer, providing an energy resolution of 45 meV to calibrate the X-ray energy transmitted through the polarizer. The polarizer and energy analyzer were each placed on a high-precision turntable (KOHZU, KTG-16W, 0.0025 arcsec/step) fixed on a high-load X-Z motorized stage (KOHZU, KHI-4SK, 1 m resolution and 100 mm stroke). First, the polarizer was rotated around the 45° Brewster angle to obtain the RC recorded by the PD after the polarizer, as shown in Fig. 4(b). The Bragg angle of the polarizer was set at the center of the RC’ s flat-top region. Subsequently, the polarizer and energy analyzer were configured in a dispersion (+-+) arrangement, and the Bragg angle of the energy analyzer was rotated to obtain the RC, as shown in Fig. 4(c). Next, the DCM was rotated in steps of 1” (corresponding to an energy resolution of 63 meV), and the energy analyzer was used to accurately calibrate the photon energy passing through the polarizer using the maximum RCs of the energy analyzer, as shown in Fig. 4(c).

Fig. 4(b) shows the RC of the polarizer at approximately 12.914 keV before energy calibration, where the horizontal coordinate represents angular deviation from the Bragg angle and the vertical axis shows the photocurrent intensity recorded by the PD. Fig. 4(b) demonstrates that the angular width (FWHM) of the polarizer RC is about 66”, much larger than the 4.1”Darwin width of Si(111), and cannot meet the polarizer’ s angular/energy accuracy requirement (no more than 0.002°/7.2”), as discussed in Section 2. Fig. 4(c) shows the RCs of the analyzer at different photon energies around 12.914 keV after energy calibration, where the horizontal coordinate represents angular deviation from the Bragg angle, the vertical axis shows the photocurrent intensity recorded by the PD, and RCs in different colors indicate different energy deviations. The angular width (FWHM) of each RC in Fig. 4(c) is about 0.72” , and the corresponding energy bandwidth is about 45 meV, consistent with the Darwin width of the

Si(800) plane. The calibration accuracy of the energy analyzer is almost one order of magnitude more precise than that of the absorption edge method [39]. It can reach the level of the energy bandwidth of the Si(800) plane, which is sufficient to obtain a linearly polarized beam with polarization purity better than 10^{-10}, according to Fig. 1(b).

3.4 Polarization Purity Measurement

After orbital alignment, the SR beam position and size were limited to approximately 1 mm × 0.5 mm centered on the electron orbit plane, and the photon energy was calibrated to 12.914 keV with an energy bandwidth better than 50 meV. Therefore, the theoretical limit of polarization purity under these conditions can reach the 10^{-10} level, as previously discussed.

The optical layout of the polarization purity measurement setup is shown in Fig. 5 Figure 5: see original paper. An ionization chamber (IC) was installed before the polarizer to monitor beam intensity during experiments. The polarizer was positioned close to the beryllium window (BW) of the beamline, while the analyzer was positioned approximately 5 m downstream of the polarizer to efficiently suppress background radiation. Moreover, the position and angle of the polarizer crystal were adjustable in seven dimensions, including crystal translation along the X-, Y-, and Z-axes relative to the crystal turntable, crystal rotation of the pitch angle (Bragg angle), yaw angle (in-plane angle), and translation of the crystal turntable along the X- and Z-axes. In contrast, the analyzer crystal adjustment mechanism was more complex and included three additional rotations of the crystal turntable: the pitch angle (around the X-axis), yaw angle (around the Z-axis), and roll angle (around the Y-axis, defined as the analyzer angle—the angle between the diffraction planes of the analyzer and polarizer crystals). The adjustment accuracy and range of the pitch, yaw, and roll angles were 0.004" in $±$5°, 0.72" in $±$2°, and 0.72" in $±$175°, respectively. The polarimeter system comprised 12 reflections: four in the polarizer crystal to adequately suppress π-mode photons while ensuring reasonable transmission of σ-mode photons, and eight in the analyzer crystal to minimize scattered photons as much as possible. The scanning range of the analyzer angle was 0°–95°; the 0° and 90° positions corresponded to parallel and perpendicular orientations of the two diffraction planes of the polarizer and analyzer crystals, respectively. First, the polarizer and analyzer were preliminarily aligned using a laser to ensure that the bases of the two channel-cut crystals were at the same height as the incident beam. Subsequently, the SR beam was limited to approximately 1 mm × 0.5 mm, centered on the electron orbit plane, and the photon energy was calibrated to 12.914 keV, as discussed previously. Meanwhile, the Bragg angle of the polarizer was maintained at 45.002° with an appropriate in-plane angle to avoid multiple-beam diffraction effects. Next, the position and altitude of the analyzer were adjusted to ensure that the SR beam was perpendicular to the turntable plane of the roll angle and passed through its rotation center, which was indispensable for maintaining the same Bragg angle of the analyzer

crystal across the scanning range of the analyzer angle. Finally, the analyzer angle was rotated from 0° to 95°, and three different detectors recorded the signals: a PD measured the RCs of the analyzer at analyzer angles from 0° to 85°, a homemade avalanche photodiode detector (APD) measured RCs from 85° to 89.97°, and a two-dimensional single-photon detector (2D-SPD, SPECTRUM, Lambda 250K) placed behind the analyzer recorded the intensity, shape, and position of the exit beam at each analyzer angle. The integration time of the 2D-SPD was varied from 1 s to 10000 s to avoid detector saturation and obtain sufficient photons, depending on the analyzer angle.

Fig. 5(b) shows the spot distribution of the diffracted beam from the polarimeter system, where the horizontal coordinate represents the analyzer angle of the analyzer crystal and the vertical axis represents the relative height of the diffracted beam imaged by the 2D-SPD. Each spot was imaged at the Brewster angle of the analyzer, corresponding to the maximum RC at each roll angle position, and the final results were normalized to the integration time. The analyzer rotation radius of the roll angle was 45 mm, creating a 45 mm relative height between the parallel and perpendicular positions. The maximum photon flux (0° roll angle) entering the 2D-SPD was approximately 3 million photons/s in the parallel position. The exposure time was set to the maximum achievable limit of 10000 s at the current noise floor of the 2D-SPD to collect a credible number of photons near the perpendicular position. A photon flux of 25 photons/10000 s was recorded at the perpendicular position, with an uncertainty from background noise of approximately 1 photon/10000 s. As shown in Fig. 5(b), the measurement results indicate that the intensity range of the 21 spots spans more than eight orders of magnitude as the analyzer moves from 0° to 95°, and each spot represents a DuMond diagram of the diffracted beam. Meanwhile, the inclined angles between the DuMond diagrams and the horizontal direction gradually approach 35°, as demonstrated more clearly in the inset, which is an enlarged view near the perpendicular position. This follows the dynamic theory of X-ray diffraction based on orthogonal crystals [40], where the inclined angle of the DuMond diagram relative to the horizontal direction can be expressed as $\alpha = \tan^{-1}(\tan\theta_{Bp}/\tan\theta_{Ba})$, where θ_{Bp} and θ_{Ba} are the Bragg angles of the polarizer and analyzer, respectively, at a given X-ray energy. Therefore, we obtain $\alpha = 35°$ when the X-ray reaches the Brewster angles for both polarizer and analyzer crystals ($\theta_{Bp} = \theta_{Ba} = 45°$).

Fig. 5(c) shows the polarization purity measurement results—a quantitative analysis of the spot integral intensities in Fig. 5(b)—where the horizontal coordinate represents the analyzer angle of the analyzer crystal and the vertical axis represents the normalized intensity of the diffracted beam, i.e., the polarization purity of the exit beam. The inset in Fig. 5(c) depicts the Bragg angle peaks of the RCs at the parallel position and near the perpendicular position, where the horizontal coordinate represents angular deviation from the Bragg angle and the vertical axis represents the photocurrent intensity of the diffracted beam recorded by the PD and APD. The inset reveals that the Bragg angle of the RC peak at the parallel position is shifted by less than 1°, indicating satisfactory

parallelism between the X-ray beam and the axis of the roll angle (analyzer angle). Furthermore, the width (FWHM) of the RC is quite close to the theoretical Darwin width limit of the Si(800) plane at the parallel position, increasing to about 3.5" when moving to the perpendicular position. This is partly due to the excellent crystal quality and processing technology, which minimized bandwidth expansion caused by lattice deformation during diffraction. Additionally, high-precision electron orbit alignment and photon energy calibration technologies enable achieving a small angular divergence of less than 25 rad and a small energy deviation of less than 50 meV. Notably, the transmission efficiency of the system can exceed 20% within the bandwidth of the polarizer and analyzer due to high-quality crystals with reflectivity exceeding 90%. Finally, the intensity was normalized to the incident photon flux, and the result indicates that the flux of π-mode photons can be suppressed by a factor of 9.8×10^{-10}.

4 Conclusion

We designed and built a high-precision X-ray polarimeter based on multiple Brewster reflections from channel-cut crystals at an energy of 12.914 keV. A 2D-SPD was employed to record the shape and intensity of the diffracted beam. The measured polarization purity was 9.8×10^{-10} using precise electron orbit alignment and photon energy calibration technology, representing a significant step toward exploring vacuum birefringence in China. The polarization purity is primarily limited by the brightness of the BM source, which is several orders of magnitude lower than that of an undulator source. In the future, polarization purity better than $\sim 10^{-10}$ can be expected based on X-ray sources with higher brightness and lower divergence, such as diffraction-limited storage rings (DLSRs) and FELs, and through further improvements to X-ray polarimeters, such as using different crystals with lower atomic numbers.

Author contributions: All authors contributed to the conception and design of the study. Experimental preparation, data collection, and analysis were performed by Shang-Yu Si, Zhong-Liang Li, Wen-Hong Jia, Lian Xue, Lin-Gang Zhang, Liang-Liang Ji, Hong-Xin Luo, and Ren-Zhong Tai. The first draft of the manuscript was written by Shang-Yu Si, and all authors commented on previous versions. All authors have read and approved the final manuscript.

Data Availability Statement: The data supporting the findings of this study are openly available in Science Data Bank at https://cstr.cn/31253.11.sciencedb.15964.

Acknowledgments: We thank Prof. Xiao-Wei Zhang, Dr. Jun-Liang Yang, Senior Engineer Qian-Shun Diao, and Zhen Hong of the Beijing Institute of High Energy Physics for their valuable support and assistance with experimental methods and crystal processing. We thank Prof. Qiu-Ju Li and Dr. Zi-Yu Bao of the Beijing Institute of High Energy Physics for their support in manufacturing and operating the APD. We thank Drs. Hai-Peng Zhang and Chang-Zhe Zhao of the Shanghai Synchrotron Radiation Facility for their help with data acquisition and image processing.

This work was supported by the Shanghai Municipal Science and Technology Major Project (Grant No. 2017SHZDZX02), the National Natural Science Foundation of China (Grant No. 12205360), and the Youth Innovation Promotion Association of the Chinese Academy of Sciences (Grant No. 2018297).

References

1. C.G. Barkla, Polarisation in Röntgen Rays. Nature 69, 463 (1904). https://doi.org/10.1038/069463a0
2. K.S. Schulze, R. Loetzsch, R. Rüffer et al., X-ray dichroism in polyimide caused by non-resonant scattering. Synchrotron Radiat. 176-180(2021). https://doi.org/10.1107/S1600577520015568
3. M. Hart, X-ray polarization phenomena. Philos. Mag. B 38, 41-56 (1978). https://doi.org/10.1080/13642817808245319
4. S. Mukherjee, J.K. Streit, E. Gann et al., Polarized X-ray scattering measures molecular orientation in polymer-grafted nanoparticles. Nat. Commun. 12, 4896 (2021). https://doi.org/10.1038/s41467-021-25176-4
5. L. Paolasini, C. Detlefs, C. Mazzoli et al., ID20: a beamline for magnetic and resonant X-ray scattering investigations under extreme conditions. J. Synchrotron Radiat. 14, 301–312 (2007). https://doi.org/10.1107/S0909049507024879
6. E.E. Alp, W. Sturhahn, T.S. Toellner et al., Vibrational Dynamics Studies by Nuclear Resonant Inelastic X-Ray Scattering. Hyperfine Interact. 144, 3-20 (2002). https://doi.org/10.1023/A:1025452401501
7. E.E. Alp, W. Sturhahn and T.S. Toellner, Polarizer–analyzer optics. Hyperfine Interact. 125, 45-68 (2000). https://doi.org/10.1023/A:1012673301869
8. G. van der Laan and A. I. Figueroa, X-ray magnetic circular dichroism-A versatile tool to study magnetism. Coord. Chem. 277-278, (2014). https://doi.org/10.1016/j.ccr.2014.03.018
9. A. Ney, V. Ney, K. Ollefs et al., X-Ray Linear Dichroism: An Element-Selective Spectroscopic Probe for Local Structural Properties and Valence. J. Surf. Interfaces Mater. 2, 14-23 (2014). https://doi.org/10.1166/jsim.2014.1031
10. T. Heinzl, B. Liesfeld, K. U. Amthor et al., On the observation of vacuum birefringence. Opt. Commun. 267, 318-321 (2006). https://doi.org/10.1016/j.optcom.2006.06.053
11. F. Karbstein, H. Gies, M. Reuter et al., Vacuum birefringence in strong inhomogeneous electromagnetic fields. Phys. (2015). https://doi.org/10.1103/PhysRevD.92.071301
12. H.P. Schlenvoigt, T. Heinzl, U. Schramm et al., Detecting vacuum birefringence with x-ray free electron lasers and high-power optical lasers: a feasibility study. Phys. Scr. 91, 023010 (2016). https://doi.org/10.1088/0031-8949/91/2/023010
13. F. Karbstein, Vacuum birefringence in the head-on collision of X-ray free-electron laser and optical high-intensity laser pulses. Phys. Rev. D 98, 056010 (2018). https://doi.org/10.1103/PhysRevD.98.056010

14. J. J. Klein and B. P. Nigam, Birefringence of the Vacuum. Phys. Rev. 135, B1279 (1964). https://doi.org/10.1103/PhysRev.135.B1279
15. C.G. Barkla, Polarisation in Rontgen Rays. Nature 69, 1904 (1794). https://doi.org/10.1038/069463a0
16. W. Friedrich, P. Knipping, M. von Laue, Interferenzerscheinungen bei Rontgenstrahlen. Ann. Der Phys. 346, 971-988 (1913). https://doi.org/10.1002/andp.19133461004
17. C.G. Darwin, The Theory of X-Rag Reflexion. Philos. Mag. 27, 315-333 (1914). https://doi.org/10.1080/14786440208635093
18. H. Cole, F. W. Chambers and C. G. Wood, X-Ray Polarizer. J. Appl. Phys. 32, 1942-1945 (1961). https://doi.org/10.1063/1.1728267
19. A. Authier, S. Lagomarsino and B. K. Tanner. X-Ray and Neutron Dynamical Diffraction. 1st edn. (Springer, New York, 1996), pp. 91-109. https://doi.org/10.1007/978-1-4615-
20. D.P. Siddons, I.M. Hart, Y. Amemiya et al., X-Ray Optical Activity and the Faraday Effect in Cobalt and Its Compounds. Phys. Rev. Lett. 64, 1967-1970 (1990). https://doi.org/10.1103/PhysRevLett.64.1967
21. R. Röhlsberger, E. Gerdau, R. Rüffer et al., X-ray optics for mu eV-resolved spectroscopy. Nucl. Instrum. Meth. A 394, 251-255 (1997). https://doi.org/10.1016/S0168-9002(97)00710-9
22. B. Marx, I. Uschmann, S. Höfer et al., Determination of high-purity polarization state of X-rays. Commun. (2011). https://doi.org/10.1016/j.optcom.2010.10.054
23. B. Marx, K.S. Schulze, I. Uschmann et al., High-Precision X-Ray Polarimetry. Phys. Rev. Lett. 110, 254801 (2013). https://doi.org/10.1103/PhysRevLett.110.254801
24. K.S. Schulze, B. Grabiger, R. Loetzsch et al., Towards perfectly linearly polarized X-rays. Phys. Rev. Res. 4, 013220 (2022). https://doi.org/10.1103/PhysRevResearch.4.013220
25. H.X. Yin, J.B. Guan, S.Q. Tian et al., Design and optimization of diffraction-limited storage ring lattices based on many-objective evolutionary algorithms. Nucl. Sci. Tech. 34, 147 (2023). https://doi.org/10.1007/s41365-023-01284-2
26. J. Chen, Y.B. Leng, L.Y. Yu et al., Optimization of the cavity beam-position monitor system for the Shanghai soft X-ray free-electron laser user facility. Nucl. Sci. Tech. 33, 124 (2022). https://doi.org/10.1007/s41365-022-01117-8
27. Z.Y. Ma, S.J. Zhao, X.M. Liu et al., High RF power tests of the first 1.3 GHz fundamental power coupler prototypes for the SHINE project. Nucl. Sci. Tech. 33, 10 (2022). https://doi.org/10.1007/s41365-022-00984-5
28. J. Yang, Y.C. Du, L.X. Yan et al., Laser–RF synchronization based on digital phase detector. Nucl. Sci. Tech. 28, 57 (2017). https://doi.org/10.1007/s41365-017-0205-z
29. C. Jiang, Z.X. Zhang, H. Dong et al., Generation and application of high-contrast laser pulses using plasma mirror in the SULF-1PW beamline. Chin. Opt. Lett. 21, 043802 (2023). https://doi.org/10.3788/COL202321.043802
30. X.M. Lu, X.Y. Liang, Y.X. Leng et al., Improvement of the

large aperture Ti:sapphire amplifiers in the petawatt femtosecond laser system at SIOM. Chin. Opt. Lett. 8, 1008 (2010). https://doi.org/10.3788/COL20100810.1008
31. H.T. Li, B. Zhao, X.Z. Zhang et al., Development of a portable laser heating device for synchrotron radiation in situ experiment. Nucl. Tech. 46, 020101 (2023). http://doi.org/10.11889/j.0253-3219.2023.hjs.46.020101
32. J. Eberhard, Jaeschke, K. Shaukat, Jochen R. et al., Synchrotron Light Sources and Free-Electron Lasers. (Springer, Switzerland, 2020), https://doi.org/10.1007/978-3-030-23201-6
33. N.S. Huang, Z.P. Liu, B.J. Deng et al., The MING proposal at SHINE: megahertz cavity enhanced X-ray generation. Nucl. Sci. Tech. 34, 6 (2023). https://doi.org/10.1007/s41365-
34. B.F. Shen, Z.G. Bu, J.C. Xu et al., Exploring vacuum birefringence based on a 100 PW laser and an x-ray free electron laser beam. Plasma Phys. Control. Fusion. 60, 044002 (2018). https://doi.org/10.1088/1361-6587/aaa7fb
35. J. Eberhard, Jaeschke, K. Shaukat, Jochen R. et al., Synchrotron Light Sources and Free-Electron Lasers. 2nd edn. (Springer, Nature Switzerland, 2020), pp. 57-58. https://doi.org/10.1007/978-3-030-23201-6
36. A. Authier. International Tables for Crystallography. (Springer, Dordrecht, 2010). Vol. B, Chapter 5.1, pp. 626-646. https://doi.org/10.1107/97809553602060000108
37. Z.L. Li, Y.C. Fan, L. Xue et al., The design of the Test Beamline at SSRF. In 13th International Conference on Synchrotron Radiation Instrumentation (SRI2018), 2054, (2019). https://doi.org/10.1063/1.5084671
38. K.S. Schulze, Fundamental limitations of the polarization purity of X rays. APL Photonics. 3, 126106 (2018). https://doi.org/10.1063/1.5061807
39. Z.L. Li, J.L. Yang, S.Y. Si et al., Simple, high-resolution method for measurement of the natural relative energy bandwidth of Si(111) double crystal monochromators. Nucl. Instrum. Meth. A 983, 164526 (2020). https://doi.org/10.1016/j.nima.2020.164526
40. M. Servidori, F. Cembali and S. Milita, 3D DuMond diagrams of multicrystal Bragg-case synchrotron topography. I. Flat sample. Appl. Phys. A 73, 75-82 (2001). https://doi.org/10.1007/s003390100843

Note: Figure translations are in progress. See original paper for figures.