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High precision measurement of undulator polarization in the regime of hard x-rays

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We have measured the polarization purity of undulator radiation at 12.9 keV, with hitherto unachievable precision. We could measure a polarization purity of 1.8×10^{-4} by using a silicon channel-cut crystal with six Bragg reflections at 45° as analyzer. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4890584]

The creation of extremely brilliant x-ray beams in synchrotrons and free-electron lasers (FELs) would be unconceivable without undulators. Their history started in 1947, when Ginzburg[1] analyzed the idea for the first time in a theoretical paper. The first undulator was already built by Motz and coworkers in 1953.[2] Many studies on undulator radiation have been performed since then. Pioneers have been Alferov *et al.*[3,4] and Nikitin and coworkers.[5,6]

The range of application of brilliant x-ray beams is large and many experiments make use of the natural polarization of the undulator radiation. Angle resolved photoion measurements of molecules in gas phase,[7] experiments on surface magnetism,[8] and magnetic small angle scattering[9,10] are just a few examples in this respect. For these kind of experiments, it is important to know the exact polarization state of the undulator radiation to avoid errors in the analysis of the experimental data. Accordingly, polarization measurements of undulator radiation have been performed. In the soft x-ray regime multilayers[11] and synthetic mica crystal polarizers[12] were used. Kimura, e.g., used two Ru/Si multilayer mirrors with a polarizance of 0.97, one as a phase shifter and the other one as an analyzer, to carry out a full polarization measurement on beamline 11 A at the Photon Factory. In the best case, he measured a degree of linear polarization (DOLP) of 0.99 ± 0.01 for a wavelength of 12.8 nm. Imazono made use of a synthetic mica single crystal with the rotating analyzer method to determine the degree of linear polarization of the undulator beamline BL23SU at SPring-8 to 0.993 ± 0.004 for a photon energy of 880 eV. The polarizance of their analyzer was determined to 0.997 ± 0.002.

Here, we report on a respective experiment in the x-ray regime. The accuracy in measuring the degree of linear polarization was improved by two orders of magnitude to 0.99908 ± 0.00005 using a silicon channel-cut crystal with six Bragg reflections at exactly 45° as an analyzer. Our method make use of the polarization properties at 45° of the Thomson scattering amplitude. This has been exploited for the first time by Ramaseshan for x-ray crystal polarimeters.[13] The advantages of using multiple reflection were described by Bonse and Hart in 1965.[14]

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We performed the precision measurement on the undulator polarization at the "High Resolution Dynamics Beamline" P01 at PETRA III in Hamburg. To date, PETRA III is the most brilliant storage-ring-based x-ray source. With a circumference of 2304 m, a horizontal positron beam emittance of 1.0 nmrad, and a positron energy of 6 GeV, brilliances up to 10^{21}ph/(smm^{2}mrad^{2}0.1%BW) can be achieved.

During our measurements, the synchrotron was operating in the 240 bunch mode with a ring current of 100 mA in top-up mode. The schematic setup of the experiment is shown in Fig. 1. The undulator U32 at P01 consists of two segments, each 5 m long and with a minimum gap of 12.7 mm. In order to fulfill the polarization condition of the channel-cut analyzer crystal, i.e., a Bragg angle of exactly 45° for the Si (800)-reflection, the x-ray beam was monochromatized at 12914 eV by a Si (111) double-crystal monochromator with an energy bandwidth of 0.013%. Due to its Bragg angle of $\theta_B = 8.8°$, the monochromator reflects both polarization components with $R_i^\sigma = 1$ and $R_i^\pi = \cos^2(2\theta) = 0.91$ for σ- and π-polarization, respectively. The adjustment of the energy was checked by a specially prepared silicon crystal monolith, with reflecting surfaces parallel to the (100) and (001) planes. Therefore, the monolith is assembled in place of the analyzer crystal in the setup. The intensity of the doubly reflected beam inside the monolith is maximized when the energy fulfills Bragg's law at a Bragg angle of exactly 45.000°. The divergence of the undulator beam was confined by a variably adjustable slit. For analyzing the polarization of the incoming beam, a 6-reflection Si (800) channel-cut was used.

In order to record the rocking curves, the analyzer crystal was mounted on a goniometer with a full-step resolution

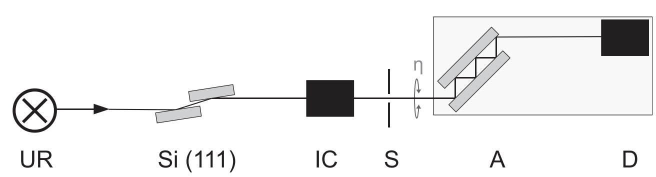

FIG. 1. Experimental setup of the polarization measurement. The incoming undulator radiation (UR) is monochromatized by a Si (111) monochromator, then restricted by a slit (S) and finally analyzed by a 6 reflection channel-cut crystal. The photon flux behind the monochromator is monitored by an ionization chamber (IC).

of 0.9 arc sec. A second goniometer with the same resolution was attached on the first one to rotate the analyzer crystal around the incoming beam (η-circle). The rotation axis of the η-goniometer was adjusted with an alignment laser and two variable slits defining the direction of the incoming beam from the monochromator. When rotating the η-circle, we measured an elastic distortion of the attached channel-cut mount due to its own weight of less than 0.05°.

The entire analyzer setup was positioned 33 m downstream of the monochromator with the slit being placed 1.1 m in front of the analyzer. The distance between monochromator and the center of the undulator is 48.5 m. For the measurement of the photon flux $I_{\text{photo diode}}$, a calibrated Si photodiode was used as a detector behind the analyzer. An ionization chamber behind the monochromator was used to normalize the detected photon flux to the incoming photon flux I_{pitch} from the undulator.

The polarization of the undulator radiation was measured by rotating the analyzer channel-cut crystal from 0° (i.e., the linearly polarized undulator radiation is perpendicular on the diffraction plane of the crystal) to 90°. For each analyzer position, the rocking curve was measured with an integration time of 0.1 s per angular position. The measurement was done for two different slit parameters: One for an aperture of 1 mm × 1 mm and the other for 3 mm × 3 mm. This restricts the horizontal and vertical divergences of the beam to (1.0 × 1.3) arc sec and (3.1 × 3.8) arc sec, respectively. Fig. 2 shows the measured rocking curves, which are normalized to the photon flux incident on the analyzer, at different analyzer positions (varying from 1° to 95°) on logarithmic and linear scales. For visual convenience, the rocking curves have been shifted with respect to each other.

It is obvious that the shape of the rocking curves is atypical: The plateau-like wings of five rocking curves near the passing direction were clearly indentified by a fault of the stepper motor. These artefacts were corrected for the data analysis.

On the contrary, the rocking curves near the extinction position show an increasing tip for both slit settings. This is obviously an Umweganregung (multiple beam case) caused by the orientation of the channel-cut crystal to the incoming beam and has to be discarded for the calculation of the polarization purity of the beamline. A precise alignment of the channel-cut crystals like described in Refs. 15 and 16 is necessary to prohibit this effect a priori in future measurements.

To determine the polarization of the undulator radiation, we use the degree of polarization purity δ_0 (Ref. 17) instead of the DOLP, because the values of DOLP are very close to one. For the calculation of δ_0, the integrated intensity of each rocking curve of Fig. 2 is determined and normalized to the integrated intensity of the rocking curve in the parallel direction ($\eta = 0°$). Fig. 3 shows the result of this calculation, when effects of the step motor controlling and

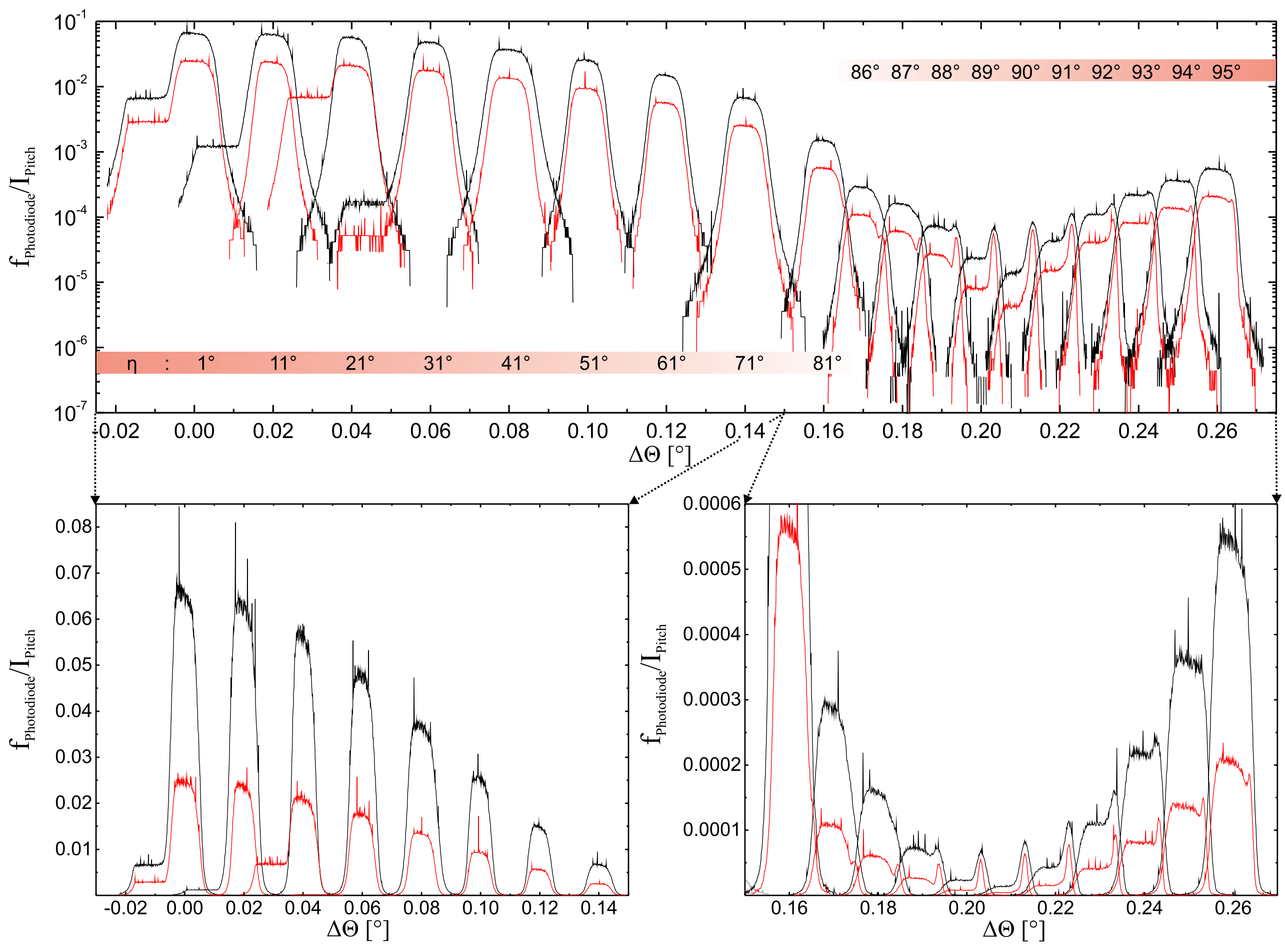

FIG. 2. Rocking curves for a 6-reflection Si (800) channel-cut measured at different analyzer positions η and using a photon energy of 12.914 keV. The beam was restricted to 1 mm × 1 mm for the red rocking curves and to 3 mm × 3 mm for the black ones. The lower panels display the same curves on a linear scale.

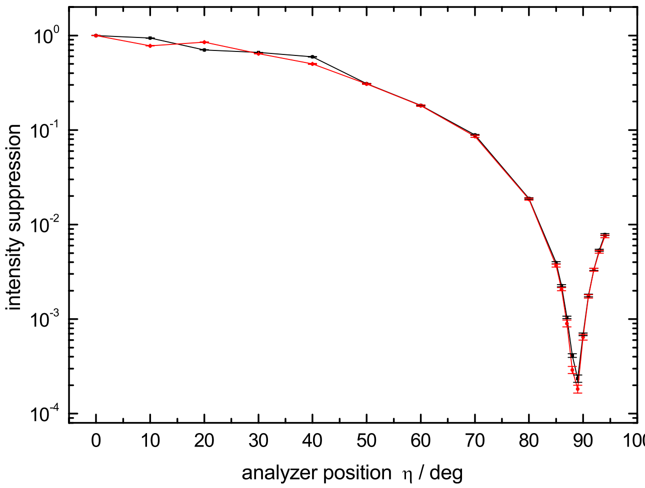

FIG. 3. Polarization purity measurement for two beam diameters: 1 mm × 1 mm—red dots and 3 mm × 3 mm—black squares, measured at a photon energy of 12.914 keV.

Umweganregung are discarded from the rocking curves. The minimum of the curve corresponds to the polarization purity. For the 3×3-mm^2 slit, the polarization purity is $(\delta_0 = 2.4 \pm 0.2) \times 10^{-4}$, while the value for the 1×1-mm^2 slit is $(\delta_0 = 1.8 \pm 0.2) \times 10^{-4}$.

The theoretical estimation of the polarization purity of the beamline can be done by using the angular spectral power distribution of a plane strong undulator.[18] The angular spectral power distribution

$$\frac{d^2P_m}{d\Omega d\omega} = P_u \gamma^{*2}[F_{m\sigma}(\vartheta,\phi) + F_{m\pi}(\vartheta,\phi)] f_N(\Delta\omega_m) \quad (1)$$

of the harmonic m depends on the averaged total power emitted by an electron in the undulator (Eq. (2)), which on its part is a function of the classical electron radius r_0, the speed of light c, the rest mass of the positron m_0, the undulator period wave number k_u, the undulator parameter K_u, and the Lorentz factor γ.

$$P_u = \frac{r_0 c m_0 c^2 k_u^2 K_u^2 \gamma^2}{3}. \quad (2)$$

The normalized angular distribution functions for the σ- and π-component

$$F_{m\sigma}(\vartheta,\phi) = A\frac{\left(2\sum_{m1}\gamma^*\vartheta\cos\phi - \sum_{m2}K_u^*\right)^2}{(1+\gamma^{*2}\vartheta^2)^3}, \quad (3a)$$

$$F_{m\pi}(\vartheta,\phi) = A\frac{\left(2\sum_{m1}\gamma^*\vartheta\sin\phi\right)^2}{(1+\gamma^{*2}\vartheta^2)^3}, \quad (3b)$$

contain the sums of Bessel functions (Eqs. (5) and (6)) which are depending on the parameters a_u and b_u (Eq. (7))

$$A = \frac{3m^2}{\pi\left(1+\frac{K_u^2}{2}\right)^2 K_u^{*2}}, \quad (4)$$

$$\sum_{m1} = \sum_{l=-\infty}^{\infty} J_l(ma_u) J_{m+2l}(mb_u), \quad (5)$$

$$\sum_{m2} = \sum_{l=-\infty}^{\infty} [J_l(ma_u) J_{m+2l+1}(mb_u) + J_{m+2l-1}(mb_u)], \quad (6)$$

$$a_u = \frac{K_u^{*2}}{4(1+\gamma^{*2}\vartheta^2)}, \quad b_u = \frac{2K_u^*\gamma^*\vartheta\cos\phi}{1+\gamma^{*2}\vartheta^2}. \quad (7)$$

The angles ϑ and ϕ are spherical coordinates of a sphere with the origin lying in the center of the undulator. $K_u^* = K_u/\sqrt{1+K_u^2/2}$ and $\gamma^* = \gamma/\sqrt{1+K_u^2/2}$ describe the reduced undulator parameter and gamma factor. The spectral function (Eq. (8)) depends on the number of periods N_u of the undulator, which amounts to 154 for the undulator at P01 and the fundamental undulator frequency off axis ω_1

$$f_N(\Delta\omega_m) = \frac{N_u}{\omega_1}\left(\frac{\sin\left(\frac{\Delta\omega_m}{\omega_1}\pi N_u\right)}{\frac{\Delta\omega_m}{\omega_1}\pi N_u}\right)^2. \quad (8)$$

The deviation of the frequency to the frequency of the higher harmonic is expressed by $\Delta\omega_m = \omega - m\omega_1$.

By computing the spectral angular power distribution to the second lowest power of K_u^*, and integrating over the divergence and bandwidth given by the monochromator, one gets the radiated power for each polarization component. Table I shows the calculated polarization purity for the different slit sizes and for different slit positions, that means the center of the slit is shifted to the center of the incoming beam for the 3rd harmonic.

The theoretical calculations for an ideal undulator demonstrates the dependence of the polarization purity on slit size and slit position. The calculations show a better polarization purity than the measured ones at the center of the beam. A slight shift of the 1 mm × 1 mm slit position of 0.7 mm results in a value similar to the measured one. In order to explain a polarization purity comparable to the one measured for the 3×3 mm^2 slit, a shift of 1.5 mm would be necessary. Because the alignment of the slit was only done with a laser and photosensitive paper, a shift of the slit towards the center of the beam cannot be excluded. Nevertheless, the calculation is only an approximation for real undulators, neglecting, for example, effects of positron distribution, magnet errors of the undulator, and depolarization influences of used diamond and Kapton® windows on the beamline.

The polarization purity of beamline P01 at the PETRA-III synchrotron was measured with a hitherto not achieved precision. A polarization purity of 2.4×10^{-4} and 1.8×10^{-4} is obtained for two different beam sizes.

TABLE I. Calculated polarization purities δ_0 of the 3rd harmonic for different slit sizes and positions of the slit respective to the center of the beam.

shift (mm)	1 mm × 1 mm	3 mm × 3 mm
0	8.2×10^{-6}	5.9×10^{-5}
0.7	3.5×10^{-4}	4.8×10^{-5}
1.5	8.4×10^{-2}	1.5×10^{-4}

Our measurements show that the rotating-analyzer method with a 6-reflection silicon channel-cut crystal is a very sensitive method to determine the polarization purity of undulator beamlines in the x-ray regime. As a result high definition x-ray polarimetry can be used to determine the precise polarization purity of synchrotron radiation and FEL radiation which provides an important input parameter for polarization sensitive measurements. Further it can be used as a powerful diagnostic to prove the beam paths of positrons or electrons through undulators as well as the high performance beam quality of real undulators providing synchrotron radiation and hard x-ray FEL radiation.

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