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Spectral properties of the polarizing devices at SRRC

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User requirements at SRRC for high-brilliance synchrotron light in various polarization states will be fulfilled in the near future by the implementation of two types of polarizing devices in the storage ring: the elliptically polarizing undulator (EPU) and the elliptically polarized bending magnet (EPBM). The EPBM provides a broadband polarized spectrum up to the soft X-ray range with rapid alternation of the left and right helicities. The EPU, which has a magnetic period length of 56 mm, generates a high-brilliance harmonic spectral intensity in the range 80–1400 eV with abundant polarization states, including circular ones. The optimal merit flux is evaluated for the operation of these two polarizing devices in the SRRC 1.5 GeV storage ring. The available polarization states are also surveyed.

Keywords: undulators; bending magnets; polarization.

1. Introduction

User requirements at SRRC for synchrotron light with various polarization states will be fulfilled in the near future by the implementation of an elliptically polarizing undulator (EPU) and an elliptically polarized bending magnet (EPBM), thereby allowing polarized radiation to be generated in the VUV to soft X-ray spectral range. As planned, the 3.9 m-long elliptically polarizing undulator will be configured with a magnetic period length of 56 mm (Wang *et al.*, 1996) and is therefore referred to as EPU5.6. Brilliant polarized light covering the spectral range 80–1400 eV can be emitted. In addition, EPU5.6 can be operated in either Sasaki mode (Sasaki, 1994) or Helios mode (Elleaume, 1994). EPU5.6 will be mounted on a dual base-frame, thereby allowing another long-period-length elliptically polarizing undulator to be installed in the same straight section so that high-merit-flux undulator light can also be generated in the low-energy spectral range. The elliptically polarized bending magnet (EPBM) will be implemented to utilize the polarized synchrotron radiation up to the soft X-ray range and is capable of rapidly alternating the left and right helicities (Chen, 1996).

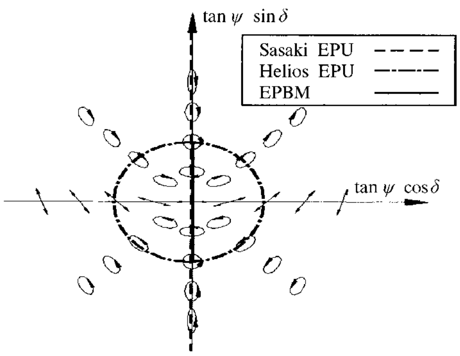

Figure 1
Use of the polarization-state plane to describe completely the available polarization states of the synchrotron radiation emitted from the SRRC polarizing devices EPU5.6 and EPBM.

The polarizing spectral performances are evaluated during operation in the SRRC 1.5 GeV storage ring, focusing primarily on the optimal merit flux and on the available polarization states. The merit flux, a function of the circular polarization rate and the spectral flux, is used to examine the polarizing spectral performances of both devices, reflecting the signal-to-noise ratio in circular-dichroism measurements. The polarization state of the synchrotron light is precisely defined by the phase and strength of its vertical and horizontal electric field vectors at a fixed observation point, for a specific photon energy. By using the phase difference between the electric field vectors $\delta = \delta_y - \delta_x$, together with the ratio of their components in terms of $\tan\psi = E_y/E_x$, the polarization state can be described completely, including the orientation, sense of revolution and the polarization ellipticity. Such a description creates a one-to-one mapping of a specific polarization state of the synchrotron radiation emitted from a polarizing device onto a single point on a complex plane [in terms of ($\tan\psi\cos\delta$, $\tan\psi\sin\delta$)] (Yariv & Yeh, 1984). This plane was named a polarization-state plane, and is illustrated in Fig. 1. The points (0, ±1) on the vertical axis correspond to the right- and left-circular polarization. The origin represents the horizontal polarization. The vertical polarization is located at an infinite distance from the origin. The linear polarization with arbitrary orientation is related to points on the x axis. For instance, linear polarization with ±45° orientation is mapped onto the points (±1, 0).

2. Elliptically polarizing undulator (EPU)

The elliptically polarizing undulator EPU5.6 to be installed in the storage ring at SRRC consists of four longitudinal periodical magnetic arrays, assembled with pure NdFeB permanent-magnetic blocks. In contrast to Sasaki's original design, all four magnetic arrays of EPU5.6 can be longitudinally shifted by a distance of two magnetic period lengths. Therefore, EPU5.6 can be operated in either Sasaki mode or Helios mode, depending on the phase relationship between the four periodic magnetic arrays. This feature allows the polarized light to be emitted with extended polarization states, including linear polarization, with specific orientations which are in general neither vertical nor horizontal. For an elliptically polarizing undulator, the polarization states of the emission radiation are mechanically tunable. Owing to the enormous magnetic force between the magnetic arrays, rapid modulation of the polarization states is practically difficult in our design.

By operating EPU5.6 in Sasaki mode, the on-axis magnetic field profile can be expressed as

$$B_x = -\hat{B}_x \sin(\varphi/2)\cos\left[(2\pi/\lambda_u)z + (\varphi/2)\right], \qquad (1)$$

$$B_y = +\hat{B}_y \cos(\varphi/2)\sin\left[(2\pi/\lambda_u)z + (\varphi/2)\right], \qquad (2)$$

where λ_u denotes the undulator period length and φ denotes the phase shift between the upper-front/lower-back and upper-back/lower-front arrays (jaws). $\hat{B}_x$ and $\hat{B}_y$ represent the maximum available strength of the on-axis horizontal and vertical magnetic field components, as determined by factors such as the dimensions of the permanent-magnetic blocks and the remanence. The phase-difference between the on-axis vertical and horizontal magnetic field components is always kept at 90° out of phase at all array phases and magnetic gaps. This relationship results in a 90° phase difference between the horizontal and vertical electric field vectors of the on-axis emitted synchrotron light. The square sum of the horizontal and vertical magnetic field amplitudes and the ratio of these two components depend on the array phase and, therefore, both the harmonic energy and the polarization state can be varied by adjusting the array phase at a specific magnetic gap. Nevertheless, for a specific harmonic energy, the available polarization states of a Sasaki-type elliptically polarizing undulator are still mapped onto the y axis in the polarization state plane, as shown in Fig. 1.

By operating EPU5.6 in Helios mode, the upper arrays are initially adjusted to generate only the vertical magnetic field on the electron beam, and the lower arrays to generate only the horizontal magnetic field (or *vice versa*). Adjusting the magnetic phase between the upper and lower arrays only results in a variation of the phase between the on-axis vertical and horizontal magnetic field profile; neither the amplitudes nor the ratios of the magnetic field components are changed. The device-emitted harmonic energy becomes invariant by adjusting the array phase. The on-axis magnetic field profile of a Helios device can be expressed as

$$B_x = 0.5\hat{B}_x \cos\left[(2\pi/\lambda_u)z + (\varphi/2)\right], \tag{3}$$

$$B_y = 0.5\hat{B}_y \cos\left[(2\pi)/\lambda_u)z - (\varphi/2)\right]. \tag{4}$$

These magnetic characteristics lead to the selection of elliptical polarization states which are mapped onto an ellipse or circle in the polarization-state plane, as shown in Fig. 1. For an array phase φ equal to zero, the polarization is linear with a specific orientation which is in general neither horizontal nor vertical. The radiation is generally elliptically polarized for an array phase φ equal to $\pm 90°$. By assuming that the vertical distance between the upper (or lower) magnetic arrays and the electron orbit plane is independently adjustable, it is possible to select the harmonic light with right- or left-circular polarization (for the first harmonics having non-zero flux) or with $\pm 45°$ orientation linear polarization. Obviously, most polarization states cannot be generated by operating the elliptically polarizing device in either Helios mode or Sasaki mode.

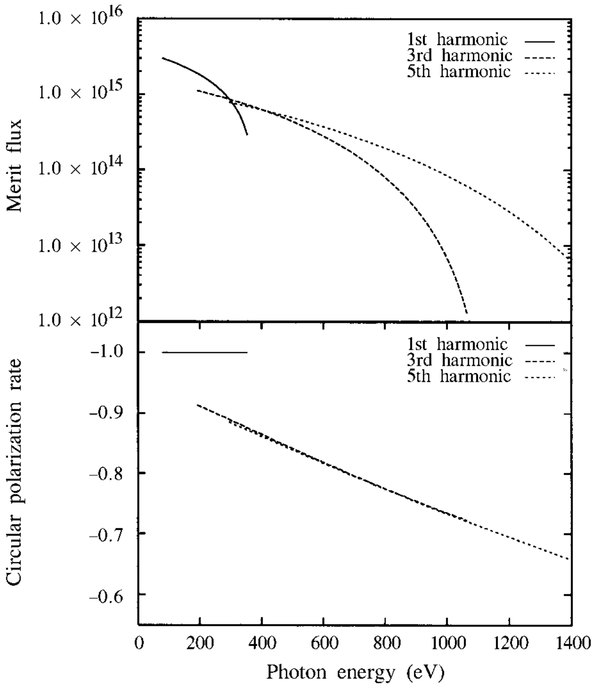

Figure 2
The optimal merit flux (0.1% bandwidth) for the first three odd harmonics and corresponding circular polarization rates of EPU5.6 operated in Sasaki mode. The machine is operated at 1.5 GeV with a 200 mA beam current.

The total spectral flux F of the nth odd harmonic emitted from an N-period Sasaki-type elliptically polarizing undulator with beam current I_b (measured in A) can be expressed (in photons s^{-1} at 0.1% bandwidth) as

$$F_n = 1.431 \times 10^{14}\left(\frac{nNI_b}{1+0.5K_{\rm eff}^2}\right)\left[K_y^2(JJ_-)]^2 + K_x^2(JJ_+)^2\right], \tag{5}$$

where

$$(JJ_\pm) = J_{(n+1)/2}(nD/4) \mp J_{(n-1)/2}(nD/4)$$

and

$$D = (K_x^2 + K_y^2)/(1 + 0.5K_{\rm eff}^2).$$

$K_{\rm eff}$ is the square root of $K_x^2 + K_y^2$ which determines the device harmonic energy. The normalized Stokes parameter or the circular polarization rate S_3 can be expressed as

$$S_3 = 2\varepsilon(JJ_-)(JJ_+)/[(JJ_-)^2 + \varepsilon^2(JJ_+)^2], \tag{6}$$

where ε denotes the ratio of the horizontal to vertical magnetic field strengths. Fig. 2 shows the optimal merit flux $S_3^2F_n$ for EPU5.6 operated in Sasaki mode.

3. Elliptically polarized bending magnet (EPBM)

As generally known, the synchrotron radiation emitted from a bending magnet can be elliptically polarized under circumstances in which the observation angle is out of the orbit plane. The vertical and horizontal electric field vectors are always 90° out of phase with each other; however, they have unequal strengths. In the orbit plane the vertical electric field strength vanishes, and the radiation is horizontally polarized. The circular polarization rate increases monochromatically with increments in the vertical angle Φ; it is compensated by reducing the flux. The desired merit flux can be selected by a trade-off between the vertical angular acceptance and the vertical offset or slope. The available polarization states are mapped onto a line segment of the y axis of the polarization-state plane, from (0, −1) to (0, 1), as shown in Fig. 1.

A rapid alternation between the left and right helicities can be achieved by implementing a mechanical chopper in front of the beamline (Chen, 1992). Such a mechanism can also be accomplished by creating a dynamic local bump or kick with pairs of correctors located close to both ends of the bending magnet to vary the vertical position or slope of the electron trajectory in the vicinity of the light source point of the bending magnet (Chen, 1996). The latter mechanism generates elliptically polarized synchrotron light in the mid-plane and is referred to as an elliptically polarized bending magnet (EPBM). A rapid helicity alternation using the latter mechanism can be achieved electronically. Such an alternation allows for a faster repetition rate than that achievable by the mechanical scheme. Moreover, an AC modulation of the polarization states is highly promising.

The merit flux for the radiation emitted from an elliptically polarized bending magnet relies heavily on factors such as the

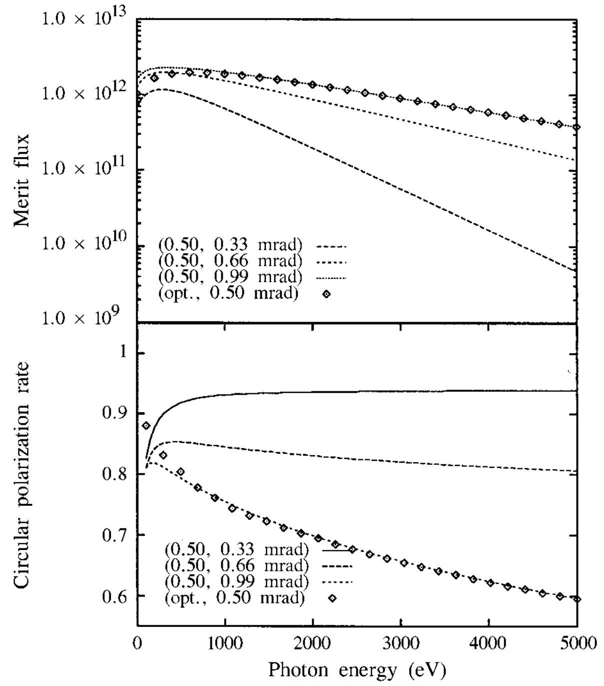

Figure 3
The merit flux of EPBM (1 mrad horizontal angular acceptance and 0.1% bandwidth) with corresponding circular polarization rates. The solid curves are for merit flux with a fixed vertical slope of 0.50 mrad and with vertical angular acceptances of 0.33, 0.66 and 0.99 mrad. The point curve indicates the optimal merit flux for 0.50 mrad vertical angular acceptance.

vertical angular acceptance $\Delta\Phi$, the vertical slope of the electron orbit in the bending magnet with respect to the storage ring mid-plane $\Phi_{\rm kick}$, and the photon energy. The dependence on the horizontal observation angle is usually insensitive and is neglected in our calculation. The influence of the emittance and energy spread of the electron beam on the polarization property is not within the scope of this investigation and is not discussed here. The spectral performance can then be evaluated by the integral merit flux F_M defined as

$$F_M = \int\limits_{\Phi_{\rm kick}-\Delta\Phi}^{\Phi_{\rm kick}+\Delta\Phi} P_c|P_c| \tfrac{{\rm d}F}{{\rm d}\Phi} {\rm d}\Phi. \qquad (7)$$

The average circular polarization rate $\langle S_3 \rangle$ is given by

$$\langle S_3 \rangle = \left(\int\limits_{\Phi_{\rm kick}-\Delta\Phi}^{\Phi_{\rm kick}+\Delta\Phi} P_c \tfrac{{\rm d}F}{{\rm d}\Phi} {\rm d}\Phi \right) \Bigg/ \left(\int\limits_{\Phi_{\rm kick}-\Delta\Phi}^{\Phi_{\rm kick}+\Delta\Phi} \tfrac{{\rm d}F}{{\rm d}\Phi} {\rm d}\Phi \right). \qquad (8)$$

P_C denotes the circular polarization rate for the bending magnet spectral intensity. Fig. 3 shows the merit flux available from an elliptically polarized bending magnet operated in the 1.5 GeV 200 mA storage ring with 1 mrad horizontal angular acceptance and 0.1% bandwidth. This figure also reveals the corresponding circular polarization rate for three different vertical acceptance angles, 0.33, 0.66 and 0.99 mrad, and with a fixed orbit slope of 0.50 mrad. Fig. 3 also shows the optimal merit flux for a vertical angular acceptance of 0.50 mrad for comparison. The definition of the spectral intensity dF/dΦ and the circular polarization rate P_C for the synchrotron radiation emitted from the bending magnet can be found elsewhere (Chen, 1992; Marks *et al.*, 1995).

4. Discussion

This work has evaluated the optimal merit flux and its corresponding circular polarization rate for EPU5.6 and EPBM. This work also introduces the polarization-state plane to illustrate the various polarization states generated by these two polarizing devices. For the elliptically polarizing undulator, the available polarization states are related either to the points on the *y* axis or to an ellipse or circle in the polarization-state plane which is dependent on the operation modes. These states are restricted to a line segment for the elliptically polarized bending magnet. The elliptically polarized bending magnet provides a broadband polarized light which can rapidly alternate between left and right helicities. EPU5.6 generates a high-merit-flux harmonic spectrum which ranges from 80 to 1400 eV and has a magnitude up to three orders higher than that generated by the bending magnet. EPU5.6 is under construction in-house at SRRC and expected to be commissioned in a year. Furthermore, the control electronics for the elliptically polarized bending magnet have already been developed (Hsu *et al.*, 1997) and are under test. Beamlines are also being constructed for such polarizing devices.

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