PERFORMANCE OF A PROTOTYPE VARIABLE ELLIPTICAL LY POLARIZED UNDULATOR

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Abstract

A prototype one-meter-long elliptical polarization undulator (EPU) device with Apple II structure is used to study the magnetic field features, the spectrum performance, and the electron beam dynamics effect. This device permits an exchange between right and left elliptical (circular) polarization and linear polarization between 0^o and 180^o. Meanwhile, an adjustable phase undulator (APU) mode can be operated in this structure to replace the open-close gap mechanism for tuning the energy on the horizontal linear polarization mode. The flatness of roll-off on the two transverse axes is worst than that of the conventional undulator. However, when the undulator is operated at SRRC 1.5 GeV storage ring, the photon flux performance of the four polarization modes can still maintain over 80% in a photon energy range from about 50 eV up to 1000 eV. The variation of electron orbit position in different polarization radiation modes is insignificant under a feed-forward algorithm with global feedback system.

1 INTRODUCTION

The helical field has recently been used to generate helically polarized radiation. Various combinations of electromagnets and permanent magnets have been proposed and designed to create the circular or helical magnetic field [1-4]. Most helical insertion devices strive to achieve high efficiency via the phase change undulator with pure magnet arrangement. The EPU device with Apple II structure [2] is conventionally used worldwide because it has the widest tunable range of circularly polarized radiation. This device provides polarization radiation of all kinds by alternating the phase mode [5]. In this study, a prototype one-meter-long EPU5.6 device with Apple II structure [6] has been constructed to examine the features of the magnetic field profile, the performance of photon spectra, and the effect of electron beam dynamics in the storage ring. The overall magnet system design of the one-meter-long EPU5.6 device is shown in Fig. 1. There are four motors which change the phase by remote control and the magnet gap can be opened manually. The gap between the magnet arrays on the girder is designed to be 1 mm for the phase shift mechanism. Main parameters of the magnet structure are shown in Table 1.

Both magnet sorting and shimming methods [7] are required to control the quality of magnetic field and spectrum in various phasing modes. There are two measurement systems, a three-axis orthogonal Hall probe system [8] and a long-loop-flip coil system [9], for characterizing the performance and features of the magnetic field. The electron beam position monitor (EBPM) and photon beam position monitor (PBPM) were coupled with the feed-forward algorithm (FFA) and global feedback system (GFS) to investigate the behavior of electron and photon beams under a variety of phasing modes. In EPU5.6, there are four independent corrector magnets with combined horizontal and vertical fields and to associate with EBPMs to correct the position and angle of the electron and photon beams.

Table 1: Parameters of the magnet structure and the lattice parameters in the EPU straight section.

β_x/β_y (m)	10.515/2.936
$\varepsilon_x/\varepsilon_y$ (m rad) (10^{-9})	19.8 /0.198
Number of poles	33
Period length (cm)	5.6
Total length (cm)	95.2
Range of row shifting distance (cm)	±2.8
Gap between magnet array, l (mm)	1
Range of magnet gap, g (mm)	$18 \leq g \leq 100$
Peak field strength B_x/B_y (T)	0.46 /0.7
Magnet properties, materials	Nd-Fe-B
Magnet block size, (L ×H ×W) (cm^3)	1.4 ×4.0 ×4.0

2 SPECTRUM PERFORMANCE AND FEATURES

Figure 2 (a-d) reveal the relationships between the photon energy, flux density, flux ratio between ideal and measured magnetic field, and polarization rate for different polarization modes. This spectrum is calculated with no energy spread. The spectrum performances of flux ratio at different harmonic spectra for the four polarization modes are greater than *80%*. Figure 2(b) (Figure 2(c)) indicates that the elliptical (linear polarization at $45^o/135^o$ direction) polarization rate is a function of the magnet gap. Especially, the polarization rate of any harmonic spectra in the elliptical polarization mode always exists a strong correlation with energy (see Fig.2(b)).

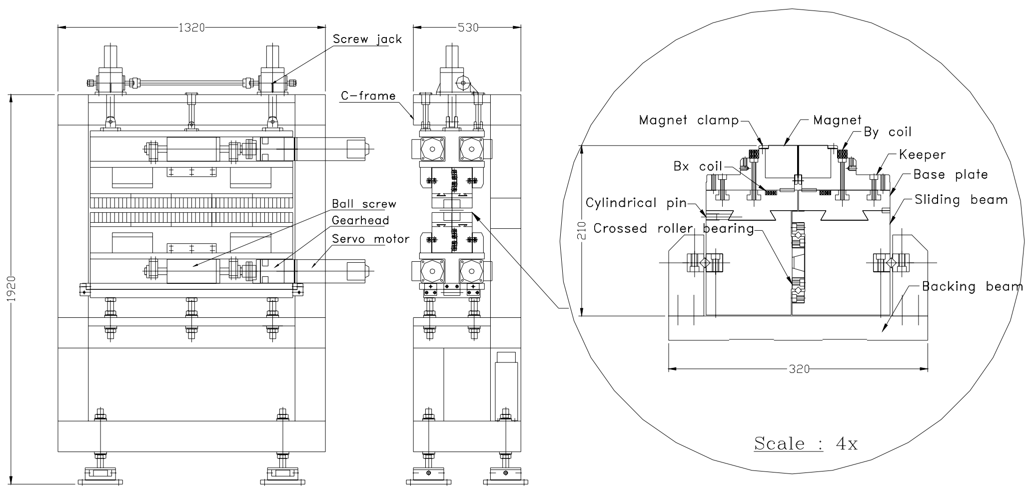

Figure: 1 The overall design of the prototype one-m-long elliptical polarization undulator.

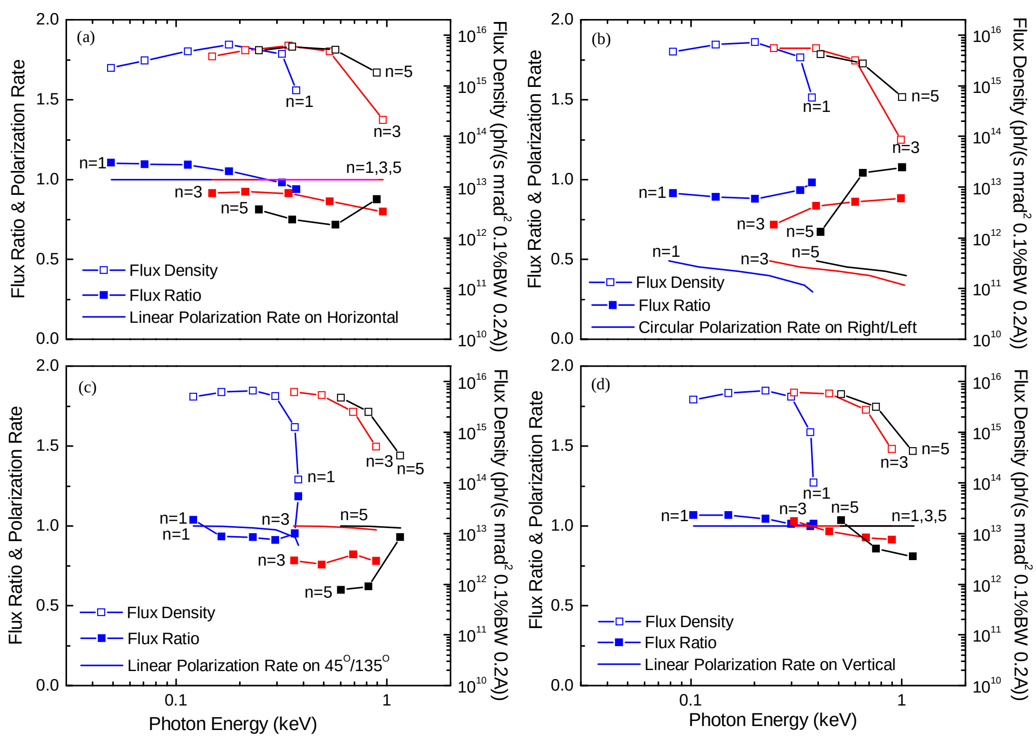

Figure: 2 Photon flux density, flux ratio, and polarization rate are calculated at distinct polarization modes, (a) horizontal polarization (phase $\theta=0$), (b) elliptical polarization (phase $\theta=1.131$), (c) linear polarization, $45^o/135^o$ (phase $\theta=1.822$), (d) vertical polarization (phase $\theta=3.141$).

Therefore, the phase shift should be optimized to get the figure of merit (photon flux multiplied by the square of polarization rate) [5] when tuning the photon energy. However, the harmonic spectrum beyond the first harmonic of the linearly polarized on $45^o/135^o$ direction is insensitive to the phase shift. Consequently, the phase shift should be optimized to get the figure of merit on the right/left circular polarization mode in any harmonic spectrum, and that of $45^0/135^0$ linear polarization mode in the first harmonic spectrum [5]. The figure of merit of all harmonic spectra of horizontal and vertical linear polarization modes is kept constant and is independent of gap (see Fig. 2(a) and 2(d)). This result reveals that the polarization rate of both horizontal and vertical linear polarization modes always remain constant.

To minimize the optical phase and electron trajectory error, care is taken when assembling the magnet on block keepers. The block keeper should be installed precisely in each base plate for keeping the exact relative longitudinal position between each magnet array. For this purpose, the errors in block size and block keepers as well as the assembly precision, particularly in the longitudinal direction, should be controlled within ± 0.025 *mm*.

3 MAGNETIC FIELD EFFECT ON STORAGE RING

EPU5.6's magnetic gap was fixed at *28 mm* (the peak field strength is approximately $B_x = 0.21\ T$ and $B_y = 0.42\ T$) to test performance in the storage ring. In order to keep the orbit distortion is well within the tolerance of one tenth of a beam size (σ_x and σ_y are about *0.3 mm* and *0.1 m m*, respectively). A feed-forward algorithm with global feedback system was developed using four EBPMs, a two-dimensional field correction table, and four correction magnets with very low hysteresis and a bandwidth of about 0.001 Hz. The schematic diagram of the electron and photon beam control algorithm is shown in Fig.8. Four corrector magnets with combined horizontal and vertical fields, and four EBPMs were located at both sides of the EPU5.6 undulator. The horizontal and vertical correctors were charged by the four independent power supplies (two for B_x and two for B_y) to compensate for the integral field deviation in horizontal and vertical planes. The output current was excited at *0.001Hz* with an offset current by means of the cross talk from the EBPM reading. The offset current output was set according to the two-dimensional field correction table (TFCT), with the follow-gap and follow-phase, and the *0.001Hz* output current matching the global feedback algorithm. With the new feed-forward algorithm and GFS system [10], the orbit distortion outside the EPU5.6 becomes insignificant during various phase operations. This feed-forward algorithm with GFS can also be employed for tuning the energy. The orbit distortion of the reading in EBPM (PBPM) was within $0.5\ 10^{-6}$ ($5\ 10^{-6}$) *m* when the feed-forward algorithm with GFS was switched on. Otherwise, the deviations of the reading in EBPM and PBPM would have been *1 (12) m* and $75\ (120)\ 10^{-6}$ *m*, respectively, in the vertical (horizontal) direction. Notably, in APU mode operation, there was a much smaller deviation [11] in the absence of the feed-forward algorithm with GFS system.

In addition, when the polarization mode is changed from horizontal linear polarization to right and left elliptical polarization, the intrinsic second-order focusing strength in the horizontal and vertical planes will be changed, thus producing the two-dimensional tune shift, beta beating , and the change in beam size. The tune shift $\Delta Q_{x,y}$ and beta beating $\Delta\beta_{x,y}/\beta_{x,y}$ are expressed as Eq. (1) and (2) [11], respectively when the phase or the gap is changed.

$$\Delta Q_{x,y}=K_{x,y}\, L\, \beta_{x,y}(1+L^2/12\beta^2_{x,y})/4\pi \qquad (1)$$

$$\Delta\beta_{x,y}/\beta_{x,y}=K_{x,y}\, L\, \beta_{x,y}\,(1-L^2/12\beta^2_{x,y})/2\sin\mu_{x,y} \qquad (2)$$

where L is the total length of the EPU5.6, $\beta_{x,y}$ and $\mu_{x,y}$ are the beta function and one-turn phase advance, respectively in the absence of the EPU5.6 undulator on horizontal and vertical planes. $K_{x,y} = (eB_{xt,yt}/\gamma mc)^2/2$ is the second-order focusing strength on horizontal and vertical planes of the EPU5.6 magnet. According to Maxwell's curl equation $\nabla\times\boldsymbol{B}=0$, the effective total field combining both transverse and longitudinal fields will induce focusing strength defined as $B_{xt}= (B^2_x+B^2_z)^{1/2}$ and $B_{yt}= (B^2_y+B^2_z)^{1/2}$, respectively when the phase shift or the magnet gap is changed[12]. Equation (1) is used to calculate the tune shift when the polarization mode is changed on the fixed magnet gap of 28 mm. There is only a slight change in the tune shift of $\Delta Q_x=0.0007$ ($\Delta Q_{,y}$=0.0008) on the horizontal (vertical) plane. Meanwhile, the measured results of tune shift in the storage ring are no noticeable change with a resolution of about *0.001*. However, if the EPU5.6 undulator is very long and has strong magnetic field strength, the tune shift will be dramatic. But if the APU operation mode is used for energy tuning, the tune shift should be insignificant and the measured results in the storage ring also indicate no noticeable change. In this case, the tune is maintained at $\nu_y=4.090$ and $\nu_x=7.160$.

According to Eq. (2), the beta beating on the magnet gap of 28 mm is about 0.8% (1%) on the horizontal (vertical) plane. Therefore, the measured result of beam size is no noticeable change with a resolution of about *0.005mm*. However, the longer undulator with strong magnetic field strength like as our 4-m-long EPU5.6 operating at the magnet gap of 18 mm will have a significant beta beating which will induce variation in beam size. Meanwhile, the lifetime at various operation modes were also measured, and no change was detected.

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