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Investigating excitation-dependent and fringe-field effects of electromagnet and permanent-magnet phase shifters for a crossed undulator

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ABSTRACT

To enhance the flux density or to control polarization, a phase shifter was designed and used to modulate the phase matching between segmented undulators. A larger hysteresis loop causes, however, a repeatability issue in the phase matching; the fringe field of the phase shifter creates an extra magnetic-field error. The design of the phase shifter must therefore minimize the hysteresis loop and fringe field to maintain the phases exact and to ignore the crosstalk effect. Two critical issues are the hysteresis-loop problem and the fringe-field effect, which determine the radiation performance and the stability of the ring. To investigate these issues, a phase shifter was constructed to operate in accordance with electromagnetic- and permanent-type magnets; the results from the field measurements and shims are discussed here. The shimming algorithm and a compact permanent-magnet phase shifter that eliminates the issues are also presented.

1. Introduction

To control the polarization or to increase the intensity of the undulator radiation (UR) spectrum, schemes for a crossed undulator [1] and a progressively segmented undulator [2] have been proposed and implemented in several facilities [3–5]. Through the superposition of UR emitted from undulators in series, the characteristics of UR can be modulated through a variation of the phase between segmented undulators; the phase is tuned with a phase shifter. Another important application of the phase shifter is to fulfill the condition of power saturation in a free-electron laser [6]. Phase shifters are inserted into a long undulator system to match the phase of the UR. The phase shifter, therefore, plays a key role in these accelerator facilities for light sources.

By creating a chicane of the electron beam, the phase shifter provides a tunable phase delay between the electron and the photon. Two essential requirements for the phase shifter are that (1) the range of the tuning phase must cover the full range of photon energy provided by the undulators and (2) the net effect on the electron beam must be negligible over the full operating range. The former condition serves to match conditions in the longitudinal direction; the latter serves to provide a stable orbit in the transverse direction. To achieve the former, a magnet provides a tunable magnetic field using a variable excitation of the current in an electromagnet (EM) [7–9] or a change in the gap of a permanent magnet (PM) [10–12]. Although the influences on the electron beam were considered and optimized in the design phase, several practical conditions, such as the material property, the reproducibility of the excitation source and the environment in which a magnet is installed, degrade the performance of this phase-shifter scheme. A properly working phase shifter is thus determined by whether these practical considerations are improved to decrease the adverse effects when operating the phase shifter.

According to the first requirement, a proto-EM-type phase shifter was designed and built for a tandem elliptically polarized undulator (EPU) system at Taiwan Photon Source (TPS) [13]. The magnetic field was optimized, but two problems arose: the reproducibility failed due to the material property and the crosstalk effect with the nearby magnets was untreatable. A comprehensive study and a progressive design for a PM-type phase shifter are hence presented herein. We organized the paper as follows. The basic conditions for phase matching for the tandem EPU at TPS appear in Section 2, which presents also the results of measurement for phase shifters of two types. In Section 3, we discuss the excitation-dependent field integral; the results of measurements and the shimming methods for both types are presented, and the reproducibility problem is discussed. In Section 4, we discuss the crosstalk effect induced by the fringe field, before the conclusion.

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2. Basic principles of phase matching

Because an electron is deflected in a magnetic field, an electron passing through a magnetic field accumulates a phase delay $\Delta\varphi$ with respect to a photon of wavelength λ_r [14].

$$\Delta\varphi = \frac{2\pi}{\lambda_r}\frac{e^2}{2(\gamma m_0 C)^2} PI \tag{1}$$

Here, e is the electron charge, γ is the Lorentz factor, m_0 is the rest mass of an electron, and C is the velocity of light. The phase integral PI is given by

$$PI = \int_{-\infty}^{z} \left(\int_{-\infty}^{z} B(z')dz'\right)^2 dz' \tag{2}$$

The distribution of magnetic field $B(z')$ provides the PI, resulting in a phase delay.

At TPS, there are triple quadrupole magnets (QM) for the double-mini β_y lattice, a phase shifter and correctors at the intersection of two EPU. The total phase difference $\Delta\varphi_T$ between the two UR emitted from the two EPU is expressible as

$$\Delta\varphi_T = \Delta\varphi_{ID} + \Delta\varphi_D + \Delta\varphi_{PS} + \Delta\varphi_Q + \Delta\varphi_C \tag{3}$$

Here, $\Delta\varphi_{ID}$ is induced by the fringe field at the terminations of the EPU; $\Delta\varphi_D$ is the phase advance in drift space; $\Delta\varphi_{PS}$, $\Delta\varphi_Q$ and $\Delta\varphi_C$ are contributed from the magnetic field of the phase shifter, the QM and the corrector, respectively.

In principle, $\Delta\varphi_Q$ is zero because the electron beam passes through the center of the QM. $\Delta\varphi_D$ is determined when both EPU are installed. $\Delta\varphi_{ID}$ and $\Delta\varphi_C$ depend on the gap of the EPU. For phase matching, the current for the EM type or the gap of the PM type must be chosen such that its contribution $\Delta\varphi_{PS}$ modifies $\Delta\varphi_T$ to be a multiple of 2π. To detail the operation of a phase shifter at TPS, the EPU emits UR with λ_r =6.2–0.7 nm. If $\Delta\varphi_T$ already satisfies a multiple of 2π, the magnetic field of a phase shifter must be zero; in other cases, the difference in $\Delta\varphi_T$ from a multiple of 2π must be compensated with $\Delta\varphi_{PS}$. In principle, the required maximum $\Delta\varphi_{PS}$ is 2π, corresponding to PI =1240 T^2 mm^3, which is calculated with λ_r =6.2 nm, γ =5870. Fig. 1 shows the result of measurement of PI of both types with a varied current or gap. In addition to operating $\Delta\varphi_{PS}$ at 0–2π (operation I), both types can be operated within $\Delta\varphi_{PS}$ 2π – 4π (operation II); operation II has a smaller tuning range than that of operation I. Operation II hence saves the time consumption of operation because of a small operating range, but requires much accuracy to control the current and the gap.

3. Decreasing the excitation-dependent field integral and increasing reproducibility

The on-axis residual-field integral, corresponding to the dipole error, of a magnet is known to cause a closed-orbit distortion (COD), leading to a variation in the focusing point of the entire beamline for all beamlines in the ring. In general, a residual-field integral induced by insertion devices (ID) is corrected with a pair of correctors and/or a fast orbit-feedback system. In the case of crossed undulators, the transverse requirement is achieved during beam-base alignment and beamline commissioning; the longitudinal requirement is attained using a feed-forward table of a phase shifter. The former requirement cannot be disturbed while operating a phase shifter. In general, there is no specific corrector for a phase shifter; the residual-field integral of a phase shifter must thus be negligible, otherwise the implementation becomes complicated and causes significant difficulties in the operation of the accelerator. In operating a phase shifter, the behavior of the residual-field integral can be classified into an excitation dependence and a reproducibility at a particular excitation. Although the former was considered and optimized in the design phase, both kinds depend on several practical conditions and thus require efficient shimming. Shimming is widely implemented in ID [15–17]. The method in this work relies on providing an iron shim pad, which was shown to correct a phase-dependent [18] and gap-dependent [19] field integral. The shimming algorithms for phase shifters of both types are given in the following sections.

3.1. EM phase shifter

A proto-EM-type phase shifter consists of three C-type dipole magnets, which are made of a silicon-steel lamination of thickness 1 mm. The lengths (in the direction of the electron beam) of the three poles conform to ratio 1:2:1 to cancel the field integral. The design consideration is available elsewhere [13]. A deviation of the ratio, due to a production error, causes the current-dependent field integral to attain up to 200 G cm. According to the interference requirement of TPS, the field integral must be limited to ± 9 G cm. Table 1 gives a summary of the requirements. To fulfill the requirement, the deviation was corrected with shim pads (passive) and a trim current (active).

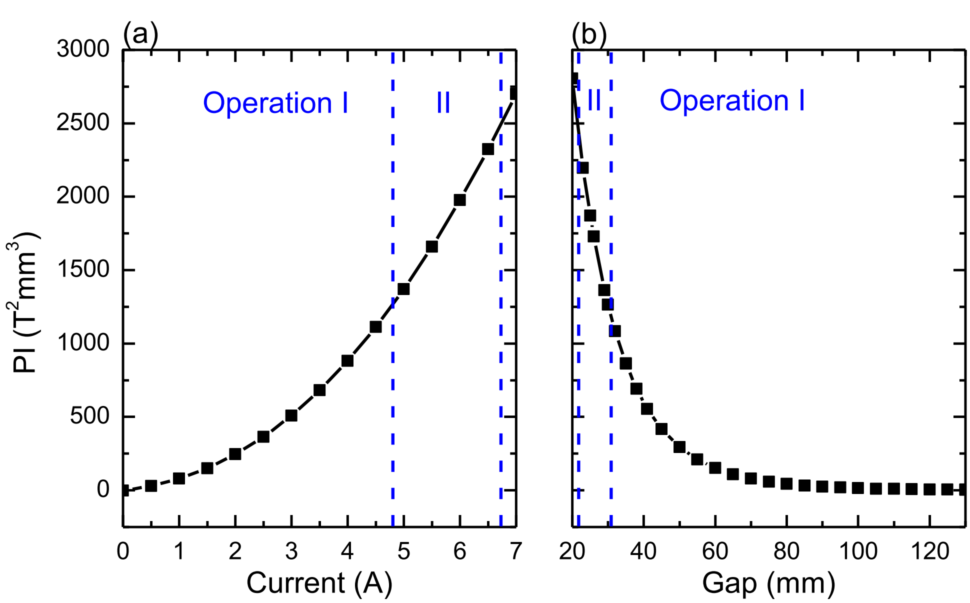

Fig. 1. Phase integral (PI) as a function of (a) current of the electromagnet type and (b) gap of the permanent-magnet-type phase shifter. The ranges of the operating phase delay with 0–2π and 2π–4π are indicated with operations I and II. The phase delay is calculated with radiation wavelength 6.2 nm and electron energy 3 GeV.