A prototype phase shifter for phase matching between undulators at TPS

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Abstract. Phase shifters of various kinds have been studied to match the double undulators that were installed in the same double-mini Betay-function straight section in TPS. A prototype phase shifter, designed to satisfy the requirement for phase matching between two undulators, comprises three C-type dipole magnets for convenient operation and tuning of the magnetic field to cover photon energies over a wide range. The phase shifter, operating at 5 A, provides phase delay 555° for minimal photon energy 300 eV. A trim current at the side coils serves to compensate for the first and second field integrals. The main current is varied to cover photon energies 0.3-20 keV. Our design takes into account an effect of cross talk with nearby magnets.

1. Introduction
Taiwan Photon Source (TPS) is under construction and will be commissioned during the first quarter of 2014. In the first phase of operations, four in-vacuum undulators and two elliptical-polarization undulators (EPU) will be installed at three long straight sections with two minima of the vertical Beta functions [1]. To increase brightness, synchrotron radiation from two insertion devices (ID) at each section must be coherent. To achieve phase matching, a phase shifter provides a chicane for electrons traveling between two ID. Phase matching is obtainable on matching the distance of the intersection to the radiation wavelength. A phase shifter is built from electromagnets (EM) [2] or permanent magnets (PM) [3]. The PM type has advantages of compactness and a small leakage field, but there are economic issues and a lack of capability of fine tuning during operation. At TPS, we chose three dipole electromagnets to build a prototype phase shifter. In this article, we describe the design concept that must be suitable for operation over a wide photon range and under a criterion of dense space. We take into account also the cross talk with nearby magnets, such as quadruple magnets and correctors. This intricate coupling can be corrected using a trim-current circuit.

2. Design concept and specifications
The relative phase \( \varphi(z) \) of an electron with respect to the radiation field is expressible as

\[ \varphi(z) = 2\pi \left\{ \frac{L}{2\lambda y^2} + \frac{1}{2L} \int_{-\infty}^{z} a^2 \, dz \right\} \]  

(1)
Here $L$ is the drift space between ID; $\lambda$ is the radiation wavelength; $\gamma$ is the Lorentz factor, and $\alpha$ is the deflection angle of the electron. The first term of Eq. (1) describes the phase advance in drift space; the second represents the contribution of a magnetic field.

$$\phi(z) = 2\pi(n_L + n_B)$$

$$(2)$$

$$n_L = \frac{L}{2\lambda \gamma^2}, \quad n_B = \frac{1}{2\lambda} \int_{-\infty}^{\infty} \alpha^2 \, dz = \frac{1}{2\lambda} \int_{-\infty}^{\infty} \left( \int_{-\infty}^{\infty} B_y(z) \, dz \right) \frac{1}{B \rho}$$

$$(3)$$

We symbolize these two terms as $n_L$ and $n_B$, respectively; $\rho$ is the bending radius. For phase matching, the sum of $n_L$ and $n_B$ must be an integer. $n_L$ is determined by the lattice design, but $n_B$ is variable on adjusting the strength of vertical field $B_y$. For an electromagnet, the adjustment of $B_y$ is via varying the excitation current through a coil.

To investigate the phase matching, we made a spectrum simulation using code B2E [4]. A calculation of flux density on axis for two EPU48 in series at gap 13 mm (undulator parameter $K = 2.24$) is shown in Fig. 1. The electron beam parameters are 3GeV, 0.4A, and energy spread 0.1%. A clear interference pattern is visible in the spectrum. The two maxima exhibit destructive interference so that an almost complete loss of intensity occurs at the harmonic energy. For phase $155^\circ$, marked with the dashed line in Fig. 1, the flux density at the peak is decreased by 32 %. The radiation spectrum shows strong interference that depends sensitively on the phase between ID.

![Figure 1](image1.png)

**Figure 1.** Flux density on axis for two EPU48 in series. The solid line is for undulators in phase. Selected phase errors from $30^\circ$ to nearly out of phase at $155^\circ$ are shown with other lines.

![Figure 2](image2.png)

**Figure 2.** Schematic view of the prototype phase shifter.

The requirements of a phase shifter at TPS have been considered for the necessary magnetic field and space limitations. In spatial terms, the available space of a phase shifter must be less than 250 mm in the longitudinal direction. For magnetic field strength, at section TPS-SR21, EPU48 can produce soft X-rays at wavelengths from 4.1 to 0.7 nm; the length of the chicane must hence be at least larger than one period of the wavelength corresponding to 640 G based on a short-magnet approximation [5].

The prototype phase shifter comprises three C-type dipole magnets for convenient operation. The length of iron of the central magnet is twice that of the side one, which ensures twice the deflection angle to allow electrons back to the orbit. Figure 2 shows a plane view of our phase shifter, of total height about 430 mm, and total length less than 250 mm. The coil at the side magnets is arranged

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away from the gap, but the coil of the central magnet is divided into two parts at the horizontal symmetric plane of the gap. The pole gap is 24 mm. The pole profile is optimized to eliminate the native non-symmetric magnetic circuit of C-type iron and to obtain sufficient field uniformity.

3. Requirements of the tuning range

We used TOSCA 3D [6] to design and to simulate a prototype phase shifter. The iron material used in the simulation is PowerCore 1200-100A produced by ThyssenKrupp. Under the maximum excitation current about 10 A for 3x2 mm copper wire, three magnets are excited with one power supply at 5 A. The central magnet has 1650 ampere-turns (AT); the side magnets have 1080 AT. As a result, $B_y$ is 780 G at the gap of the central magnet; the $B_y$ profile is shown in Fig. 3(a). The central pole provides a positive field, side poles provide a negative field. The profile of the first and second field integrals, corresponding to the deflection angle and trajectory, appear in Fig. 3(b) and 3(c). The maximum kick value is about 0.33 mrad. Electrons deviate from the orbit about 30 $\mu$m at the middle of the phase shifter, but return after passing through the phase shifter. The chicane provides phase delay 555° for radiation of the largest wavelength, 4.1 nm, as seen in Fig. 3(d). The length of the chicane satisfies the maximum requirement for phase matching of two EPU48 at section TPS-SR21.

![Figure 3](image1.png)

**Figure 3.** (a) $B_y$ field distribution. (b) First field integral. (c) Second field integral. (d) Phase integral. The value at the end amounts to 555° for photons of energy 300 eV.

![Figure 4](image2.png)

**Figure 4.** (a) $B_y$ field at the central pole gap as a function of excitation current. (b) First field integral of $B_y$ as a function of horizontal position.

To achieve constructive interference for radiation wavelength 4.1 - 0.7 nm, a phase shifter should provide a chicane of appropriate length to match the track of electrons between two ID to be a suitable multiple of radiation wavelength. According to Eq. (3), $n_L$ decreases linearly with increasing wavelength. For $n_L$ integer, $L$ satisfies the condition for constructive interference. In other cases, the difference of the optical phase from a multiple of $2\pi$ must be compensated with $n_B$, as seen in Eq. (2); the value of $n_B$ is invariably between 0 and 1. The excitation current hence needs only to be within a certain range so as to satisfy phase matching for an EPU48 spectrum over the full range. In our design, the phase shifter will be operated from 4 to 6 A. The iron is not saturated within this excitation, which is observable with the linear relation between $B_y$ and current, as seen in Fig. 4(a). Figure 4(b) shows the first field integral of $B_y$ as a function of horizontal position; although the profile varies slightly at various excitation currents, it still maintains a wide region of effective field within ±25 mm.
4. Effect of cross talk
In practice, a phase shifter is installed in a section to maintain perfect phasing. A fringe field is influenced by nearby materials of large permeability; those materials create a short path for the magnetic flux and decrease the magnitude of the negative magnetic field at the side poles. The symmetry of the magnetic field relative to the middle pole becomes slightly perturbed. As a result, electrons do not return to the orbit, as seen in the solid line in Fig. 5(c). For this reason an extra function for the commissioning is necessary. We supply an additional current source into the side coil; on slight excitation of the side coil at 0.5 A, electrons become kicked back into the orbit, as seen in the dashed line in Fig. 5(c). This unwanted effect is corrected with a trim-current circuit. The capability of this circuit is shown in Fig. 6. For trim current ±1 A, the first field integral of \( B_y \) can be tuned within ±700 G cm, representing ±0.07 mrad. This amount is sufficient to cope with the undesired trajectory.

![Figure 5](image1.png)

**Figure 5.** The solid line represents a phase shifter coupled with a quadruple magnet; the configuration is the same as the practical lattice design. The dashed line represents the side coil excited with extra current 0.5 A at the same configuration. (a) \( B_y \) field distribution. (b) First field integral. (c) Second field integral.

![Figure 6](image2.png)

**Figure 6.** First field integral of \( B_y \) as a function of trim current. The trim current is excited additionally at main current 5 A on one side coil.

5. Conclusion
A prototype phase shifter has been designed and is being fabricated for phase matching of a double EPU48 at a TPS-SR21 section. In addition to mechanical considerations, we consider the magnetic-field requirements in detail. In our design, the phase shifter can fulfill the phase-matching condition for the full range of the EPU48 spectrum. Using a trim-current circuit, the first and second field integrals can be made negligible for the cross talk effect of the storage ring.

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