PHASE SHIFTER PROTOTYPE WITH LAMINATED PERMALLOY YOKES FOR A POLARIZATION-CONTROLLED UNDULATOR

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Abstract

A 27-m polarization-controlled undulator that consists of four horizontal and four vertical undulator segments and seven phase shifters will be installed and used at SPring-8 as the most highly brilliant soft x-ray source for the material science beamline of the University of Tokyo. We designed and fabricated a phase shifter prototype to satisfy requirements for the phase shifter. The phase shifter prototype consists of three H-type dipole magnets and the yokes are made of 0.1-mm thick permalloy laminations united and insulated by varnish. Field measurements of the prototype were performed and their results were in good agreement with 3-D field calculations. The phase shifter prototype showed good performance in reproducibility and frequency response.

INTRODUCTION

The University of Tokyo decided to construct a soft x-ray beamline at SPring-8 for research on advanced material science[1]. A 27-m undulator was adopted as the most highly brilliant soft x-ray source for this beamline. The new undulator, called a polarization-controlled undulator[2], consists of four horizontal and four vertical figure-8 undulator segments and seven phase shifters between the segments. Figure 1 shows a schematic view of the polarization-controlled undulator.

Each phase shifter controls the radiation phase between undulator segments by giving a bump orbit to the electron beam with its magnetic field to generate various polarization states such as horizontal, vertical, and circular polarization ones. Recently a prototype of the electromagnetic phase shifter was designed and fabricated with laminated permalloy yokes. In this paper, we present the phase shifter prototype for the 27-m polarization-controlled undulator and results of its field measurements.

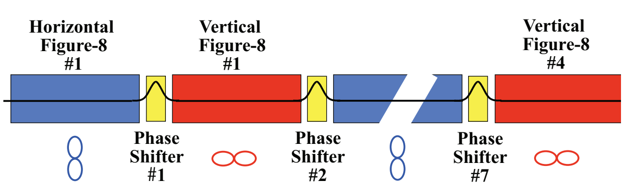

Figure 1: Schematic view of the polarization-controlled undulator.

REQUIREMENTS FOR PHASE SHIFTER

The radiation phase shift ϕ due to the bump orbit generated by the phase shifter and the angle x' and the position x of the bump orbit are expressed as

$$\frac{\phi(z)}{2\pi} = \frac{1}{2\lambda}\int_{-\infty}^{z} x'(z_1)^2\, dz_1 \quad (1)$$

$$x'(z) = \frac{e}{mc\gamma}\int_{-\infty}^{z} B_y(z_1)\, dz_1 \quad (2)$$

$$x(z) = \int_{-\infty}^{z} x'(z_2)\, dz_2 = \frac{e}{mc\gamma}\int_{-\infty}^{z}\int_{-\infty}^{z_2} B_y(z_1)\, dz_1 dz_2\,. \quad (3)$$

Here e, m, c, γ, z, λ and B_y are the electron charge and mass, the velocity of light, the Lorentz factor and the longitudinal position of the electron, the radiation wavelength, and the vertical magnetic field of the phase shifter. The phase shifter must make a phase shift of 0 to 2π for all the wavelengths to realize all the polarization states. High stability and reproducibility of the phase control and fast helicity switching of the circular polarization radiation are also required for the phase shifter. In addition, it should be able to control the angle and position of the bump orbit independently of the phase shift to avoid imperfect closure of the bump orbit.

PHASE SHIFTER PROTOTYPE

We designed and fabricated a phase shifter prototype to satisfy the requirements for the phase shifter. The phase shifter prototype consists of three H-type dipole magnets (Magnet A, B and C) with the yoke-length ratio of 1:2:1. Figure 2 shows a plan of the phase shifter prototype. Each magnet has a yoke divided into two parts at the horizontal symmetric plane and two coils for the upper and lower magnetic poles. The magnetic pole gap is 32 mm and the pole profile is optimized to obtain sufficient field uniformity in the horizontal direction.

Figure 3 shows a photograph of the fabricated phase shifter prototype. Each half yoke is made of 0.1-mm thick permalloy laminations united and insulated by varnish. Figure 4 shows a permalloy lamination used for the prototype. All the permalloy laminations are formed by stamping and annealed at about 1100 °C to maximize their magnetic permeability. The size error of the sheets is kept within ±0.1 mm even after annealing. They have a very high magnetic permeability (about 400000) and very low hysteresis. The phase shifter prototype is expected to have high reproducibility and good frequency response of the magnetic field. The coil is made of ϕ2mm enamelled copper wire insulated by epoxy resin and the turn number of the coil is 300. The three magnets are fixed between upper and lower stainless steel plates. 3-D alignment of the phase shifter prototype can be done with a positioning system equipped with a common magnet table.

The three magnets are independently excited by three identical power supplies with a maximum output current of 5 A (1500 AT (ampere−turns) for the coil of 300 turns) and, as a result, both position and angle of the electron beam can be adjusted independently of the bump size. The power supplies are linear amplifier type and produced so that ripples and drifts should be less than 100 ppm (10^{-4}) of the maximum output current. They have good frequency response up to 1kHz for pure resistance.

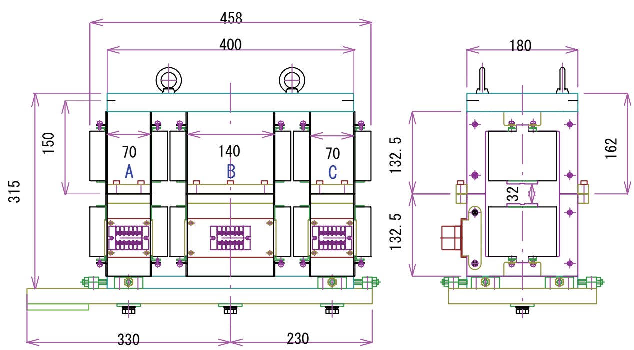

Figure 2: Plan of phase shifter prototype.

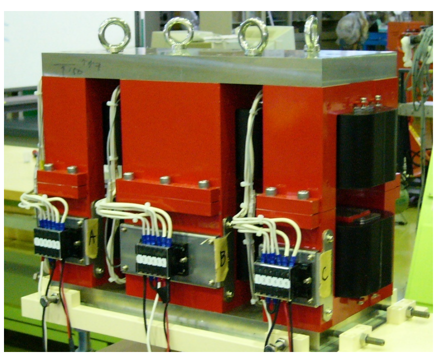

Figure 3: Phase shifter prototype.

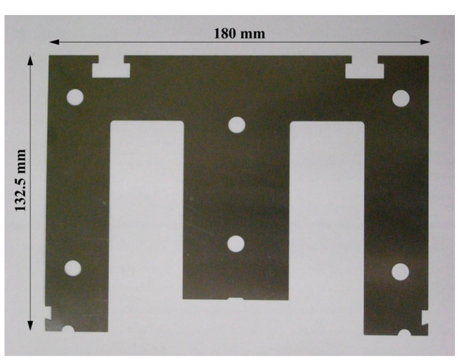

Figure 4: 0.1-mm permalloy lamination.

FIELD MEASUREMENTS

Field measurements were performed using a 3-D field measurement system with a Hall probe and a 3-D movable stage. Figure 5 shows the measured longitudinal field distribution of the prototype at coil currents of I_A=I_C=−1170 AT and I_B=1400 AT with the calculated result of a 3-D magnetic field analysis code, ELF/MAGIC[3]. The maximum magnetic field is about 1075 G at the prototype center. The measurement result is in good agreement with the calculation. The phase shifts due to the measured and calculated field distributions are also shown in Fig. 5. The maximum phase shift given by this prototype is about 4π for the radiation wavelength of λ=4.959 nm corresponding to the minimum photon energy of 250 eV and it is enough for the polarization-controlled undulator. Figure 6 shows the angles and positions of the bump orbits expected from the measured and calculated field distributions at the coil currents. In the 3-D field calculation, the coil currents of I_A=I_C=−1170 AT and I_B=1400 AT closes the bump orbit, i.e., sets the beam position and angle after the bump orbit to zero. The measured horizontal field distribution of the prototype is shown in Fig. 7 and it is consistent with the calculated result of ELF/MAGIC. The field uniformity is kept within ±0.05 % in the horizontal position range of -8 to +8 mm.

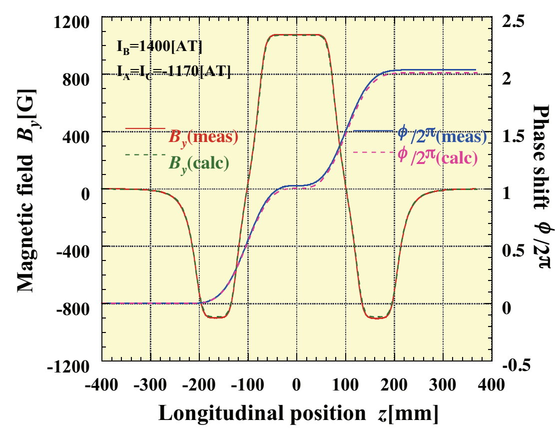

Figure 5: Measured longitudinal field distribution and its phase shift at the coil currents of I_A=I_C=−1170 AT and I_B=1400 AT. Calculated results of ELF/MAGIC are also shown for comparison.

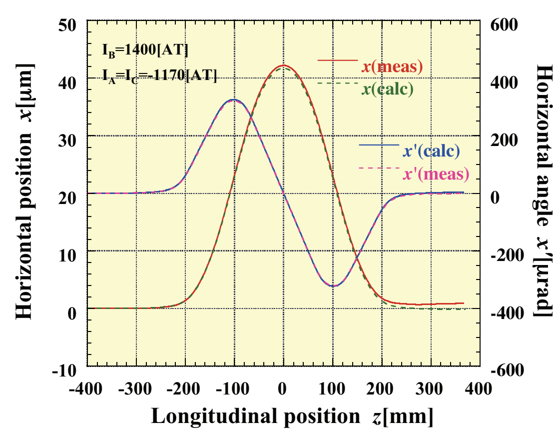

Figure 6: Beam positions and angles obtained from the field measurement and calculation at the coil currents of I_A=I_C=−1170 AT and I_B=1400 AT.

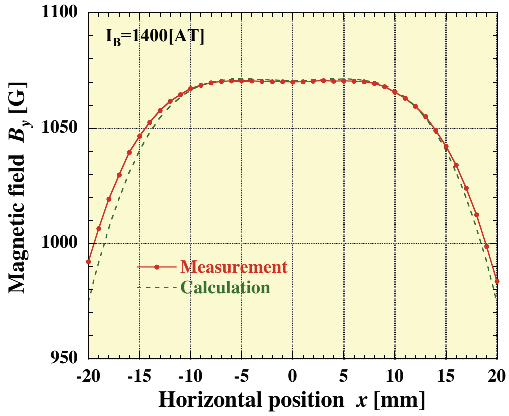

Figure 7: Measured and calculated horizontal field distributions at the prototype (Magnet B) center for the coil current of I_B=1400 AT.

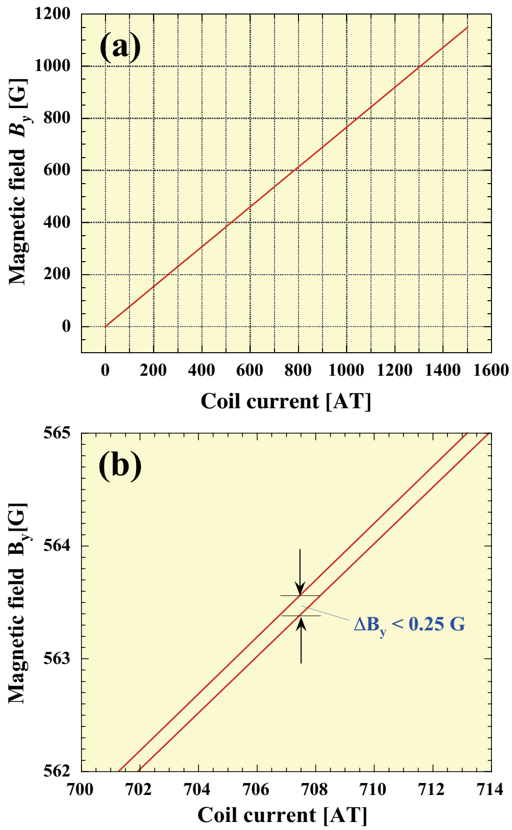

Figure 8: Excitation curve of Magnet B (a) for the coil current of 0 - 1500 AT and (b) 700 - 714 AT.

Figure 8(a) shows the excitation curve of Magnet B. The excitation curve is almost linear and the magnetic field is not saturated up to the maximum coil current of 1500 AT. In measurement of the excitation curve, the coil current was scanned from 0 to 1500 AT and 1500 to 0 AT. Figure 8(b) shows an expanded view of the excitation curve from 710 to 714 AT. Although a hysteresis effect is seen in the figure, the difference between the magnetic fields at the same coil current was only 0.25 G at maximum. This suggests that the phase shifter prototype has high reproducibility of the magnetic field due to the ultra-low hysteresis of the laminated permalloy yoke. Figure 9 shows measured frequency response of Magnet A. The gain was kept constant within 1 dB up to 500 Hz and the phase delay was less than 1 degree at 10Hz and 10 degrees at 100 Hz. Such good frequency response can perform fast helicity switching of the circular polarization radiation. If the turn number of coils, and hence the coil inductance, is reduced, the frequency response will be better.

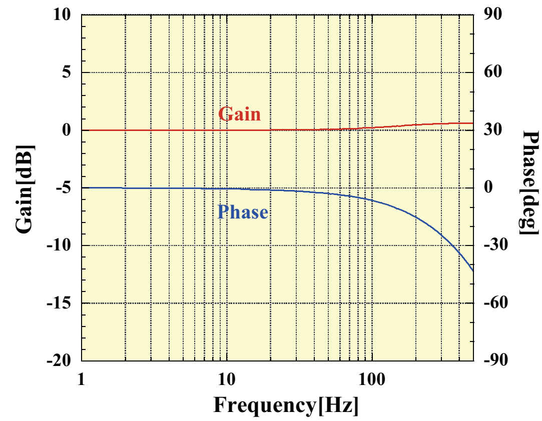

Figure 9: Measured frequency response at the center of Magnet A.

SUMMARY

The phase shifter prototype was successfully designed and fabricated with laminated permalloy yokes. The measured longitudinal and horizontal field distributions were in good agreement with the 3-D field calculations. The prototype showed high reproducibility and good frequency response of the magnetic field. Measurements of field integral for the AC coil current are now under way by using a long coil system. Based on results of the field measurements on the prototype, final design and specifications for the phase shifter including its power supplies will be decided in near future.

The four horizontal figure-8 undulator segments were already constructed and installed in the long straight section of SPring-8 in the summer of 2008. The electromagnetic phase shifters as well as the four vertical undulator segments will be constructed by March of 2010 and installed in the summer of 2010.

REFERENCES

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