DESIGN AND FABRICATION OF PROTOTYPE PHASE SHIFTER FOR PAL XFEL

H.G. Lee, D.E. Kim, W.W. Lee, K.H. Park, S.B. Lee, H.S. Suh, Y.G. Jung, H.S. Kang
Pohang Accelerator Laboratory, POSTECH, KOREA

Abstract

Pohang Accelerator Laboratory (PAL) is developing a SASE X-ray Free Electron Laser based on 10 GeV linear accelerator. Prototype phase shifters are being developed to be used for the X-ray and Soft X-ray undulator line. The phase shifters will be used to adjust the phase of the electron beam with respect to that of the radiation field. Two prototype phase shifters are being developed. One is based on the EU-XFEL phase shifter using zero-potential iron yoke, and the other one is similar to FERMI phase shifter where only permanent magnets are used. Driving system consists of 5 phase stepping motor, left/right handed ball screw and absolute linear encoder. In this paper, we describe the design, fabrication and test results of the two phase shifter prototypes.

INTRODUCTION

The phase shifters are needed to match the radiation phase of the each undulator. All SASE FEL system using a variable gap undulator needs phase shifters to make the phase shift of each undulator system to multiples of 2pi. Pohang Accelerator Laboratory (PAL) is developing a 0.1 nm class SASE based FEL using 10 GeV class S-band linear accelerator. PAL-XFEL will have one soft X-ray undulator and one hard X-ray undulator lines at the completion of phase 1. Additional space for two more hard x-ray undulator lines, and one more soft X-ray undulator lines is reserved for future expansion [1].

PAL-XFEL hard X-ray undulator lines needs 22 units of EU-XFEL type hybrid undulator system. Also soft X-ray undulator line needs 14 planar undulator and a few additional EPUs for polarization control. Therefore, PAL-XFEL will need about 40 units of phase shifters.

The details of the design requirements for phase shifter are thoroughly discussed by H.H.Hu et al. [2, 3]. For PAL-XFEL, the strong phase shifter requirement comes from the tuning of the soft X-ray line from 1.0 nm to 3.0 nm at 3.15 GeV electron beam energy.

In this report, we summarize the efforts in building EU-XFEL type phase shifter, and a PAL-XFEL type phase shifter only using permanent magnets.

EU-XFEL TYPE PHASE SHIFTER

EU-XFEL type [2] phase shifter is well advanced and many prototypes were already built and tested. We built a phase shifter based on EU-XFEL design with some minor modifications. The modifications include an absolute linear encoder measuring the gap directly, and application of servo motor instead of stepping motor to improve the response speed and accuracy. Also LM guides are implemented restraining the motion of the magnetic structure only in the gap direction. The B field profile measured and calculated is plotted in Fig.1 showing good agreement. Also the gap dependence of the peak field and phase integral is plotted in Fig.2 also agreeing with the calculation. The residual integrated fields of Bx and By are shown in Fig.3. It's exceeding the EU-XFEL requirement which is 4Gcm, which is actually tighter than the measurement accuracy. Unfortunately, we didn't have enough time to tune the pole to reduce the gap variation of the residual field integral. Following EU-XFEL experience, it can be improved by shimming the poles.

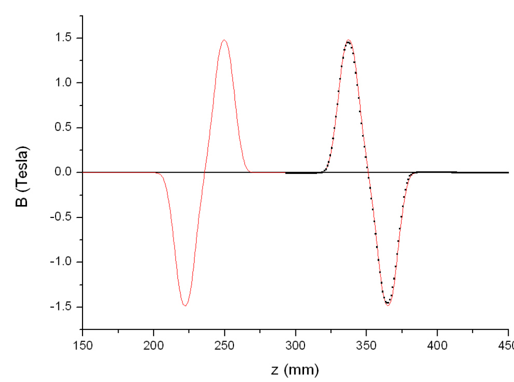

Figure 1: Comparison of the measured field profile and calculated field at the minimum gap. Solid line is the measured data and the dot is the design data.

PAL-XFEL TYPE PHASE SHIFTER

PAL-XFEL will have one soft X-ray undulator line and one hard X-ray undulator line for SASE lasing at the initial stage of completion. The toughest requirement for phase shifter comes from the tuning of the soft X-ray FEL from 1.0 nm to 3.0 nm at electron beam energy of 3.15 GeV. For continuous tuning of the phase during the energy scan, we need to use high phase number [3]. The inter-undulator space is rather short compared to hard X-ray undulator lines. The detailed design for all components in the inter-undulator space is not completed and the inter undulator length is assumed to be 0.8 m for soft X-ray lines. In this case the required phase integral defined in Ref [4] is given by

$$PI = \left(\frac{mc}{e}\right)^2 \left(\lambda_R \gamma^2 \nu - L\right) \cdot$$

Here, λ_R is the radiation wavelength, γ is the usual relativistic factor, ν is the phase number, L is the length of the drift space between the undulator, m, c, e is the mass, speed of light, electron charge, respectively. Above equation is shown in Fig.4, and we can see that for phase number larger than 22 must be used for continuous tuning of the radiation wavelength. With phase integral of 6300 T^2mm^3, phase number ranging from 22 to 26 can be used depending on the phase advance of the undulator.

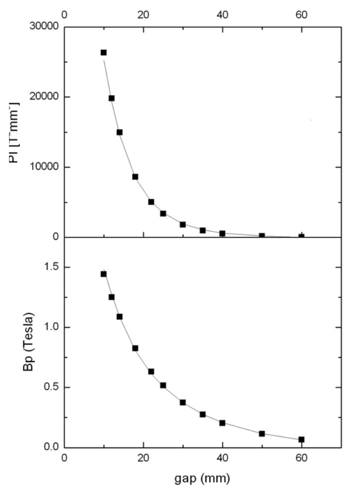

Figure 2: The gap dependence of the phase integral (top) and peak field (bottom) of the EU-XFEL type phase shifter. The maximum design phase integral at the minimum gap is 25300 T^2mm^3.

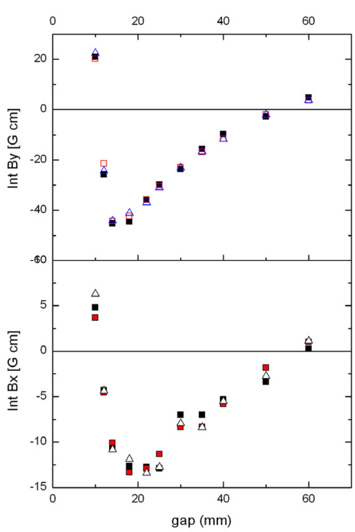

Figure 3: The gap dependence of the residual field integral By (top), Bx (bottom) for EU-XFEL type phase shifter. The results are as assembled and without any shimming.

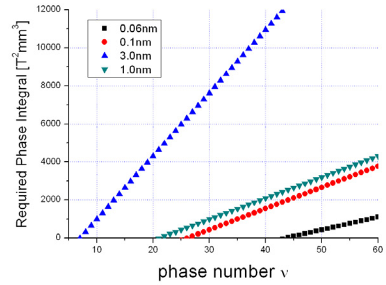

Figure 4: The required phase integral vs phase number. The toughest requirement comes from the tuning of 3.0 nm to 1.0 nm at 3.15 GeV, where we need more than 5500 T^2mm^3 for continuous phase change.

Since the space budget is very tight, instead of 230 mm EU-XFEL type phase shifter design, an alternative design with shorter length, and smaller phase integral are studied [4]. In the design, only permanent magnet is used as shown in Fig.5 with total length about 100mm. Magnetic period is approximately 80mm. Most block thickness are 20 mm or 10 mm. But some 10mm thick are slightly thicker by 0.99 mm to tune the field integral. The magnetization direction of the end magnet deviates from conventional type to limit the fringe fields. The model is analysed using RADIA [5] and the RADIA model is shown in Fig.5. The results of the design calculation are summarized in Table 1 and Fig.6. Figure 6 shows the field profile, and the field integral profile and phase integral. A prototype is built to confirm the calculation. At minimum gap of 7.2 mm, the phase integral is about 7000 T^2mm^3 which exceeds the design value of 6300 T^2mm^3. The discrepancy mostly comes from the higher remanence of the magnet actually used.

Table 1: Major Parameters of the PAL-XFEL Phase Shifter

Symbol	Unit	Value
Device Length	mm	100.0
Min gap	mm	7.2
Max gap	Mm	>80
Magnetic period	mm	~80
Phase control accuracy	degree	±10
Gap control accuracy	μm	±20
Magnet Material		NdFeB
Remanence at 20 C	T	>1.26
Hcj at 20C	kA/m	>1670
Peak Field	Tesla	1.25
Max phase integral	T^2mm^3	6300

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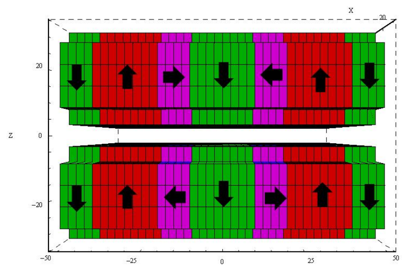

Figure 5: RADIA model of the PAL-XFEL type phase shifter. This kind of design is also used at FERMI [2].

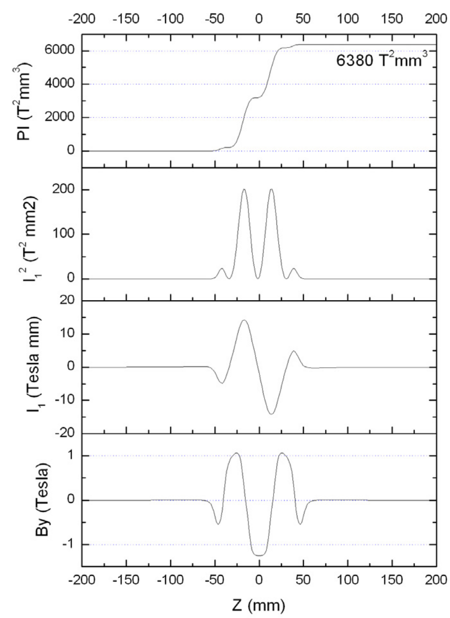

Figure 6: The design profile of the PAL-XFEL type phase shifter. From bottom, By, I_1, I_1^2, phase integral.

MECHANICAL DESIGN

On the basis design of EU-XFEL phase shifter for EU-XFEL [6], we implemented some modification, fabricated and tested. Linear motion guide at each side of the magnet structure are installed to reduce a friction and guide magnet structure. Two absolute linear encoders are used at upper and lower magnet beam to test the gap movement. A left/right handed ball screw is used in order to change the magnetic gap. In this way only one single stepping motor drive system is sufficient to control the magnetic gap. The deformation of the magnet structure depends on the magnetic gap. There are two magnet structure and a backing beam. The structure is analyzed using ANSYS [7], including the complicated geometry structure. A solid geometry is adopted for the backing beam and magnet structure, which is fixed on the backing beam rear plate. The maximum deformation is 5.98 μm with magnets. The gap position is determined by the ball screw using the values of the absolute linear encoder. It measures the motion of the gap with a dial gauge. Figure 7 shows the gap moving test. The tests were performed to the gap range of 10-30 mm, where magnetic forces are higher and the other gaps are negligible. The mechanical deformation of the magnet supports at minimum gap leads to a deviation of about 23 μm. This hysteresis is due to mechanical movement, back lash, elasticity and friction of the magnet systems in the iron yoke and in the guiding system.

Figure 7: Gap Moving Test.

SUMMARY

In this report, the status of the PAL-XFEL phase shifter system is described. Firstly, EU-XFEL type phase shifter is built with some modifications including, absolute gap measuring encoder, servo motor system, and reinforce LM guide to enforce the mechanical rigidity. The measurement results show very reproducible results without any hysteresis, yoke magnetization problem. The residual field level is somewhat high but it can be improved after pole shimming. To reduce a shorter phase shifter, FERMI style phase shifter using only permanent magnets are built and measured. Preliminary measurements confirm the design calculation, and the gap dependence of the residual field integral is being corrected. Also the effects of the fringe fields and nearby ferromagnetic components will be evaluated soon.

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