A PERMANENT MAGNET PHASE SHIFTER FOR THE EUROPEAN XFEL

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Abstract

In undulator systems with variable gaps phase shifters are needed to exactly control the ponderomotive phase between electrons and the radiation field over the length of the whole undulator system. A phase shifter based on Permanent Magnet technology for the use in the European XFEL has been developed and tested. This paper will explain its magnetic principle and focus on test results and the applied correction schemes.

Key words: undulator, phase shifter, XFEL

INTRODUCTION

The European XFEL will be a user facility in the wavelength range from 0.1 to 1.6nm [1]. High power radiation will be generated using Self Amplified Spontaneous Emission (SASE). Saturation requires a typical undulator system length of more than 200m [2, 3]. The radiation wavelength can be changed by changing the electron beam energy or by changing the undulator gap.

In undulator systems with variable gaps phase shifters are needed to exactly match the phase between individual segments so that constructive superposition of the emitted light occurs. Besides providing the appropriate phase delay a phase shifter should be neutral and cause no beam deflection to the beam.

The PM phase shifter was first described in detail in [1]. In contrast to the electromagnetic (EM) design proposed in [4] the PM device is more compact. It is free of stray fields and has no measurable hysteresis.

This paper will focus on the PM phase shifter, explain its magnetic principle and discuss the results obtained on a prototype. Correction schemes, which were applied in order to compensate field errors are discussed as well.

PRINCIPLE AND SIMULATION

Figure 1 shows a schematic of the PM phase shifter. The magnetically active parts are encaged by a zero potential soft iron yoke. PM blocks and poles are arranged in a similar configuration as in the case of a hybrid undulator. There is a high degree of symmetry in the arrangement of the magnets. All flux lines generated by the magnets cross the orbit plane twice but with opposite direction. So the field integral is always balanced to zero. The magnets between poles and the zero potential yoke are used to enhance the pole strength. Slight vertical movement of these magnets can be used for error correction. The zero potential yoke terminates the fields very effectively and thus avoids stray fields outside the phase shifter. The field strength is controlled via the gap between the poles, which are movable, while the iron yoke is kept fixed as indicated in Fig 1.

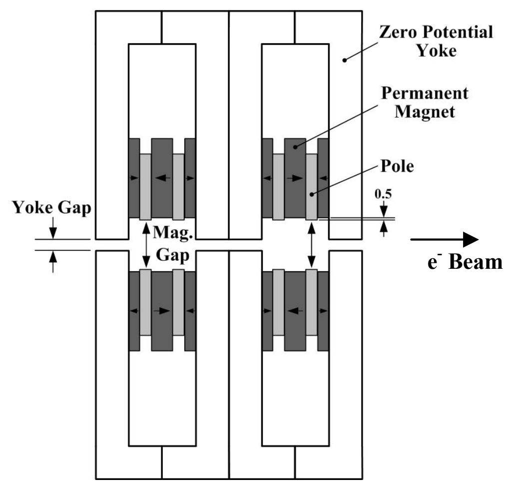

Figure 1:Working principle of the PM phase shifter

In the forward direction, along the symmetry axis of the phase shifter, the optical phase can be expressed as [4]:

$$\varphi(z) = \frac{2\pi}{\lambda_s}\left\{\frac{z}{2\gamma^2} + \frac{1}{2}\int_{-\infty}^{z} x'^2(z')dz'\right\} \quad (1)$$

Here $z = ct$, λ_s is the radiation wavelength and x' is the electron deflection angle. The first term describes the phase advance in free space. The second represents the additional contribution of a magnetic field to the phase delay. x' can be derived from the along the field along the beam axis , $B_y(z)$, by:

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

By means of equations (1) and (2) the optical phase can be evaluated from calculated or measured magnetic field data.

The phase shifter is intended to be used as a standard device for the XFEL undulator systems. Here the soft X-

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Ray undulator system SASE3 sets the scale for the worst case requirements. At a beam energy of 17.5GeV this relates to the longest achievable wavelength of 1.6nm. Here the maximum phase delay should at least be 4π in order to be on the safe side.

The parameters used for the construction of the prototype were determined using RADIA [5]. Pole dimension were 9.5 x 60 x 60mm^3 (Length × Width × Height) and magnet dimensions were 18 x 75 x 75mm^3 for the full and 9 x 75 x 75mm^3 for the half magnets. The iron yoke thickness was chosen to 30mm. The resulting total length was 230mm.

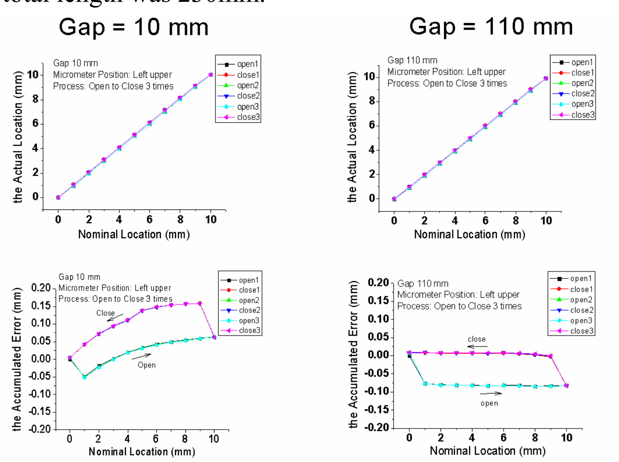


Figure 2: Mechanical accuracy and reproducibility of the gap motion

PROTOTYPE AND CHARACTERIZATION

Control System

In order to change the gap between the magnetic parts a double translation stage with a right/left handed spindle was used. By doing so on central motor is sufficient. A MAXON servo motor drive system is used to open and close the pole gap. For simplicity the gap position was deduced from the servo motor controller. There is no direct measurement of the gap.

Mechanical accuracy

To test the mechanical accuracy, two digital micrometer gauges with a measurement length of 10mm and an accuracy of ±1µm were mounted on the moving top and bottom magnetic blocks units. Measurements were made at two different gaps one at 10mm, where magnetic forces are substantial and the other at 110mm, where they can be neglected. Typical results of movement tests are shown in Figure 2. In order to get an impression on reproducibility three open/close cycles are included. The top figures show the dial reading plotted against the spindle position of the motor control. The bottom figures show the difference between the readings of the gauges and the control system.

Some conclusions can be made: 1.) Linearity as seen in the top of Fig.2 is very high. 2.) There is hysteresis between open and close cycles as can be seen in the bottom figures. It amounts to about 100µm. It is caused by mechanical play, friction and the resulting slip stick effect. Its form is gap dependent. 3.) The reproducibility for different cycles, however, is much higher. Different curves reproduce within typically ±1µm or better and differ less than the line thickness in Fig 2. Thus by watching the direction of movement, i.e. by moving to a position from one side a position can be reproducibly found with this accuracy.

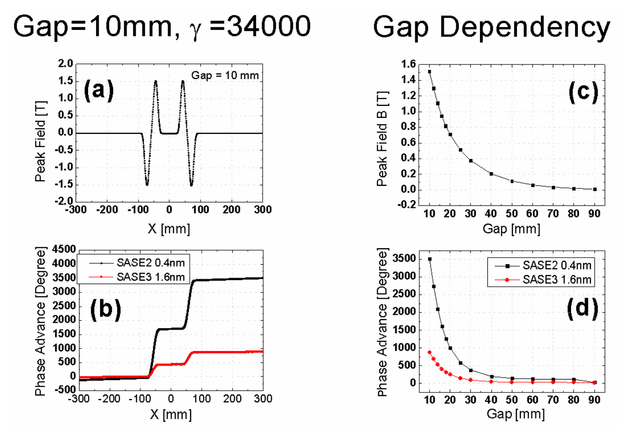


Figure 3: Results of magnetic measurements: (a) Vertical field distribution along the beam axis at a fixed gap of 10mm; (b) Corresponding phase advance for 0.4 and 1.6nm at 17.5GeV; (c) Gap dependence of vertical peak field; (d) Gap dependence of the total phase advance for 0.4 and 1.6nm

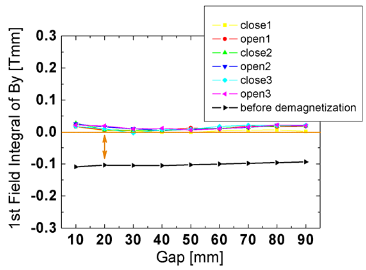
Magnetic performance

Fig. 3 shows results of magnetic measurements. Fig. 3 (a) shows the field distribution along the electron beam axis at a gap of 10mm. A peak field of ±1.52T is observed. The resulting change in phase shift corresponding to the second term in Eq. (1) is shown in Fig 3 (b) for two cases: The black curve shows the phase advance for SASE2 at 0.4nm. Here about 3520° or 61.5rad are obtained after the phase shifter. The SASE3 case is show for illustration: For 1.6nm the phase delay is 880° (15.4rad), which fulfils requirements. The gap dependence of peak field and total phase delay are shown by Fig 3 (c) and (d). From the slope of the SASE2 curve the required accuracy can be estimated: In order to adjust the phase delay better than 5° the gap should be adjusted better than 0.02mm. This is the worst case at 10mm gap. For larger gaps or longer wavelengths the requirements much more relaxed.

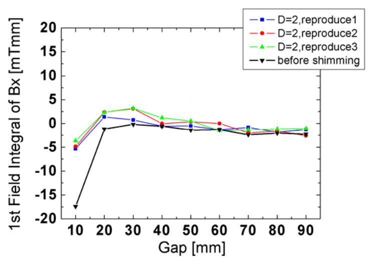
Fig 4 shows the first horizontal and vertical field integrals as a function of the gap. The black curve in Fig 4 (a) was the initial state as found at the beginning of the measurements. It shows a quite constant value of −0.1Tmm independent of the gap. It was found to be due to a remanent magnetization of the iron yoke. Using an external coil and applying an excitation of about

±3200Ampere turns with decreasing amplitude the yoke was demagnetized and the error was brought below 0.03Tmm as can be seen from the other curves in Fig.4(a).

The gap dependent horizontal field integral is shown in Fig 4 (b). Again the black curve shows the initial state. At small gaps its maximum deviation is −17mTmm, which is already a small value. In order to get a further reduction



(a) Vertical field



(b) Horizontal field

Figure 4: First field integral measurements. Initial status (black curves) and after correction (coloured curves). Notice that the scales differ by a factor 10^3 between (a) and (b)

horizontal shims are used, see Fig 5. Fig 5 (a) shows the geometric arrangement. Fig 5 (b) explains the dimensions and nomenclature used. In order to further reduce the gap dependence four parameters were varied: Length (L), Width (W), Thickness of the shims (T) and the Distance between the shims (D). Different shim arrangements were tried out and ranked according to their capability to correct the observed gap dependence.

Optimum shim dimensions, which minimize the gap dependence of the horizontal first field integral, were found to be: 8mm × 3mm × 0.1mm × 2-5mm (Length ×Width × Thickness × Distance). The final results and their reproducibility are shown as Figure 4 (b). As compared to the initial value there is a reduction by a factor 3-4.

SUMMARY AND CONCLUSION

A first PM phase shifter prototype for the use in the European XFEL has been built and tested. The results show that the magnetic principle is working well. The maximum observed phase delay for 1.6nm and 17.5GeV corresponds to 15.4rad and thus exceeds the required 4π. Magnetic measurements showed that the vertical field integral can compensated to 0.03Tmm or even better. However control of the remanence of the iron in the yoke is of great importance and needs special attendance for future developments. Choosing suitable soft magnetic iron grades and subsequent annealing steps will be needed.

Horizontal field integral errors were already small: They could be further decreased by applying suitable shims. This technique is of general interest for error correction. For the phase shifter the horizontal field integral error could be reduced to better than 4mTmm.

The measurements have shown that gap control better than 0.02mm is sufficient to control the phase delay better than 5° at 0.4nm over the full gap range. Thus an encoder for direct gap measurement, which would be prone to radiation damage is not needed.

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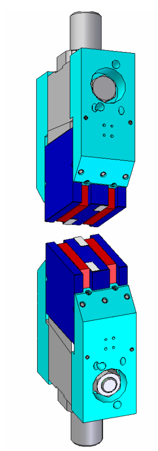

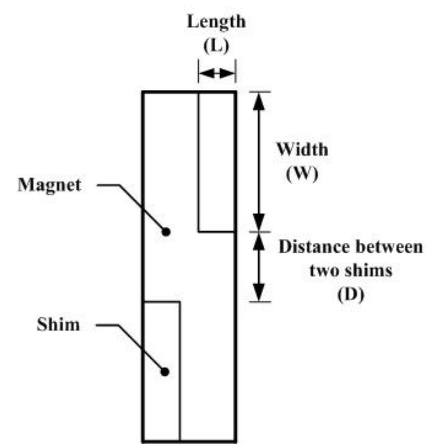

(a) (b)

Figure 5: (a) Placement schematics for horizontal shims (b) definition of dimensions

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