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Permanent Magnet phase shifters for FLASH2020+ FEL

Permanent Magnet phase shifters for FLASH2020+ FEL

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Abstract. The development of a simple and compact permanent magnet (PM) phase shifter is presented in this paper. The design is based on four PM blocks per girder (8 PM blocks in total), and uses only one type PM block with horizontal magnetization and 15mm length. The magnetic field provides a net zero and second field integral and a phase integral of $2 \cdot 10^{-6}\, T^2m^3$ for 60mm overall magnet length. The study of the numerical model with Radia shows that this design is mainly sensitive to angular magnetization errors. The correction strategy is based on pairing the PM blocks in order to cancel the sum of magnetization angle error, and the remaining magnetic field error is corrected with a stack of magic fingers located around the magnet. Finally, a prototype was built, and the magnetic measurements results are presented here.

1. Introduction

The upgrade of the present FLASH 1 beamline towards a seeded FEL line is a major part of the FLASH2020+ project at DESY [1]. The new FEL layout consist of 12 variable polarization undulators (APPLE III) of 2.5m length, with intersections of about 0.8m length between the undulators. The intersection contains various e-beam diagnostics, vacuum instrumentation, a quadrupole magnet and a phase shifter chicane magnet. The phase shifter magnets (PS) are used to delay the electron beam trajectory in order to phase the radiation of the adjacent undulators which interfere constructively and radiate coherently. Currently, an electromagnetic PS of 150mm length is in operation at the FLASH 2 intersections [2]. However, for the FLASH upgrade, the longitudinal space is constrained and impacts the allocated length for the PS which is reduced to 100mm. In order to obtain a compact PS design, a permanent magnet PS design is considered. Several permanent magnet (PM) PS are successfully operating at different FEL facilities [3,4,5,6]. This paper presents the development and the prototype results of a simple and efficient PM-based PS design.

2. Specification

A PS magnet is designed to provide a phase advance to the electron beam defined as:

$$\Delta\varphi = \frac{2\pi}{\lambda_R}\int_{-\infty}^{s}\frac{x'(s)^2}{2}\mathrm{d}s\ [\mathrm{rad}] \qquad (1)$$

where λ_R is the undulator radiation wavelength and $x'(s)$ is the electron beam trajectory angle related to the first field integral. Generally, a maximum phase advance value of 2π is specified, and the phase tuning in the range of 0 to 2π is done by varying the magnet gap. In terms of magnetic performance of the magnet, the phase integral defined as $\Delta\varphi' = \int_{-\infty}^{s}\frac{x'(s)^2}{2}\mathrm{d}s\ [\mathrm{T^2m^3}]$ is more suitable for performance comparison. Table 1 summarizes the design parameters of the PS.

Table 1. Specified design parameters.

E	1.35	GeV
λ_u	30	mm
Gap	8	mm
$\Delta\phi$	>1.5x2π	rad
L_{mag}	<100	mm

In addition to the design parameters, the first and second field integral of the magnet related to the electron beam angle and position at the exit of the magnet, respectively, must be zero to avoid the use of additional correction coils. Also, the magnetic fringe field extent should be kept sufficiently small in order to avoid magnetic interaction with the quadrupole electro-magnet located 10cm away from the PS.

3. Magnetic design

The design of the PS is derived from the LCLS compact design [3] where a simplified solution is obtained with an analytic model. We start with the Halbach magnet configuration with an arbitrary gap between the PM blocks as shown in figure 1.

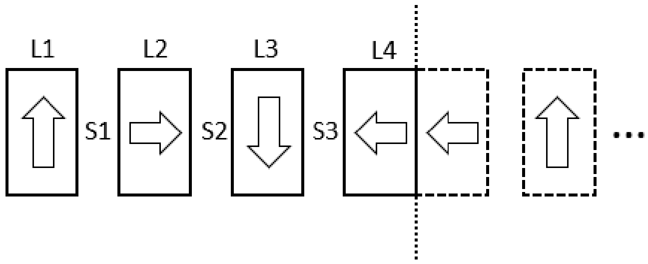

Figure 1. Antisymmetric Halbach magnet array (top array only). The magnet center is represented by a dashed vertical line.

The magnet array is composed of vertically and horizontally magnetized PM blocks and the variables *Lx* and *Sx* are the length of the PM block and the gap between the PM, respectively. Considering that a vertical magnetization PM block introduces a kick of strength *kx* to the electron beam localized at the center of the PM block, and the horizontal magnetization PM block introduces two opposite kicks located at the extremity of the PM, a simple model of the electron trajectory amplitude is obtained and given by equation (2):

$$y = k1\left(\frac{L1}{2} + S1 + L2 + S2 + L2 + L3 + S3 + L4\right) + k2(L2 + S2 + L2 + L3 + S3 + L4) - k2(S2 + L2 + L3 + S3 + L4) - k3\left(\frac{L3}{2} + S3 + L4\right) - k4(L4) \quad (2)$$

The kick strength *kx* depends on the PM block length and height. The first and second field integral of the magnet arrangement must be zero, i.e. the sum of the kicks must be zero, and the sum in equation (2) must zero as well. Solving equation (2)with these constraints, one possible solution is given by $L1=L3=0$, $S1=S2=S3=0$ and $L2=L3$. This particular solution cancels the vertical magnetization PM block and the gap between the PM blocks as shown in figure 2.

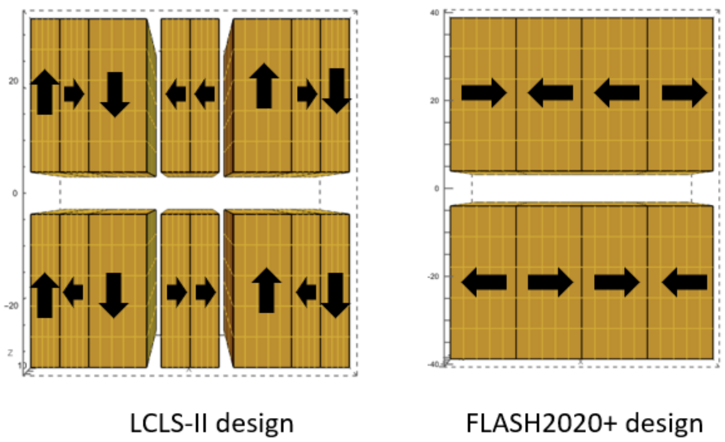

Figure 2. PM phase shifter design. The LCLS-II and the new design for FLASH2020+ are presented.

Compared to the LCLS-II PS design, the FLASH2020+ design uses only 4 PM blocks per array with horizontal magnetization. This design allows for using one type of PM block which simplifies the sorting as the PM blocks can be swapped. The magnetic field of the two designs with 60mm magnet length each is shown in figure 3. The PM blocks' dimensions are 15mm length, 29mm height and 33mm width for the FLASH2020+ design.

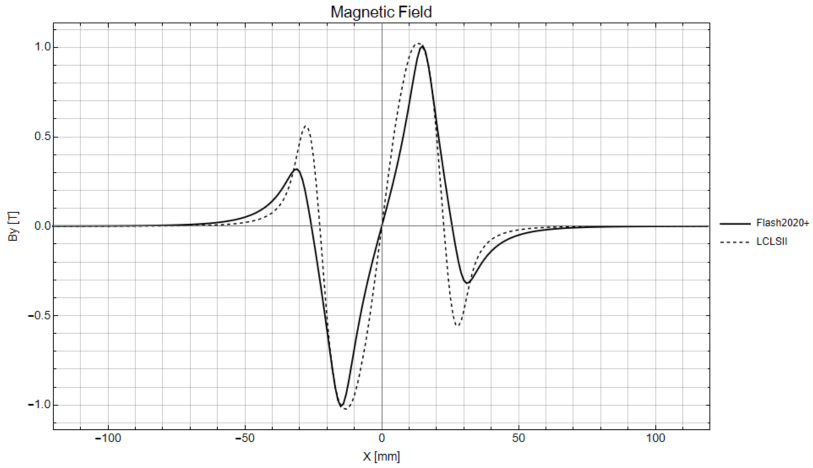

Figure 3. Magnetic field of FLASH2020+ (bold) and LCLSII PS magnets (dashed).

Both designs provide a zero first and second field integral as well as a similar phase integral. However, the fringe field extent is lower for the LCLS design. Despite the much sharper field termination in the LCLS design, we consider the cross-talk into the nearby quadrupole as negligible.
The maximum demagnetization field inside the PM block of the FLASH2020+ design is around 1000kA/m. NdFeB PM material grade with 1.25T remanent magnetization and H_{cj} well above 1500kA/m is used. A sensitivity study of magnetic and mechanical errors shows that the new design is mainly sensitive to magnetization angle errors. This result tells us that the magnetic and mechanical tolerances of the PM block can be relaxed. A specification of 2° magnetization angle error is set. The magnetic correction scheme relies on sorting and pairing the PM blocks in order to cancel their errors. A square cross-section PM block of 35mm height and width is used in order to increase the pairing possibilities by rotating the PM block. Special stacks of small cubic block magic fingers are located along the magnet and at the extremities (figure 5) and can be used to correct remaining vertical and horizontal field integrals as well as multipole errors. Magnetic measurements of all PM blocks are done by a Helmholtz coil (average magnetization) and by a stretched-wire bench (local magnetization distribution) in order to improve the sorting and pairing result.

4. Prototype

A prototype was built to verify the feasibility of the design and check the magnetic performance in relation to the numerical model. The main challenge of this design is the magnetic force between two oppositely magnetized PM blocks as shown in figure 4.

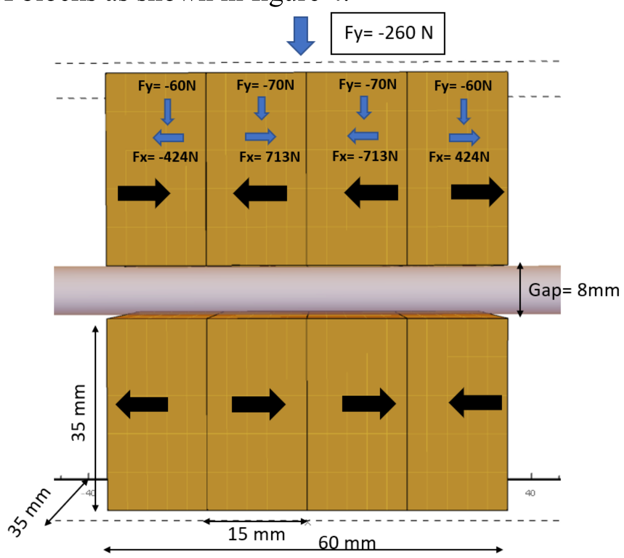

Figure 4. Magnetic forces on the PM blocks. The force directions are indicated by the blue arrows, while the black arrows indicate the direction of magnetization.

These strong forces between the PM blocks require a dedicated tool for assembly. The magnet container must keep the PMs in place, especially for the outer PM blocks which tend to be repelled away. A magnet container equipped with clamps to fix the PM blocks and walls of 3mm thickness at the extremities to stand the longitudinal forces is used. The mechanical design of the prototype is shown in figure 5. The main body of the PS prototype is a linear stage unit with two carriages for the magnet containers' support, which is coupled to an electric motor for the gap drive. The gap adjustment is in the range of 8mm to 50mm.
A sketch of the assembly process is shown in figure 6. The two PM blocks at the extremities are installed first in the container, then the two central PM with same magnetization direction are carefully joined using a wedged spacer, and are finally pushed into the container by means of a screw and a guide.

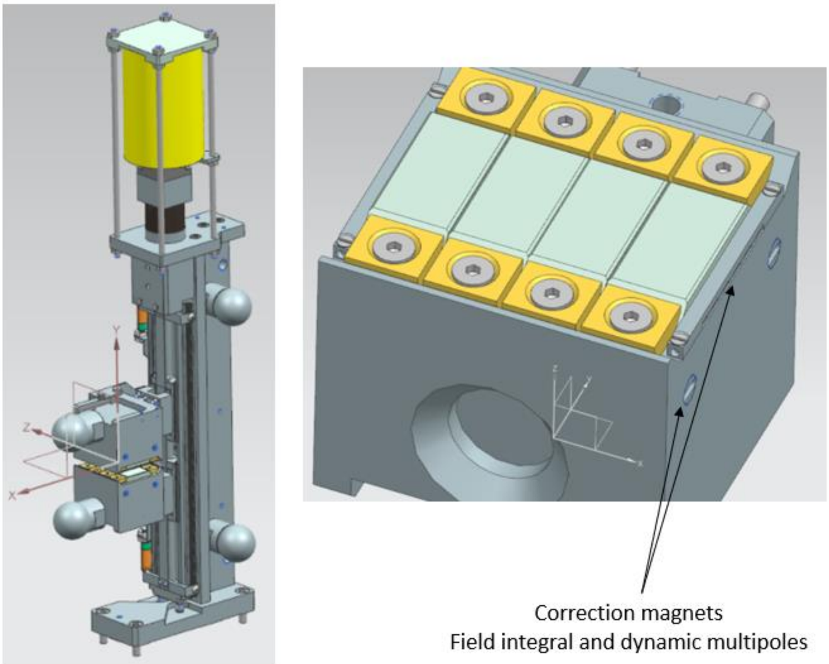

Figure 5. CAD view of the PS prototype (left). Magnet container with correction magnets (right).

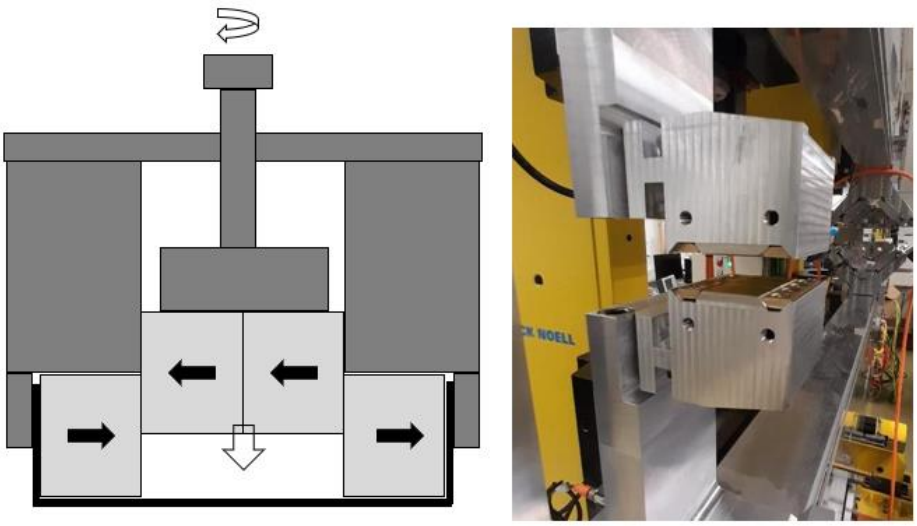

Figure 6. Sketch of mounting tool and assembly process (left). Assembled PS prototype (right) temporarily mounted on an undulator carriage.

5. Prototype magnetic measurement

The magnetic measurement of the prototype is performed by a Hall-probe bench. For this measurement, the magnet containers were mounted to an undulator carriage because the prototype translation stage was not available yet. The magnetic measurement results are shown in figures 7 and 8. The results of the protype are in good agreement with the model for the magnetic field and the phase advance. The slight difference comes from the gap setting at the undulator carriage which was not very well defined.

A phase advance of 2.5x2π radian is obtained with this prototype which corresponds to a phase integral of $2 \cdot 10^{-6}\ T^2m^3$. The gap dependence of the vertical and horizontal field integral (I1V & I1H) with respect to the transverse axis is shown in figure 8. These results are obtained after final tuning of the magnets with the magic fingers. Both vertical and horizontal field integral evolution with the gap are below 0.05Tmm.

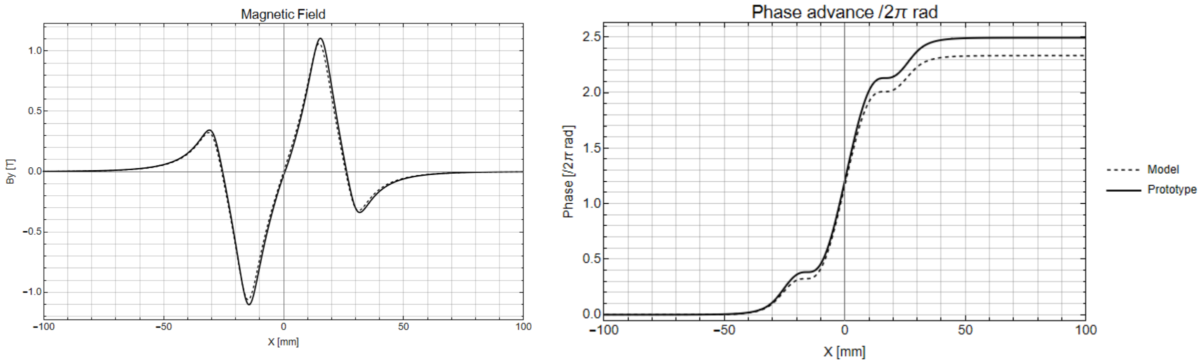

Figure 7. PS model (dashed line) and prototype (full line) comparison at 8mm gap. Magnetic field (left) and phase advance (right) results.

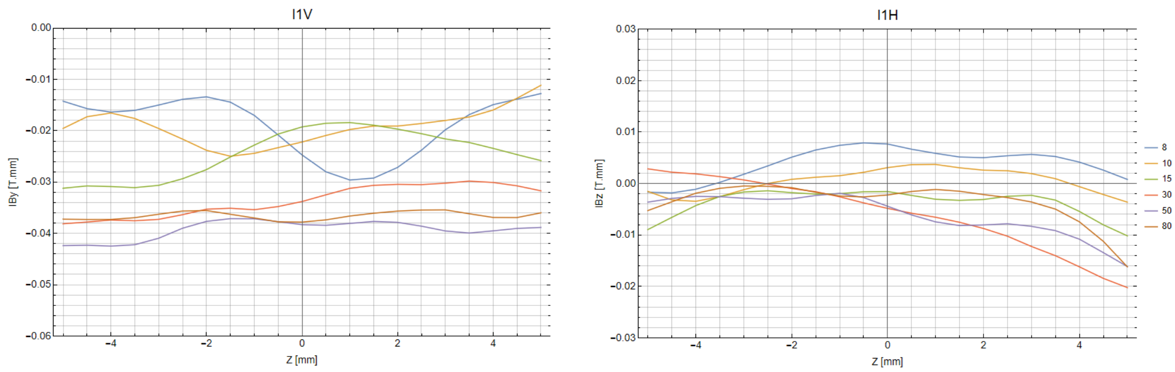

Figure 8. Vertical (left) and horizontal (right) field integral vs. transverse position, from minimum (8mm) to maximum gap (80mm).

6. Conclusion

The development of a simple and efficient permanent magnet phase shifter for the FLASH2020+ FEL has been reported. The magnet model and prototype results agree very well and the required phase advance is obtained. Thanks to the simplicity of the design, the sorting of the permanent magnets and the tuning of the magnet is simplified. Twelve phase shifter magnets will be built according to this design.

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