SHIMMING STRATEGY FOR THE PHASE SHIFTERS USED IN THE EUROPEAN XFEL

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Abstract

The undulator systems of the European XFEL need a total of 91 Phase Shifters. The 1st field integral of these devices must not exceed 0.004 T.mm for working gaps > 16mm. For smaller gaps it is slightly released. In spite of the highly magnetically symmetric design and considerable effort such as the selection and sorting of the magnets small 1st field integral errors cannot be excluded. In this paper a strategy is studied to correct small gap dependent kicking errors as expected for the phase shifters of the XFEL.EU by using shims of different geometries and sizes.

It is found, that small gap dependent kicking errors can be well corrected for using this method. This is a systematic effort to provide effective fast tuning methods, which can be applied for the mass production.

The meaning of shim signatures will be explained in this paper. The method is demonstrated by RADIA simulations.

INTRODUCTION

Gap adjustable undulators are used in the European XFEL for the easy control of wavelength. A phase shifter is needed in between adjacent undulators to match the ponderomotive phase between electron microbunches and the laser field. The undulator systems of the European XFEL need a total of 91 phase shifters [1]. In order to avoid any steering errors induced by phase shifters, the first field integral of these devices must not exceed 0.004 T.mm for working gaps larger than 16mm, which is a tight specification. In spite of the highly magnetically symmetric design [2] and considerable construction effort such as the selection and sorting of the magnets remaining small first field integral errors cannot be excluded. The XFEL.EU Phase shifters use a similar magnetic and mechanic design as the undulators for the European XFEL: The height and the tilt of the poles are adjustable [3-4]. However there might still be small residual field integral errors. Therefore an additional tuning tool is needed. By placing small pieces of iron shims on magnets or poles a small 1st integral to the phase shifter field can be induced. The 1st field integrals induced by the shims are uncorrelated to the field integrals by pole height tuning. Therefore applying shims enriches the tuning capability to compensate field integral errors and therefore can be very useful for the phase shifter tuning.

For the production of 91 devices a fast and effective tuning procedure is needed. This paper addresses on this issue and gives first results of RADIA simulations [5].

According to the experiences from the phase shifter prototypes built for the European XFEL [2] the gap dependent field integral errors demonstrate irregular curve with one or more knee points which increase the shimming challenge. Numerical simulations of shims of different geometry using RADIA [5] were performed. The strategy is similar to the method used for the undulators, which is to calculate a combination of several shims whose total contribution matches the gap dependence of an observed error. For this objective, two basic assumptions are made:

1. Linearity principle: The contribution of a shim is proportional to its thickness.
2. Superposition principle: The contribution of a combination of several shims equals to the sum of the individual shims.

First the definition for the so called shimming signature is given: It is the contribution to the gap dependent kicking of a shim of unit thickness. Based on the shimming signature and the two assumptions above one can find a combination of several shims by decomposing the target gap dependence error into a linear combination of known signatures. Two algorithms have been proposed in Ref. [6]. One is an analytical solution: Here the first step is polynomial fitting the signature of each shim as a function of gap to n^{th} order:

$$S_1 = s_{11}g + s_{12}g^2 + s_{13}g^3 + \cdots + s_{1n}g^n, \qquad (1)$$

where g is the gap and s_{ij} is the coefficient of the j^{th} order of the i^{th} type of shim. The second step is polynomial fitting the field integral error of a Phase Shifter to n^{th} order:

$$E = e_1 g + e_2 g^2 + e_3 g^3 + \cdots + e_n g^n. \qquad (2)$$

Where e_i is the i^{th} fitting coefficient. The *nth* order fitting needs a combination of *n* shims. Suppose each shim has different thickness *d* a system of linear equations is given:

$$\begin{pmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ s_{n1} & s_{n2} & \cdots & s_{nn} \end{pmatrix} \begin{pmatrix} d_1 \\ d_2 \\ \cdots \\ d_n \end{pmatrix} = \begin{pmatrix} e_1 \\ e_2 \\ \cdots \\ e_n \end{pmatrix}, \qquad (3)$$

If the matrix S can be inverted the thickness of each shim can be determined.

The second method is based on a trial and error using a large number of trials/ simulations: Several shims whose signatures are known are randomly selected with random thickness. The contribution of each combination is evaluated and compared with the error to be corrected. The combination which gives the best fit is selected for solution. The first method gives analytical solutions, which are mathematically correct but not always useful in practice requiring sometimes thick shims. The second is

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more flexible resulting in a moderate number of shims of reasonable thickness.

Gap dependent errors occur in both horizontal and vertical directions. In general single shims have an effect on both directions. So a shim which corrects an error in one direction very often induces or even enlarges an error in the orthogonal direction. By applying shims on symmetry positions such cross talk can be avoided.

The simplest symmetry contains two identical shims and examples are shown in Fig. 1 bottom and Tables 1 through 3. The discussions in this paper are limited to the field on axis. Off-axis effects leading to multipole effects are neglected. This is well justified in a single pass machines such as the European XFEL with a transverse RMS electron beam size of typically 20-30µm only.

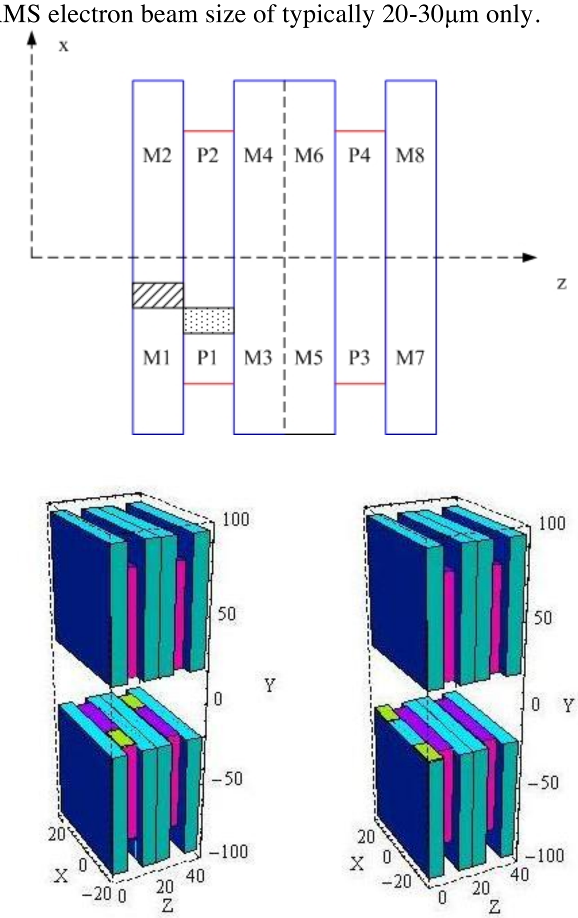

Figure 1: Top: Denotations of shimming positions in an XFEL.EU Phase Shifter: (P means shim on poles and M means shim on magnets). Lower and upper girder use the same top view convention. The numbers 1, 2, …, 8 denote the different positions.
Bottom: RADIA model of the Phase Shifter with two typical shim symmetries. In the left part, shimming positions are lower P1 and lower P4 so that only Bx with no impact on By exists. In the right part, shimming positions are lower M1 and lower M2 and only By with no impact on Bx exists.

Figure 1 denotes the coordinates of the RADIA model for the phase shifter simulation. The top plot illustrates the numbering for the shimming positions. Moreover, in order to explain the symmetry more clearly Fig. 1 bottom demonstrates two examples which contribute integral correction only to a single direction: The left generates a positive I1x component and no net I1y, see table 1. The left in contrast generates a positive I1y and no I1x, see table 2. Other symmetry solutions rather than these two can be figured out from Table 1-3.

As Fig. 1 top denotes, a phase shifter contains three groups of symmetric positions: P1,P2,P3,P4; M1,M2,M7,M8;and M3,M4,M5,M6. Positions in each group are symmetric but the symmetry is violated among different groups. For example, P1 and P4 are symmetric while M1 and M3 are not due to different end effects. Inside each group the shims at different position gives the same absolute impacts but with different signs. Tables 1 through 3 summarize the signal sign with "+" and "-" for all three groups. Adding up two shims with the same sign doubles the effect and with the reversed sign eliminates it.

Table 1: Suppose the Signal Sign of Lower Board P1 is '+'.

Lower	I1x	I1y	Upper	I1x	I1y
P1	+	+	P1	-	+
P2	-	+	P2	+	+
P3	-	-	P3	+	-
P4	+	-	P4	-	-

Table.2 Suppose the Signal Sign of Lower Board M1 is '+'.

Lower	I1x	I1y	Upper	I1x	I1y
M1	+	+	M1	-	+
M2	-	+	M2	+	+
M7	-	-	M7	+	-
M8	+	-	M8	-	-

Table.3 Suppose the Signal Sign of Lower Board M3 is '+'.

Lower	I1x	I1y	Upper	I1x	I1y
M3	+	+	M3	-	+
M4	-	+	M4	+	+
M5	-	-	M5	+	-
M6	+	-	M6	-	-

SIMULATIONS

The code RADIA [5] is used to perform the simulations. The model of a Phase Shifter and the coordinate system are explained in Fig. 1. Here x is the horizontal transverse direction, y is the transverse vertical direction and z is the direction along the undulator axis.

Dimensions and parameters follow the phase shifter design for the European XFEL [2]: Full magnet dimensions are 75*75*18mm (x*y*z), pole dimensions are 60*60*9.5mm. There is a nominal pole overhang of 0.5mm. The magnet material is NdFeB with a remanence of 1.24T and the pole material is FeCoV. The gap range is from 10-100mm.

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In a first step the accuracy of linearity and superposition principles were tested. Simulations results are shown in . 2. It is seen that in general both hold to good precision when the shimming effects are weak i.e. for thin shims. The accuracy decreases for stronger i.e. thicker shims. Consequently thin shims should be preferred. Fig. 2 top shows the results for testing the linearity principle. The normalized errors are shown for different gaps. They are calculated using:

$$\delta = I(d) - I(0.1)\times d/0.1, \quad (4)$$

where δ is the total error of the superposition, $I(d)$ is the field integral with shims of thickness d. For reference and comparison a 0.1 mm thick shims is used. The results show that the largest error δ given by pole shimming can reach more than 0.03 T.mm. In contrast for magnet shimming the largest error δ is smaller than 0.004 T.mm. The results also demonstrate that the thicker the shims the larger δ gets.

The bottom plot in Fig. 2 tests the superposition accuracy. The error function δ is given by:

$$\delta = I(a+b) - [I(a) + I(b)] \quad (5)$$

where $I(a+b)$ is the field integral of the combined

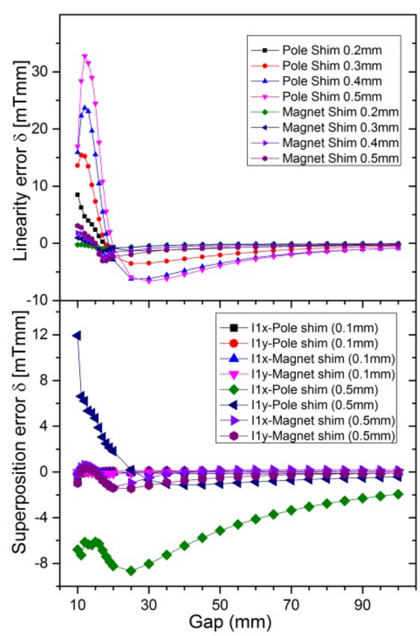


Figure 2: Top: The simulation for the test of the linearity principle for pole and magnet shimming.
Bottom: Superposition accuracy of a typical shimming. I1x and I1y denote to the field integral on the horizontal and vertical direction, respectively.

shims a, b as calculated with RADIA and $I(a)$ and $I(b)$ are the individual field integral contributions. The results again demonstrate that only with thick shims of 0.5 mm attached on poles (blue triangles) δ relatively large errors of 0.012 T.mm are reached. This result is, however, rather academic, since shims on poles limit the usable gap range. While 0.1mm is still acceptable, 0.5mm is unrealistically large. For magnet shims the errors are much smaller than 0.004 T.mm and due to the pole overhang even 0.5mm thick shims can be placed.

In the next step signatures of different shims geometries were investigated. Rectangular shims are placed either on a pole or on a magnet as shown in Fig. 1. Signatures are calculated for different shim sizes: Each shim covers the full length (z direction) of either a pole (9.5mm) or a half magnet (9mm) but its width (x direction) is varied. The RADIA simulation model is shown in Fig. 3.

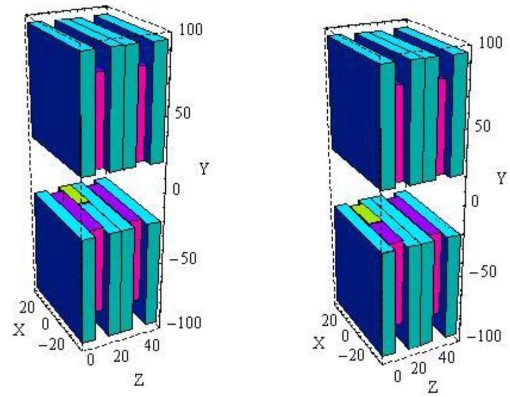
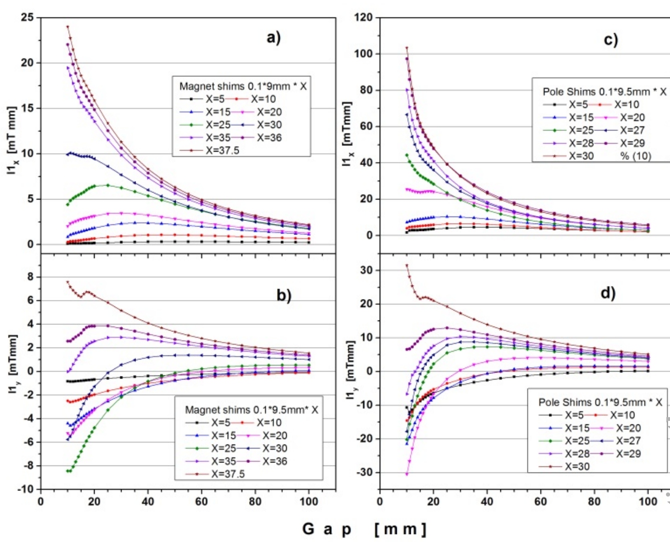


Figure 3: Geometry used for the simulations. A single rectangular shim placed on the lower M4 position (left) or on the lower P2 position (right). Each shim is placed in horizontal direction against the edge of a pole or a magnet.



ure 4: Signatures for shims with different X-extensions on magnets a), b) and poles c), d). 0.1mm thick rectangular shims are used. The geometry is shown in Fig. 3.

All signatures of horizontal and vertical field integrals of pole and magnet shims investigated for this study are shown in Fig. 4 a) through d). All are 0.1mm thick. The length of the shims (x) varies from 5mm up to 45mm. The comparison shown in Fig. 4 reveals that pole shimming (Fig. 4 c,d) is several times stronger than magnet shimming, Fig. 4 a,b). However pole shimming limits the available gap range. These signatures are the basis for compensation of a specific gap dependent kick error. An

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example for the correction of gap dependent 1st field integral errors is given in Fig 5.

By a combination of shims a curve with three knee points is generated which has a similar shape as observed in one of the prototypes Phase Shifter PS2.

Three different shim sizes were selected to compensate the errors. The three shims are named ‘a’, ‘b’ and ‘c’: ‘a’ shims of size 5*0.2*9mm (x*y*z) are placed on lower M5 and upper M3 positions; ‘b’ shims of size 12.5*0.4*9mm are placed on lower M4 and upper M6 positions; ‘c’ shims of size 25*0.1*9.5mm are placed on lower P1 and lower P4 positions. The ‘a’ shims are placed between |x|=25mm and |x|=30mm in horizontal direction and ‘b’ and ‘c’ are at x=0.

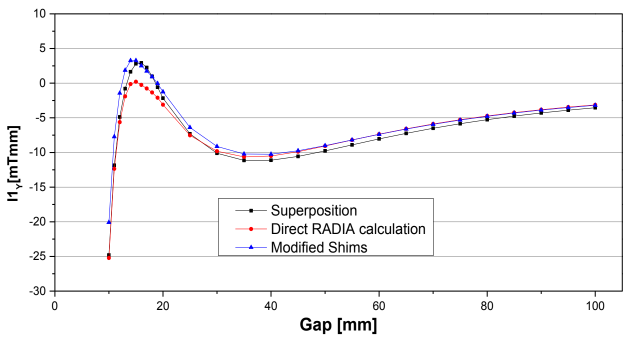

Figure 5: Demonstration of the compensation of a typical 1st field integral error by combination of several shims.

Two simulations were done with respect to this example. One is the direct add up of individual signatures and is shown by the black squared curve in Fig. 5. It is the expected shimming effect under the assumption that the superposition principle holds. The red dot curve is the direct simulation of the three shims together as calculated using RADIA.

The results show that there is a disagreement of about 0.003 T.mm around a gap of 16 mm. This may be attributed to the limited accuracy of the superposition principle. The result can be further improved by slightly changing the size of the ‘a’ shim to 6*9*0.2mm and place it between |x|=25mm and |x|=31mm. The result is seen by the blue triangle curve in Fig. 5.

CONCLUSIONS

A compensation method for gap dependence kicking errors of phase shifters was explored. Rectangular shims were placed on magnets and poles. By using the symmetry properties, cross talk between horizontal and vertical field components can be avoided. For the shims their normalized gap dependence called signature must be known.

By a linear combination of different shim sizes at different positions the gap dependence of a Phase Shifter can be modelled. This method is well suited for a numerical optimization. A combination of shims was suggested to match the gap dependence error of the Phase shifter prototype PS2.

If the gap dependence of errors is more intricate, more rectangular shims may be required to give a good match. Other shapes of shims such as circles and polygons may offer different basic signals to enrich the choices and deserve a further study, which is beyond the scope of this study. There are some messages learnt from these simulations:

1. Shimming with weak signals are preferred since they increase the accuracy of the linear combination strategy. So thin shims are preferred over thick ones and magnet shimming is preferable over pole shimming.

2. Due to unavoidable superposition errors, the signal of the combination of basic shims may have a slight difference to the combined signal. If the difference is not acceptable, the size of shims should be slightly changed to improve the compensation effect.

In this paper only RADIA simulations are used to demonstrate the strategy for correction of field integral errors. Absolute accuracy of these simulations is given by the convergence accuracy of RADIA code and is estimated at best to ±10 mT.mm on an absolute level. Limited simulation accuracy can be overcome by using measured rather than calculated signatures. The strategy presented in this paper would be the same but results would be more accurate.

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