HIGH ACCURACY SHIMMING TECHNIQUE FOR THE PHASE SHIFTERS OF THE EUROPEAN XFEL

Yuhui Li, Joachim Pflueger, The European XFEL, Notkestr 85, 22607 Hamburg, Germany

Abstract

For the European XFEL 91 phase shifters are needed, which have to fulfil stringent field integral specifications: There should be no observable beam deflection when the strength, i.e. the magnetic gap is changed

In order to facilitate the mass production of 91 phase shifters within the tough XFEL schedule a shimming technique was developed. It is based on measured shim signatures and is straight forward and fast to apply. The method is described and results are presented demonstrating that all requirements can be fulfilled.

INTRODUCTION

The undulator systems of the European XFEL need a total of 91 phase shifters. They should be transparent to the electron beam: This means that there should be no detectable effect by changing their strength i.e. their magnetic gap. As a consequence the gap dependent first field integrals error of a phase shifter must not exceed 0.004Tmm (4Gcm) for phase shifter gaps > 16mm. For smaller gaps tolerances can be relaxed as shown in table 1. In addition these requirements must be fulfilled in a good field region in the horizontal plane ±0.5mm around the device axis limiting allowed integrated gradient to below 0.004T. A summary is given in table 1.

These tolerances are tight. The magnetic design has a high magnetic symmetry to eliminate any systematic gap dependency due to geometry [1]. Nevertheless small effects may arise due to imperfections in the magnetic material and errors in the pole contours. From observations made on the first prototype [1] it became clear that the gap dependence cannot be compensated by the pole height tuning as applied to the XFEL undulators [2]. By placing shims on poles and/or magnets gap dependent effects can be compensated. Moreover a smart strategy can also provide a good field region of ±0.5mm in the horizontal plane to facilitate alignment. Therefore a systematic method was developed which allows the determination of shim parameters to compensate any measurable gap dependency and to provide a sufficient good field region.

Table 1: Gap dependent Tolerance Specifications

Gap (mm)	>16	15	14	13	12	10.5
Spec (Gcm)	±4	±7	±10	±13	±16	±18
Good field range (mm)	±0.5					

On the other hand, a fast and effective tuning procedure is a key issue for an economic and timely production of a large number of phase shifters. This paper explains a fast and systematic shimming technique to obtain the required gap dependent field integral specification and simultaneously a small enough gradient to have the required good field range. Measured results are presented.

MAGNETIC MOMENT IN SHIMS

A shim is made from highly permeable such as low carbon iron. When placed on a pole or magnet the external magnetic field induces a magnetic moment in the shim. Its effects are similar but not identical to that of an additional small permanent magnet.

Fig. 1 explains the effect and shows a schematic cut through a hybrid type magnet structure as are used for the Phase Shifters [1]. The magnetization of the magnets is parallel/antiparallel to the beam axis. The flux is redirected perpendicular to the axis by the poles. If a shim is placed on a magnet besides a pole the magnetic moment vector in the shim is mainly parallel to axis and only a small contribution is perpendicular to the axis. In contrast a shim on a pole mainly induces a perpendicular contribution and acts similar to a pole shift.

The magnetic field $\vec{B}$ of a magnetic moment $\vec{m}$ at position $\vec{r}$ is given by:

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\left[\frac{3\vec{r}\,(\vec{m}\cdot\vec{r})}{r^5} - \frac{\vec{m}}{r^3}\right]. \qquad (1)$$

Therefore the field integral caused by $\vec{m}$ perpendicular to the axis is given by:

$$\int_{-\infty}^{+\infty} B_{\perp}\,dz = \int_0^{\pi} \frac{m_{\perp}(3\sin^2\theta - 1) + 3m_{//}\sin\theta\cos\theta}{r^3}\,d\theta\,. \qquad (2)$$
$$= \frac{28\,m_{\perp}}{15\,d^3}$$

Where $m_{\parallel}$ and $m_{\perp}$ represent the magnet moment parallel and perpendicular to phase shifter axis, respectively. d is the distance from the magnetic moment to the axis as shown in Fig. 1. According to Eq. 2 only $m_{\perp}$ contributes to the vertical field integral and $m_{\parallel}$ does not. The induced magnetic moment of shims on poles is mainly $m_{\perp}$ and by shims on magnet is predominantly $m_{\parallel}$. So shims on poles are clearly more efficient. Unfortunately they eat up the effective phase shifter gap and are not self-adhesive by magnetic forces and therefore need to be restrained (glued). In contrast shims on magnet don't narrow the gap due to a 0.5mm pole overhang with respect to magnets. Experimental tests have demonstrated that in contrast to Eq. 2 magnet shims still give a small strength suitable for weak corrections. They stay on magnets firmly. They are a convenient choice Phase Shifters shimming.

The field induced by the shim on the beam axis depends on the distance *d*. Therefore by changing the transverse dimensions and positions of the shims the gap dependent contribution to the field integral is changed. So different gap dependencies may be created with different shim geometries.

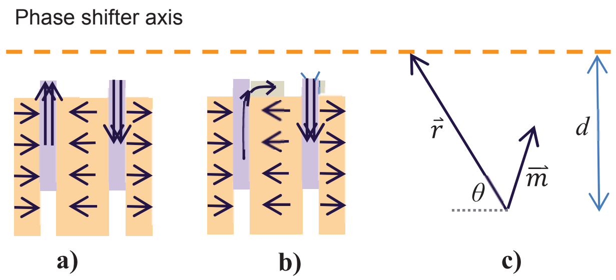

Figure 1: a): Magnetic moments in magnets and poles in a hybrid undulator. b) Magnetic moments in shims on magnets and poles. c) The orientation of a magnet moment vector and its contribution to the field in a point.

SYSTEMATIC TUNING STRATEGY

Two Basic Assumptions

Field integrals and transverse field integral gradients are changed by shims. A systematic tuning technique must determine shim geometry and placement. To do so two assumptions are essential [3,4]:

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

It was demonstrated by RADIA simulations as well as by measurements that for the magnet shimming these assumptions hold fairly well [3,4]. In practice the shim thickness varies from 0.1mm to 0.5mm.

Geometry

Fig. 2 illustrates the magnet configuration of a Phase Shifter: It is comprised by four identical magnet modules. Each contains one full magnet and two half magnets. Fig. 2 defines 32 different positions where shims can be placed. Symmetry requires that shims on different positons function accordingly. Experience has shown, that the symmetry principle for half and full magnets needs to be applied differently. Accordingly the 32 different positions can be grouped in two types: Shims on half magnets and shims on full magnets. In each group the function of the shim follows the symmetry properties.

Without loss of generality position 1 in Fig. 2 is selected to represent the "original" position "O" for half magnets and position 3 as the original position for full magnets.

Positions opposite to the original positons on the X axis such as 2, 4 are named "mirror" positions, "M". Positions on poles with opposite sign are named as "reversed" position "R". There are positions which are both opposite to the original position and on the reversed poles. They are named "MR".

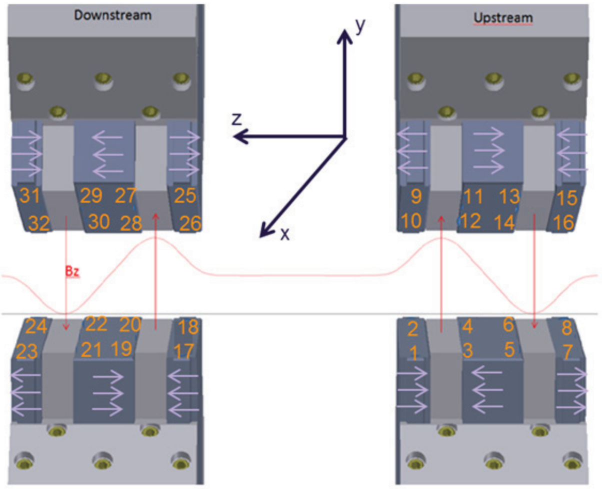

Figure 2: Illustration of the four modules of a phase shifters and definition of the 32 different magnet positions.

Table 2: Combination of Shims and Functions

Combination Type	Expression	Function
"O"+"O"	2f(x)	Integral doubles, gradient doubles;
"O"+"M"	f(x)+f(-x)	Integral doubles, gradient eliminates
"O"+"R"	f(x)-f(x)=0	Integral eliminates, gradient eliminates
"O"+"MR"	f(x)-f(-x)	Integral eliminates, gradient doubles
"M"+"M"	2f(-x)	Integral doubles, gradient double & reverse
"M"+"R"	f(-x)-f(x)	Integral eliminates, gradient double & reverse
"M"+"MR"	f(-x)- f(-x)=0	Integral eliminates, gradient eliminates
"R"+"R"	-2f(x)	Integral double & reverse, gradient double & reverse
"R"+"MR"	-f(x)-f(-x)	Integral doubles & reverse, gradient eliminate
"MR"+"MR	-2f(-x)	Integral doubles & reverse, gradient double

The field integral induced by a shim on an "O" position as a function of the transverse position x is described by a function of $f(x)$, $x = 0$ is the axis position. Here $f(x)$ can stand for horizontal or vertical field integral. The contributions by shims on the other symmetry positions can be described using $f(x)$ and applying the according symmetry operation: For "M" shims it goes like $f(-x)$, for "R" shims like $-f(x)$ and for "MR" shims like $-f(-x)$. These relationships regularize important geometric properties for a combination of shims on different positions in terms of both gap dependent field integrals and transverse gradients. Table 2 summarizes the combination function of shims at two different positions. Two things need to be emphasized: 1.) The symmetry operations apply only to shims which have identical geometry. 2.) The shims may be distributed over different locations i.e. on different sides of a pole and/or on poles with different polarity so each position gives a contribution to the field integral.

Full and half magnets are not equivalent and need to be distinguished. In addition each shim produces both a horizontal and vertical field integral.

So there are four cases, which need to be considered separately: Shims on half/full magnets and their effects to vertical/horizontal field. For each case there are the "O", "M", "R" and "MR" positions. The magnet positions related to Fig. 2 for these cases are different.
The magnet positions the "O", "M", "R" and "MR" positions for the four cases are summarized in Table 3.

Table 3: Magnet Positions with "O", "M", "R", "MR" Symmetry for Horizontal/Vertical Field Integrals and Half/Full Magnets

Magnet & work direction	Symmetry Group	Positions Labelled in Fig. 2
Half magnet & Vertical field	"O"	1, 9, 17, 25
	"M"	2, 10, 18, 26
	"R"	7, 15, 23, 31
	"MR"	8,16, 24, 32
Full magnet & Vertical field	"O"	3, 11, 19, 27
	"M"	4, 12, 20, 28
	"R"	5, 13, 21, 29
	"MR"	6, 14, 22, 30
Half magnet & Horizontal field	"O"	1, 15, 17, 32
	"M"	8, 10, 24, 26
	"R"	7, 9, 23, 25
	"MR"	2, 16, 18, 32
Full magnet & Horizontal field	"O"	3, 13, 19, 29
	"M"	6, 12, 22, 28
	"R"	5, 12, 21, 27
	"MR"	4, 14, 20, 30

The symmetry relations described in Table 2 and Table 3 are the basis for the shimming technique:

According to Table 2 the effect of two shims can be eliminated and according to Table 3 the symmetry group for horizontal or vertical field contains different positions. It allows to combine shims to correct the field error in one direction without changing the other direction. On the other hand, according to Table 2 the compensation to gap dependent field and gradient errors can also be separated. So small gap dependent field integral and gradient errors can be compensated at the same time.

In order to demonstrate the strategy by using symmetry groups of "O", "M", "R", "MR" in Table 3 the impact of a shim of dimension 36x8x0.4mm placed on a full magnet was measured.

Following Table 3 eight different positions 3, 4, 5, 6, 11, 12, 13, 14 out of the 16 allowed for the vertical field integrals of full magnet were selected for the test. Fig. 3 demonstrates the results. Fig. 3 top shows the original data for these eight measurements. Sign and dependence depends on the symmetry group. Two measurements were made on each symmetry position "O" at 3, 11; "M" at 4,12; "R" at 5,13; "MR at 6,14. All pairs are in good agreement. In Fig. 3 bottom the curves are transformed back to "O". Using the relations of table 3 and table 2 the overlap of these curves is quite good demonstrating that the assumptions on symmetry hold well.

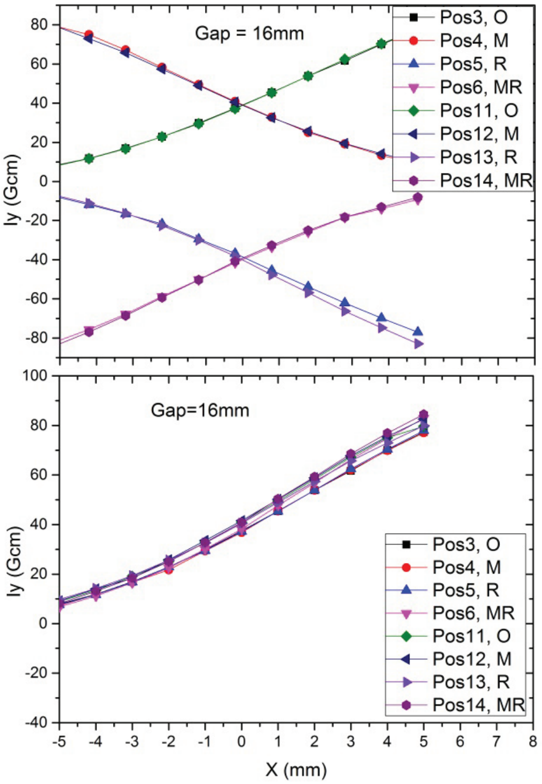

Figure 3: Measurements for test the positions in groups of "O", "M", "R" and "MR". Top: Impact on the vertical field integral of a shim of 36x8x0.4mm on 8 different positions. Bottom: Data transformed back using the symmetry group in Table 3.

FIELD INTEGRAL TUNING

For the large scale production of the 91 Phase Shifters a fast tuning method was developed. It is based on: a) measured signatures of a selection of 5 types of shims with different geometries on half and full magnets, b) the consequent use of the symmetry properties described in tables 2 and 3, c) the application of the linearity and superposition principle and finally d) the numerical optimization using superposition of combinations of shims and their signatures by trial and error with subsequent evaluation of field integrals and gradients. Discrete steps were selected for the thickness of the shims: 50, 100, 200, 300, 400 and 500µm.

Shimming Signatures

For the numerical optimization the dependence of horizontal/vertical field integrals and on-axis gradient on the Phase Shifter gap needs to be known for different shim geometries and for full and half magnets. A linear dependency on thickness is assumed. These dependencies are called “Signatures”. Many different shim geometries were investigated. Five shims with different dimensions and positions were selected for further work. The criterion was that their signatures were quite different. Fig. 4 top illustrates the gap dependence of the horizontal field integral for these five shims. Fig. 4 bottom shows the dependency of the vertical field integrals on x at a Phase Shifter gap of 10.5mm. At this gap field integrals and gradients are highest. The gradient for the optimization is represented by the slope at x=0.

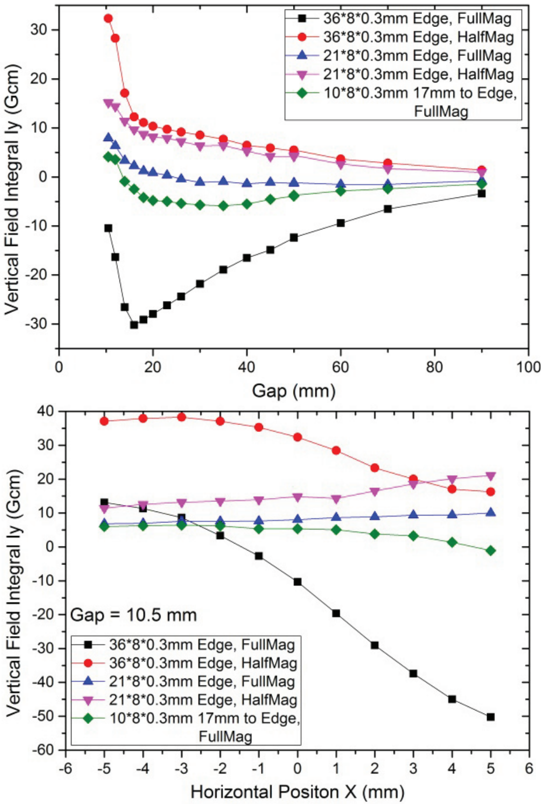

Figure 4: Signatures of the five types of shims selected for the tuning. Top: Signatures for gap dependent field integrals. Bottom: the signature for the gradient was evaluated from the slope of the Field integral vs. x at x=0. Shim dimensions are given. The positions with respect magnet edges are indicated.

Tuning Results

Results for the vertical field integrals and gradients are shown in Fig. 5. One of the prototype phase shifter was used for demonstration of these results. Fig. 5 top demonstrates the efficiency of the tuning. A large deviation, especially at large gaps, could be reduced so that it fits into the specs window, see table 1. The gradient is low enough that these specs are preserved inside the good field area of ±0.5mm around the axis. This is explicitly shown in Fig. 5 bottom by the dependence on x at the minimum gap of 10,5mm before and after tuning.

SUMMARY

A systematic strategy for the field integral tuning for the phase shifter of the European XFEL was developed. It is based on measured signatures of a set of known shims using the linearity and superposition principle. A shim configuration, which minimizes field integral errors and transverse gradient, is found by numerical simulation on a large number using a numerical trial and error method. This is a fast method to tune the field integrals and gradients for the Phase Shifters for the European XFEL to specifications or even below. It is being now used for the mass production of these devices.

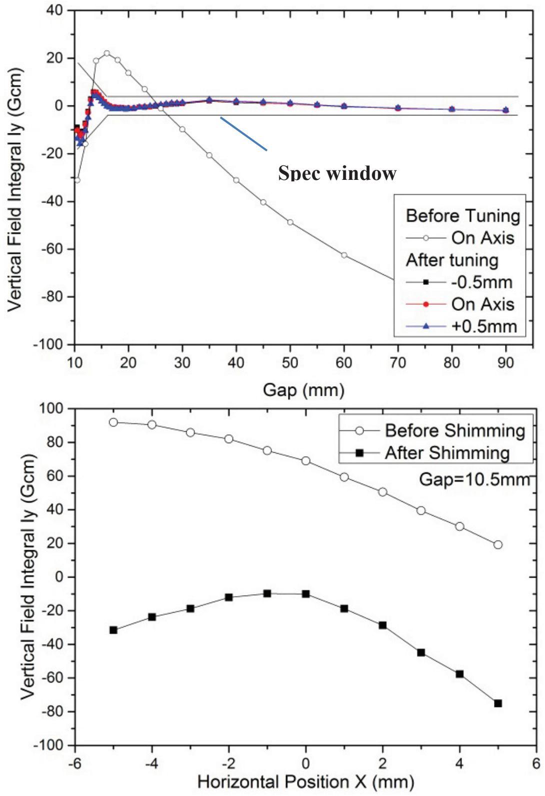

Figure 5: Demonstration of the tuning of the vertical field integrals. Top: Open symbols, status as found. Full symbols: Field integral after tuning: On axis red and at ±0.5mm blue, black. The specs window, see table 1, is indicated for comparison. Bottom: The low gradient is demonstrated by the X-dependence at 10.5mm gap before and after tuning.

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