CONTROL OF GAP DEPENDENT PHASE ERRORS ON THE UNDULATOR SEGMENTS FOR THE EUROPEAN XFEL

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Abstract

Strong magnetic forces in long undulators always result in some girder deformation. This problem gets more serious in long gap tuneable undulators. In addition the deformation varies with changing forces at different gaps resulting in gap dependent phase errors. For the undulators for the European XFEL this problem has been studied thoroughly and quantitatively. A compensation method is presented which uses a combination of suitable shims and pole height tuning. It is exemplified by tuning one of the undulator segments for the European XFEL back to specs.

INTRODUCTION

The European X-ray free electron laser (EXFEL) facility is currently under construction [1]. It uses a superconducting accelerator with a maximum energy of up to 17.5 GeV and the concept of Self-Amplified-Spontaneous-Emission (SASE) [2,3]. Three gap tuneable undulator systems called SASE1, SASE2 and SASE3 are used. SASE1 and SASE2 are hard X-ray FELs using 35 undulator segments each with a period length of 40mm, called U40s. Their total length is 205m. By a suitable choice of beam energy and undulator gap the wavelength can be tuned from 0.05 to 0.4nm. SASE3 is a soft X-ray FEL using 21 undulator segments with a period length of 68mm, called U68s and a total length of 121m. Its wavelength can be tuned from 0.4 to 5.2nm. All undulator segments of the EXFEL are 5m long and use identical mechanical drive and support systems, which are designed to comply with worst case requirements. Table 1 gives a summary of specifications for the Undulator Systems for the EXFEL.

Table 1: Specifications of the Undulator Segments for the EXFEL

	SASE1/2	SASE3
Undulator Type	U40	U68
Period Length [mm]	40	68
Segment Length [m]	5	5
Operational Gap Range [mm]	10-20	10-25
K-Parameter Range	1.65 - 3.9	4 - 9
Max. Phase Error [Degree]	≤ 8	≤ 8
Radiation Wavelength [nm]	0.05-0.4	0.4 – 5.2

A strong magnetic force is acting between the girders of an undulator, which is proportional to the square of magnetic field and therefore strongly gap dependent as well. For example in an U68 operated at lowest gap of 10mm the maximum magnetic force amounts to about 17 tons. This leads to unavoidable mechanic deformation of the girders, resulting in a modulation of the parallel gap profile. Although it can be minimized by a suitable mechanic design, it cannot be avoided completely. Moreover, for given girder cross section, deformation increases with the 3rd power of its length. Therefore the mechanical design of the girders for the 5m long undulator segments for the EXFEL needed to be a compromise between acceptable girder deformation and technical effort i.e. amount of material and cross section.

In this paper the effects of girder deformation on EXFEL U40 undulator segments are studied and their gap dependence and impact on magnetic and optical properties are investigated. A method using a combination of shims and pole height tuning is described, which can be used to effectively reduce optical phase errors resulting from girder deformation. It is exemplified on an U40 undulator segment for the EXFEL.

PHASE ERRORS INDUCED BY GAP DEFORMATION

On all EXFEL undulators gap dependent parabolic deformation is observed to some extent. Pole Height Tuning (PHT) is used as the standard tool for field error correction, which allows to shift each pole verticall by about $\pm 300\mu m$ [4]. It is a perfect tool for static corrections of any deformation at one gap. In order to limit overall deformation and its effect on phase jitter a “Tuning Gap” was selected, which is about halfways inside the operational gap range. 14mm and 16mm were selected for U40s and U68s, respectively. At the tuning gap any deformation of the poles is completely eliminated using PHT. The resulting deformation profile of the poles is sketched in Fig.1 a-c): At lowest gap, Fig. 1a), there is only moderate concave gap deformation. At the tuning gap, Fig. 1b), there is none. Above the tuning gaps the gap deformation gets convex. Two points should be emphasized: 1.) Girder deformation is small and the typical pole height adjustments to compensate deformation are in the range ±50-60µm or less. 2.) The focus is on pole deformation. The deformation of the aluminum support girders cannot be changed. They are perfectly flat only under force free conditions at large gaps and gradually deform from flat to concave towards small gaps. This situation is sketched in Fig. 1a-c) as well.

The result of girder deformation is that the K-parameter slightly varies parabolically along the undulator axis by typically a few tenth of a percent as shown in Fig.1. As a result the phase error varies [5]:

ISBN 978-3-95450-134-2

$$\delta\varphi(z) = -\frac{4\pi}{1+2K^{-2}}\frac{\Delta g}{{\lambda_u}^2}\left(b + \frac{2cg}{\lambda_u}\right)\left(\frac{4}{3L_U^2}z^3 - \frac{1}{5}z\right). \quad (1)$$

L_U is the undulator length. Δg is the local gap at undulator ends minus the local gap in the middle as defined in Fig.1), z is the longitudinal position in undulator, λ_u is the undulator period: The constants b and c are the fitting parameters for undulator field:

$$B_0 = a\cdot\ exp\left[b\left(\frac{g}{\lambda_u}\right) + c\left(\frac{g}{\lambda_u}\right)^2\right] \quad (2)$$

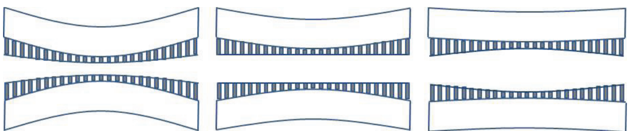

Figure 1: Girder and pole deformation on the EXFEL undulators with applied pole height tuning. (a) At small gaps Δg>0, concave case; (b) At the tuning gap Δg=0, flat case; (c) At large gaps Δg<0, convex case. The aluminium support girders gradually deform from convex at small gaps to flat at very large gaps.

For a purely parabolically shaped deformation like the one shown in Fig. 1 the resulting phase error has odd-symmetry with respect to the undulator center. The RMS phase jitter σ_φ obtained from $\delta\varphi(z)$ can be calculated from Eq. (1):

$$\sigma_\varphi = \sqrt{\frac{16}{1575}}\,\pi\,\frac{\left|\frac{b}{\lambda_u}+\frac{2c\,g}{{\lambda_u}^2}\right|}{1+2K^{-2}}N_U|\Delta g| \quad (3)$$

σ_φ is proportional to the product of the undulator period number N_U and the gap deformation Δg.

Using Eq. (3) the maximum gap deformation Δg is a function of the gap. The tolerance for the phase jitter, 8°, taken from table1 is a conservative choice and originated from Genesis1.3 studies reported in Ref. [5]. It depends on the absolute value for Δg in Eq.(3) meaning it is symmetric for positive and negative Δg corresponding to concave or convex deformation. Thereby a specification window for Δg is defined, as seen by the dashed lines in Fig. 2(a). It is seen that the tolerance for gap deformation increases with increasing gap.

Gap dependent deformation and phase jitter are shown in Fig. 2 for 10 representative U40s of the EXFEL. Considerable variation between individual devices is observed, which can be grouped in the classes: Hollow symbols, (X002, X045 X092, X044) indicate small, half-filled symbols (X043, X055) moderate and full symbols (X005, X006, X007) large gap dependence. All except the one marked with "+", X014, are inside the specification window.

The gap dependence of the phase jitter is shown in Fig. 2 b) for the same devices. Again, all except X014 are below the tolerance limit of 8°. The low deformation devices show low variation of phase jitter as well. On all devices the phase jitter shows a minimum of about 2 degrees near 14mm, which corresponds to the tuning gap.

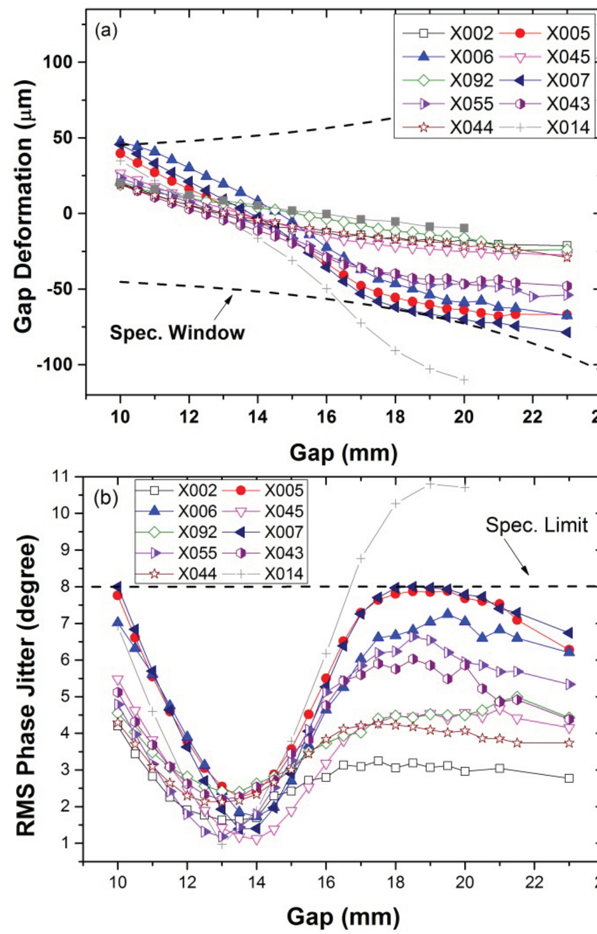

Figure 2: The status of 10 representative U40 undulator segments. a): Gap dependence of deformation. b): Gap dependence of RMS Phase Jitter. Specification limits are indicated.

COMPENSATION OF GAP DEPENDENCE

The reason of the observed variance in girder deformation is not fully understood and still under investigation. Fortunately for all devices except the X014 the Phase Errors are within specs. For this device a time consuming analysis of the mechanical support system and refurbishment was avoided in favour of a timely completion. Instead a compensation method based on using shims was developed, which is described below. It is closely related to the shimming method used at the EXFEL to tune the gap dependence of 1st field integrals of the phase shifters to very low tolerances [6-8].

Description of the Method

As demonstrated in Fig. 1 one can tune pole deformation to a symmetric balance between concave at small and convex at large gaps. However, total deformation cannot be reduced in this way. If it is too large the phase jitter gets out of the specification window as shown in Fig. 2 b). Using suitable shims, however, is an effective method to induce targeted gap dependent modifications of the magnetic field distribution [9-12].

Shims made of 0.1-0.4mm soft iron foil are used, which have the same dimensions like the magnet surface

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[9, 10]. If placed on a magnet in between two poles the field of these two poles is weakened as sketched in Fig. 3. For symmetry reasons there is no net steering. This leads to a K parameter change of ΔK resulting in a phase jump of:

$$\Delta\varphi = 2\pi \frac{K \cdot \Delta K}{1+0.5K^2} \quad (4)$$

For shims ΔK is always negative and $\Delta\varphi$ is negative as well.

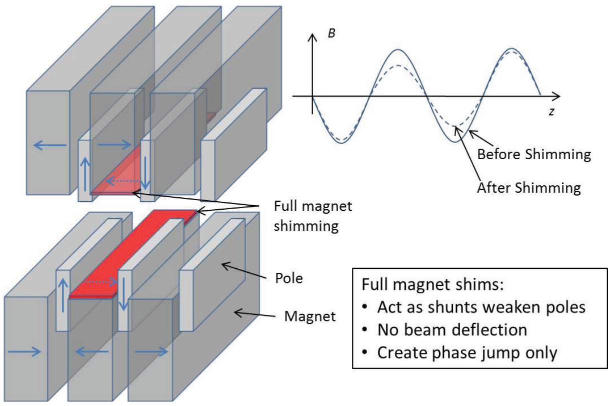

Figure 3: Principle of full magnet shims.

Alternatively a phase "jump" $\Delta\varphi$ can also be generated by pole tuning: By symmetrically changing the local gap of a pair of neighboring poles the sign of ΔK can be chosen and the strength can be varied continuously by increasing or decreasing the local gap. This is a marked difference to shimming.

The gap dependencies of shims and pole tuning were investigated experimentally. The results are presented in Fig. 4. Measurements were done using the U40-X014 again. On one period the pole height of two poles was adjusted symmetrically by -0.05, +0.025, +0.05 and +0.1mm. On another period sufficiently distant away full magnet shims of 0.1, 0.2, 0.3 and 0.4mm thickness were applied. The phase jump was measured for the operational gap range from 10 to 20mm in 2mm steps. The results are shown in Fig. 4a). The abscissa shows the amount of pole height tuning or the shim thickness, respectively. The amount of phase jump is given by the ordinate. For pole height tuning shown in the left upper part of Fig. 4a) it is observed that the phase jumps are proportional to the amount of tuning but for all gaps the jumps are identical. There is no gap dependence. Positive and negative jumps are possible. For shims the situation is different: There is significant gap dependence and all jumps are negative.

In addition Fig. 4a) gives a good impression of the linear dependence of the phase jumps on small pole adjustments or small shim thicknesses, which is an important assumption for both methods [6, 9, 10].

Phase jumps normalized to pole shifts or shim thicknesses are called signatures and are shown in Fig. 4b). Note for the sake of a direct comparison the sign of the signature for pole height tuning was reversed. These signatures are the basis for gap dependent phase tuning. It is obvious that shims and pole height tuning have different gap dependencies. This effect is used for compensation.

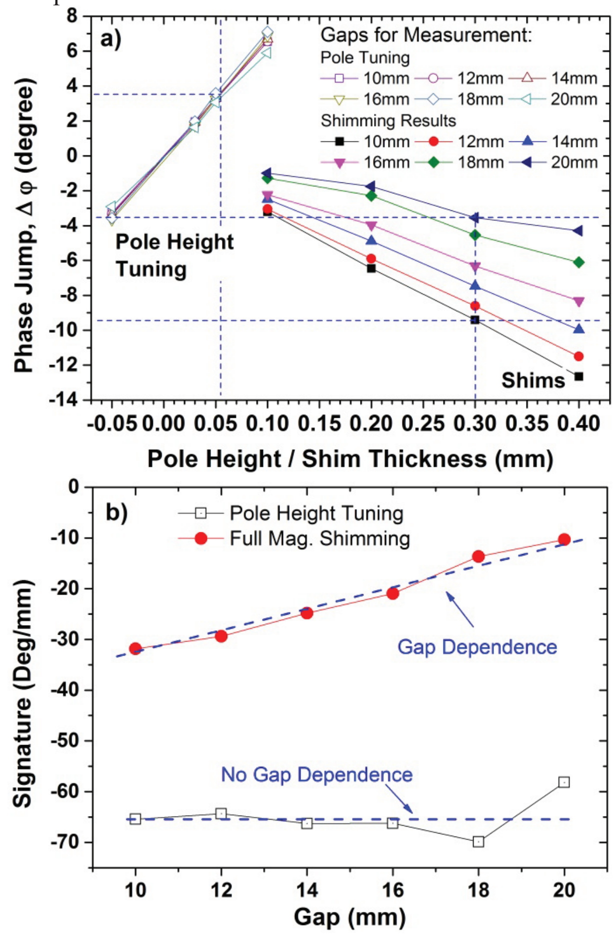

Figure 4: a) Gap dependence of phase jumps $\Delta\varphi$ induced by tuning the height of a pair of poles and by shims of different thicknesses. The abscissa shows the amount of pole tuning or shim thickness. The dashed lines should guide the eye for the determination the shimming strengths, see text. b) Resulting signatures. For pole height tuning there is no gap dependence. Note, for direct quantitative comparison the sign of the signature of pole height tuning was reversed. The undulator X014 was used for the measurements.

Phase Tuning Example

The X014 is used as the example to demonstrate the tuning strategy. The original gap deformation and phase jitter after the standard EXFEL tuning procedure using a tuning gap of 14mm was already illustrated in Fig. 2: The gap deformation and phase jitter at small gaps is within and at large gaps is outside specs.

In a first step poles where retuned so that at 20mm gap the phase jitter is well within specs. This is done by shifting the tuning gap to 16mm where now the phase jitter is 1.19° only, see Fig. 5. This is the main work, since it requires to slightly retune all 248 poles of the undulator. Now at 10mm and 20mm 12.85° and 5.36° are obtained, respectively. Since pole tuning cannot reduce total deformation only the gap range of the phase error was shifted. Now the low gap region is out of specs as seen in Fig. 5.

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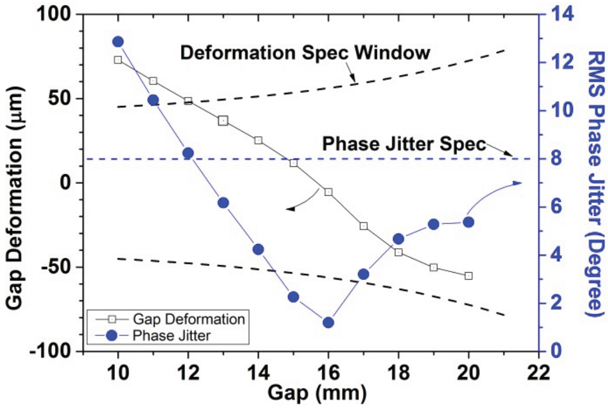

Figure 5: Effect of shifting the "Tuning Gap" to 16mm. Now at 20mm specifications on gap deformation (open squares) and the RMS phase jitter (full circles) are fulfilled, but exceeded at small gaps.

Next, the K-parameter for phase error calculation is slightly reduced resulting in an additional error, see Fig. 6 black and red curve. The K-Parameter is chosen such that the phase error at begin and end is about the same. For this purpose the K-parameter was reduced slightly by 0.0035 or 0.089% from 3.9009 to 3.8974. This initially increases the total phase error. But now there is a long section from z≈ -1300 to 1300mm where the phase error increases almost linearly with positive slope and the end sections with negative slope are shorter.

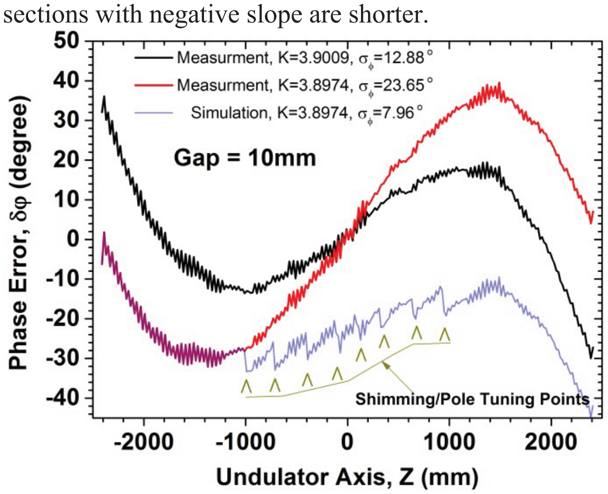

Figure 6: Phase error $\delta\varphi$ at 10mm gap. Black: K=3.9009, resulting in minimum RMS phase jitter of 12.88°. Red curve: K=3.8974 Phase error at start and end are approximately same. Blue: Expected phase error with K=3.8974 after shimming. The expected RMS error is 7.95°

In the linear section phase shims are placed, each reducing the phase error by a step amount. Parameters were selected by the following consideration using Figs. 6 and 4a): *(a)* In Fig. 6 the positive increase of phase errors in the center region extends from -30 to +40°. Only about 50° should be compensated by shims in order to limit the impact of the outer end sections with negative slope on the RMS phase jitter. However the properties at 20mm must stay unaffected. *(b)* In order to do so at that gap the effect of phase shims and pole height tuning must cancel mutually. Using the dashed lines as guides for the eye in Fig. 4a) it is seen that a 0.3mm shim at 20mm creates a negative phase jump of -3.5° which needs to be compensated by a pole shift of +0.055mm, which creates +3.5°. At 10mm this shim creates a phase jump of -9.5° while the pole contribution is constant at 3.5°. The net effect is -6° per shim/pole pair and consequently eight corrections are needed to compensate +48° and approximately fulfill the requirement. The effect of applying these corrections was simulated and is shown by the blue curve in Fig. 6. The RMS simulated phase jitter is 7.95° and inside EXFEL specs.

The final results for the optical phase are shown in Fig. 7a). The black line shows the measured phase error $\delta\varphi$ at the gap of 10mm. The blue circles show the simulated results shown in Fig. 6 shifted up by 24 degrees to match the same absolute scale. There is very good agreement. Finally Fig. 7b) shows the measured phase jitter as a function of the gap. It demonstrates that the RMS phase jitter at the gap of 10mm is reduced to 7.65 degrees, as expected. It is within specs at all gaps.

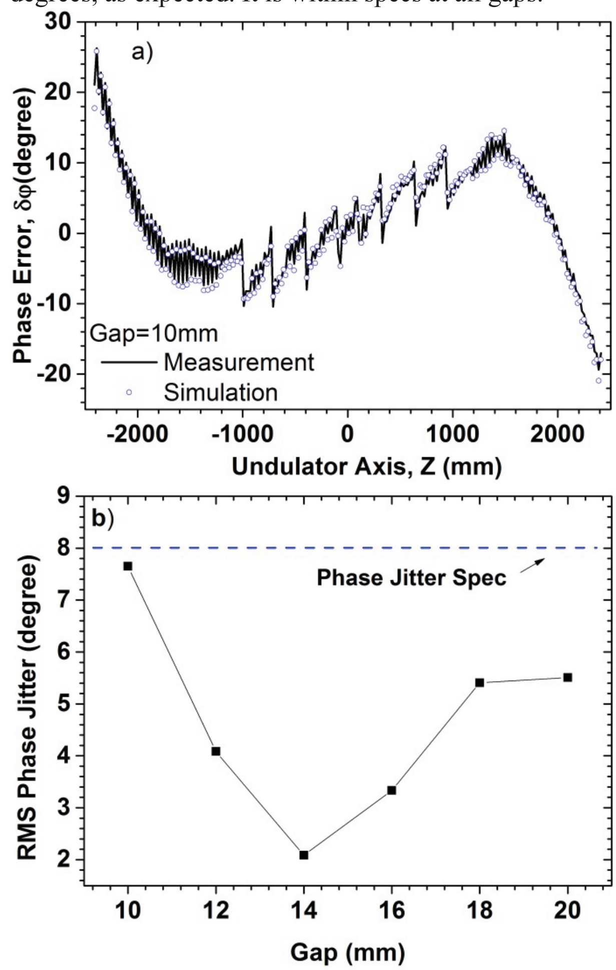

Figure 7. (a) Black curve: Measured phase error $\delta\varphi$ after tuning. Blue open circles: Simulation of Fig. 6 shifted by 24° to match scales. (b) Final gap dependence of the RMS phase jitter as a function of the undulator gap.

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SUMMARY AND OUTLOOK

Gap dependent parabolic girder deformation is commonly observed on the Undulators for the EXFEL and is found to be the dominant source for the RMS Phase Jitter. Analytical formulae are developed which allow a quantitative evaluation and the definition of specifications. Results can be universally applied.

Considerable variation of girder deformation has been observed throughout the undulators built for the EXFEL so. While most are well within specs some come close, but only one out of 91 was found to be out of specs and girder deformation could not be tolerated.

For mitigation a systematic method using shims was developed and is presented in detail. It makes use of the different gap dependencies of full magnet shims and pole height tuning as used for tuning of the EXFEL devices. Measured gap signatures for both cases are used. With this method the RMS Phase Jitter observed initially on one device, which did not comply with specs, could be reduced by about 5° with very moderate effort and brought back to specifications.

Using the method described in this report an EXFEL U40 was treated: The negative effects resulting from gap dependent girder deformation of 110µm were compensated without negative side effects.

A potential application of the method, which would be straight forward to realize could be to significantly reduce the gap dependence of the phase jitter well below the specs given in the paper. This was not needed for EXFEL but might be of great use for long undulators in storage ring operated on high harmonics. For the EXFEL devices a phase jitter of 2° or less over the whole operational gap range seems feasible. Alternatively, the girder stiffness could be reduced by tolerating more mechanical gap deformation. Thus a trade-off between mechanical effort and moderate increase of magnetic measurements and tuning can be obtained.

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ISBN 978-3-95450-134-2