STUDY OF UNDULATOR TOLERANCES FOR THE EUROPEAN XFEL

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Abstract

For an X-ray FEL facility, error tolerance simulations for undulator systems are necessary. Previous work mainly took into account random errors for each pole and then simulate their impact. However, some errors, for instance the girder deformation, are not random but periodic. In this paper both random and periodic errors as well as a combination are studied. The results are limited to non-steering errors, i.e. a reduction in overlap between electrons and photon beam has been avoided throughout this study.

Key words: tolerance, undulator, XFEL

INTRODUCTION

In the European XFEL project, photons will be generated in the X-ray range of 3.1 keV to 12.4 keV [1]. High power radiation will be generated using Self-Amplified Spontaneous Emission (SASE). Saturation will be rezched within a typical length of 100 to 150 m [2, 3]. Undulator errors unavoidably exist in this long undulator system. A first estimate for an upper limit on these errors is related to the SASE-FEL bandwidth ρ:

$$\frac{\Delta\lambda_s}{\lambda_s} \approx \frac{2\Delta K}{K} < \rho \tag{1}$$

With the value of ρ of the order of 10^{-4} for the European XFEL project, undulator gap variation should smaller than 1 μm and the temperature variation should be smaller than $0.08^o C$ [4]. If Eq. (1) could be satisfied, the power degradation and saturation length increase would be minimal. Because this is far from trivial and a mayor cost driving factor, a more detailed study is neccessary.

The European XFEL facility will supply 0.1 nm to 0.4 nm radiation. Wavelength tuning can be achieved by changing the undulator gap or the electron beam energy. Even though the tolerance level for different modes is different, their behaviour is similar. Therefore in this paper we only list the result of SASE1 with 0.1 nm mode which has the tighest tolerance requirement. A more complete study can be found in [5].

Two kinds of undulator field errors can be distinguished. One kind is random error on each undulator pole. This kind of error can be caused for example by the inhomogeneous field of magnet blocks [6]. Another kind of error changes along undulator as periodic or semi-periodic function. This kind of error exists for instance because of the girder deformation or gap tilt [7]. The previous tolerance simulation work concentrated mainly on the first kind of error. Thus this report only studies the latter one.

Some papers investigating the impact of undulator field errors show that beam wander and phase shake are the key reasons for the increase of gain length [8, 9]. Beam wander reduces the transverse overlap between electron beam and radiation. Phase shake indicates an electron ponderomotive phase variation and therefore a reduction in bunching. In this paper only the impact of phase shake is taken into account.

The FEL simulation code Genesis 1.3 is used for our simulations [10].

DESCRIPTION OF BASIC ERROR TYPES

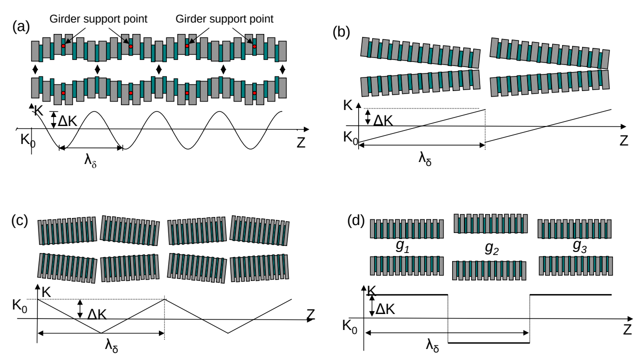

Figure 1: The induced undulator error by girder deformation and gap tilt (a) sinus, (b) sawtooth, (c) triangle and (d) constant

The periodic errors are divided into four basic types: sinus, triangle, sawtooth and (stepwise) constant. The sinus error is used to approximate undulator girder deformation due to the magnetic forces which can be compensated for one gap setting only. Fig. 1 (a) shows this effect. For the European XFEL, a four point support structure is used in order to minimize this effect. A periodic error can also be generated by the inhomogeneous movement of the undulator driving motors. Fig. 1 (b), (c) and (d) illustrate so generated three kinds of periodic errors (sawtooth, triangle and constant). The movement accuracy is assumed to be 1 μm.

Finite motor movement accuracy results some in residual random errors of which the importance has to be quantified. For this purpose, the same error model as shown in Fig. 1 is used, but in this case the resulting amplitude variation ΔK is random. In contrast to this, the undulator girder deformation is always homogeneous and thus a periodic error can always be expected. Therefore, in this paper the simulation of random sinus errors is not investigated. Fig 2 illustrates this random error.

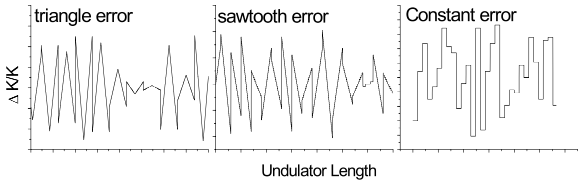

Figure 2: The random error for the three error types. The error amplitude randomly changes from error period to error period.

PHASE SHAKE CALCULATIONS WITH PERIODIC ERRORS

As already mentioned, phase shake is an important reason for radiation power degradation. For the periodic error considered in this paper, the phase shake can be analytically calculated. The undulator parameter K can be written as

$$K(z) = K_0 + \Delta K \cdot f(z) \tag{2}$$

where K_0 is the nominal undulator parameter, $\Delta K \cdot f(z)$ denotes the undulator error. ΔK expresses the error strength and $f(z)$ ($\langle f(z) \rangle = 0$, $\langle f^2(z) \rangle = 1$) the error shape.

It can be shown that the RMS phase shake for a periodic error ($f(z) = f(z + \lambda_\delta)$ with λ_δ the error period) can be approximated by:

$$\sigma_{\Delta\varphi} = \frac{k_u K_0^2}{1 + K_0^2} \cdot \alpha \frac{\Delta K}{K_0} \lambda_\delta \,, \tag{3}$$

where α is a coefficient depending on the error shape. The coefficient values are $1/\sqrt{2}\pi$, $1/\sqrt{30}$, $1/\sqrt{45}$ and $1/\sqrt{12}$ respectively for the sinus, triangle, sawtooth and constant error.

It is important that the RMS phase shake is proportional to the product of $\Delta K/K_0$ times the error period λ_δ. To illustrate this more clearly, Fig. 3 shows simulation results with a periodic sinus field error. One can see that the ΔK of black the sinus error is five times larger than the red error, whereas the error period λ_δ of the black error is ten time shorter than the red error. From Eq. (3) the red error therefore has a larger RMS phase shake. Consequently, the power growth along the undulator with the black error is expected to be closer to the ideal than the red one. This is indeed confirmed by the blue dotted line in the bottom plot of Fig. 3, which is the power growth for the ideal undulator.

ERROR SIMULATION FOR SASE1

In this section we introduce the method of our error tolerance calculation and the results for SASE1, 0.1 nm mode.

Simulation method

As mentioned for each operation mode four error types (sinus, sawtooth, triangle, constant) are simulated. For each error type, the simulation is divided into two steps:

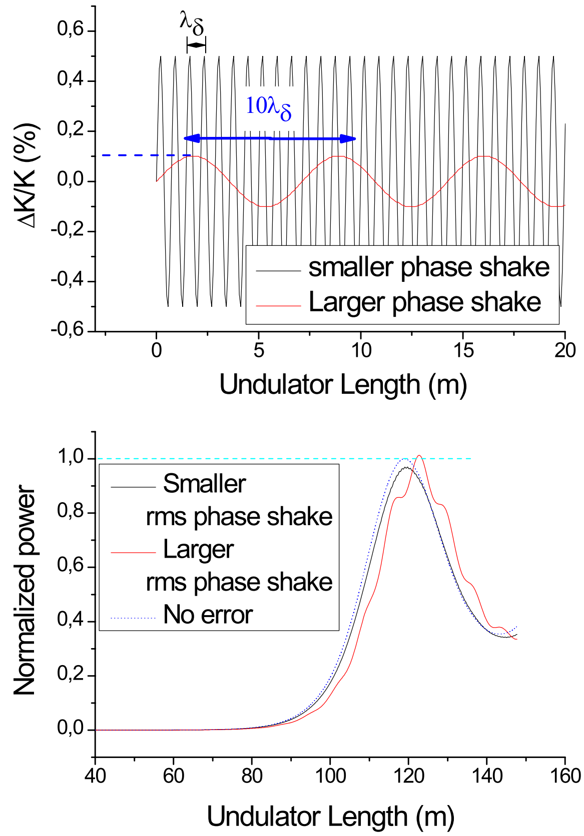

Figure 3: Two sinus error's with different amplitude and period and its impact on the power growth. The ΔK of the black line is larger but because of its shorter λ_δ its rms phase shake is smaller. Thus its power degradation is smaller thanthat of the red curve.

first simulating the periodic error and then the random error. The error models for different types are shown in Fig. 1.

First we calculate the periodic error impact. From Eq. (3) we know that the the RMS phase shake can be changed either by adjusting the error strength $\Delta K/K_0$ or the error period λ_δ. Because the power degradation is determined by the RMS phase shake, any product of $\Delta K/K_0$ and λ_δ with the same phase shake corresponds to a certain power degradation. Therefore first we have taken 9 different error strengths: $\Delta K/K_0 = 0.1\%, 0.15\%, \ldots, 0.5\%$. For each $\Delta K/K_0$, 30 different error periods $\lambda_\delta/\lambda_u = 10, 20, \ldots, 300$ are chosen. Thus the power growth with totally 270 combinations of $\Delta K/K_0$ and λ_δ is calculated.

So far the simulation for periodic error is done. Then the random error is simulated. We choose three points (combination of $\Delta K/K_0$ and λ_δ) where $10\%, 20\%, 30\%$ power degradation can be expected. Thus totally 9 points are chosen. For each point, we fix the λ_δ and set a suitable κ that if $\Delta K_i/K_0$ (i denotes the random error strength in ith period) randomly varies in the range of $[-\kappa, \kappa]$, the RMS phase shake is close to the value of the periodic error. For each combination 100 random simulations are performed and totally 900 random errors are calculated.

Simulation result for periodic error

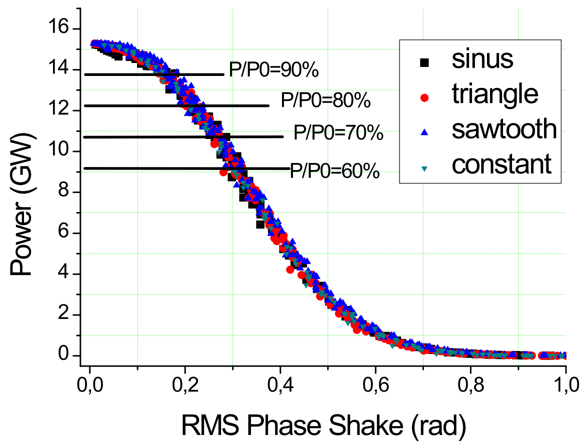

Figure 4: The power degradation versus RMS phase shake at a fixed point inside the undulator before saturation is reached. There is a perfect correlation between power and phase shake, independent of what error shape has been used.

It is interesting to illustrate the power degradation with different RMS phase shake values and different error types. Fig. 4 shows the result. The correlation between the power degradation and the RMS phase shake is good and same RMS phase shake generated by different error types results in the same radiation power. Based on this result we can imagine that for any kind of error type which is not included in our simulation, the power degradation can also be evaluated by the RMS phase shake.

Table 1: Summary of results of tolerance simulations for SASE1, 0.1 nm mode. The numbers quoted here correspond to a power reduction of 10%.

Type	RMS phase shake	λ_δ	$\Delta K/K_0$	Δg (mm)
sinus	0.146	1.2m	0.366%	0.030
triangle	0.156	10m	0.058%	0.005
sawtooth	0.165	5m	0.148%	0.013
constant	0.183	10m	0.043%	0.004

Table 1 shows the tolerance result for SASE1, 0.1 nm mode with a 10% power reduction. From this table one can see that a sinus girder deformation as large as 30 μm can be tolerated which is considerably larger than the estimate based on the Pierce parameter ρ. On the other hand a λ_δ of 10 to 12 m still requires gap control in the μm level. This, hoever, is technically no problem.

the from all of the error types, the girder deformation or the gap movement accuracy can relax to a value larger than 1 μm, which is evaluated by the Perice parameter ρ. On the other hand, the longer periodic length λ_δ brings tighter error strength $\Delta K/K_0$.

Simulation result for random error

Fig. 5 shows the correlation between the power degradation and the RMS phase shake for the random sawtooth error. Comparing to the correlation of periodic error, for the random error the power degradation still correlates to the RMS phase shake. The mean power value for a certain RMS phase shake is similar for random and periodic distributions, but the spread for random errors is larger.

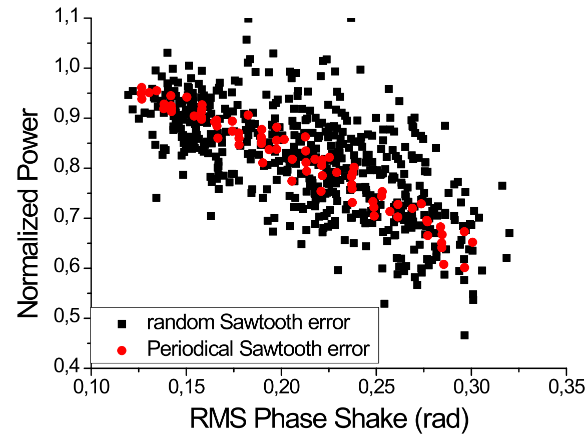

Figure 5: Power versus phase shake in case of a sawtooth error. The back squares show the results of random sawtooth amplitude and length scale. The red circles show the periodic sawtooth errors that are already shown in Fig. 4.

COMBINED ERRORS AND TEMPERATURE COMPENSATION

Combination of different errors

In the sections before, the impact of four different error types have been illustrated separately. Because in practice these errors are combined it is also necessary to study the impact of this kind of combined error.

In principal the sinusoidal girder deformation can be assumed to be always periodic. While the triangle, sawtooth and constant error are all generated because of the inaccuracy of motor movement, they are random. 20 μm of girder deformation, 2 μm motor movement accuracy and 10 μm of girder deformation, 1 μm motor movement accuracy are simulated.

The power degradation and the RMS phase shake are shown in the Fig. 6. One can see that the larger error values bring larger RMS phase shake and therefore the power degradation is larger. The largest power degradation value is about 40%. In addition, the large variation in power is mainly due to the random error, as was already shown in Fig. 5. This means that even though the girder deformation is an order of magnitude larger than the random gap error, the power degradation is not dominated by it, which confirms the result shown in Table 1.

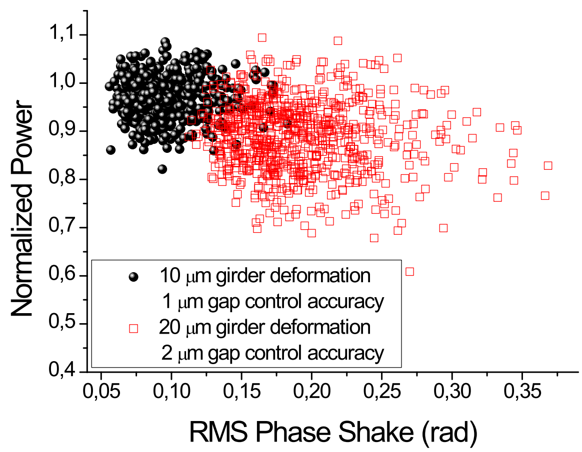

Figure 6: The power reduction due to the combined periodic sinus and random sawtooth/constant error.

Linear temperature gradient and compensation by adjusting the undulator gap

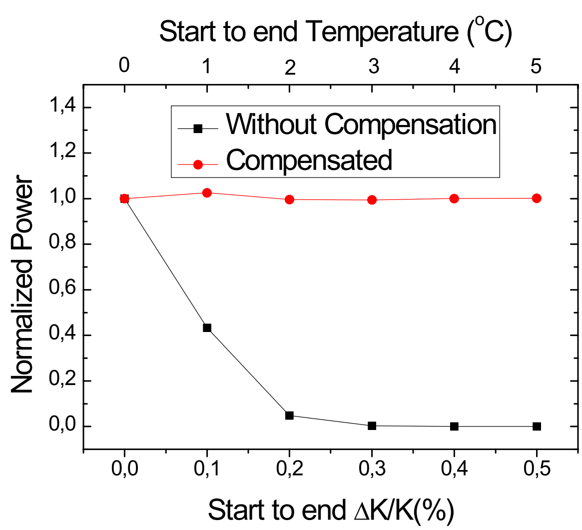

Figure 7: Power reduction due to a temperature gradient over the entire undulatorlength of up to 5 ^oC and the compensation by an appropriate adjustment of the undulator gap. The gap has been adjusted by 1 μm as soon as the measured temperature exceeds 0.1 ^oC.

Over the length of the undulator system the temperature may differ. These effects were investigated. From Eq. (1) 0.08^oC are estimated for total temperature variation. This requires a sophisticated air conditioning system with demanding properties. As a simple rule, due to the reversible temperature coefficient of the permanent magnet material 0.1^oC temperature variation corresponds to $\Delta K/K_0 = 10^{-3}$. The effect of the linear temperature variation over the whole undulator system is plotted against the radiation power in Fig. 7, black points. It is seen that a $1\,^oC$ variation reduces the power by more than 50%. For $2\,^oC$ and above there is no radiated power anymore. An effective way of compensating this effect is to locally correct the undulator gap according to the local temperature. This requires a precise local temperature measurement and a precision temperature sensor on each undulator segment. The local gap is adjusted if a threshold set by the accuracy of the sensor is exceeded. We assume 0.1^oC, which is demanding on an absolute scale. The red points in Fig. 7 show the results. The power loss can be recovered completely.

In terms of Eq. (3) the product $\Delta K/K_0 \cdot \lambda_\delta$ is 0.14 for 1^oC, $\Delta K/K_0 = 10^{-3}$, 140 m error length versus 1.8×10^{-4} for $\Delta K/K_0 = 3.57 \times 10^{-5}$ and 5 m the length of an undulator segment, which is an alternative way of explaining the above result. As shown in Fig. 7 temperature variations as much as 5^oC can be compensated completely.

SUMMARY

Error tolerances for the undulator system of the European XFEL are analyzed in this paper. It has been shown that for non steering errors, the RMS phase shake is a good number to predict the power reduction in an undulator system. For periodic errors the phase shake can be calculated analytically by the product $\Delta K/K_0 \cdot \lambda_\delta$ times a constant depending only on the error shape. Thus for small error period length comparatively large errors can be tolerated, whereas for large error periods the error level are very small. Local temperature measurement and local gap correction was shown to effectively compensate power losses caused by global temperature variation. This method can be effectively used to reduce requirements on temperature stabilization.

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