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An analytical study to determine the mechanical tolerances for the afterburner superconducting undulators at EuXFEL

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Abstract. At the European XFEL, a superconducting afterburner is planned for the SASE2 hard X-ray beamline. It will consist of 5 undulator modules plus a pre-series module called S-PRESSO. Within each module, two superconducting undulators (SCU) 2 m long are present. Such an afterburner will enable photon energies above 30 keV.

The magnetic field of the SCU determines the quality of the electron beam trajectory and the free-electron laser (FEL) radiation. The mechanical accuracy of the SCU determines its magnetic field quality. In this contribution, we present the mechanical errors and an analytical study to determine the tolerances for our SCUs.

1. Introduction

European XFEL considers the development of superconducting undulators a strategic field of research for future facility upgrades. Recently, the European XFEL has approved the project for the installation of a superconducting afterburner downstream the permanent undulators of the SASE2 hard X-ray beamline. The afterburner consists of a series of five modules. Each module accommodates two 2 m long superconducting undulators (SCU) interleaved by a phase shifter [1]. The intersection between consecutive modules copies the one between the permanent magnet undulators of the SASE2 beamline. By this time, we have specified a pre-series module named S-PRESSO and assigned its contract to the company Bilfinger Noell GmbH [2].

The FEL radiation originates from the constructive interference between the photons emitted by the electron beam at each undulator period. This process degrades when the SCU presents mechanical errors, which affect the magnetic field B, the period length λ_u and therefore, the undulator parameter $K = 93.4B[\mathrm{T}]\lambda_u[\mathrm{m}]$. In this contribution, we discuss the mechanical tolerances for a SCU undulator line to guarantee an FEL performance above 95%.

2. Impact of mechanical errors on the FEL performance

In [3], we have studied the FEL degradation in presence of mechanical deviations with GENESIS simulations [4]. This study presents the lasing performance of an SCU SASE line, where the single SCU has a length of 2 m, a period length $\lambda_u = 15\,\mathrm{mm}$ and the undulator parameter $K_0 = 2.24$.

We have performed two sets of simulations: one with ideal SCUs, having undulator parameter $K = K_0$ and the second one considering the mechanical errors. For the latest, each pole of the undulator has a different undulator parameter K. The program that prepares the input lattice file extracts the K from a truncated Gaussian distribution centred in K_0, with RMS deviation σ and cut at 4σ. In the following, we will refer to the K distribution as relative distribution of the parameter $\frac{\Delta K}{K}$ with RMS $\sigma\left(\frac{\Delta K}{K}\right)$. The simulation achieved a FEL power output better than 95% respect to the ideal FEL case by considering a truncated Gaussian distribution with

$$\sigma\left(\frac{\Delta K}{K}\right) = 1.5 \times 10^{-3}$$

and cut at $4\sigma = 6 \times 10^{-3}$.

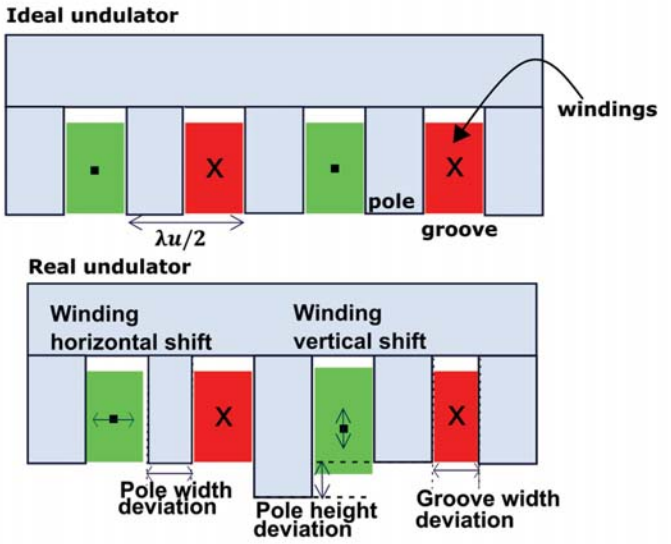

Figure 1: Top: ideal undulator. Bottom: undulator with errors.

3. Mechanical errors on the SCU

In this section, we study the effect of each error type considered on the magnetic field of the SCU. Finally, we present the tolerances that we have defined for the S-PRESSO and we crosscheck the $\sigma\left(\frac{\Delta K}{K}\right)$ that we can achieve with them.
The yoke of an SCU has ferromagnetic poles interleaved by grooves that are wound using a superconducting wire, in this case, NbTi (see Fig. 1 top). The machining of the yoke introduces deviations from the design value of the pole height or width and on the

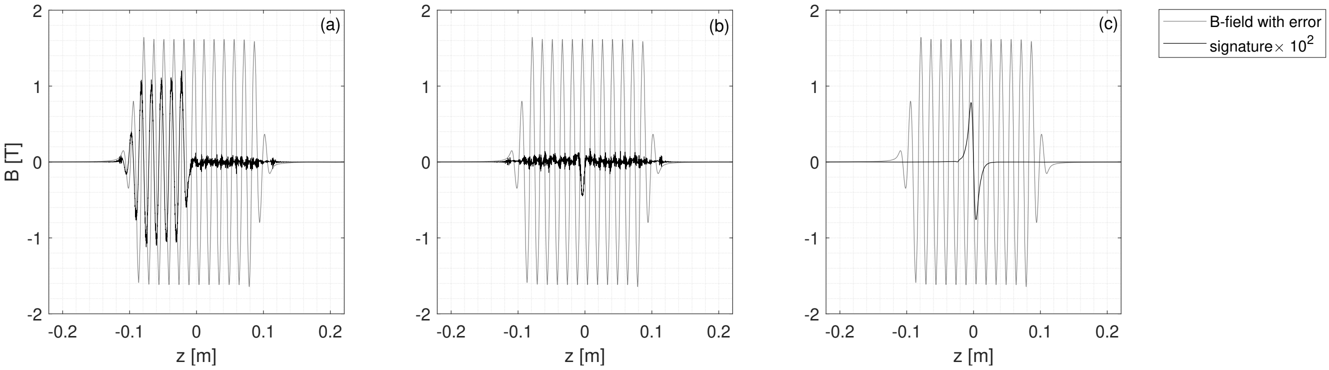

Figure 2: Signatures for (a) groove width error of 30 µm; (b) pole height error of 50 µm; (c) winding package vertical shift of 50 µm.

groove width. In addition, the winding packages can result in a vertical or horizontal shift of their centre of mass, as shown in Fig. 1 bottom.

We have performed simulations in FEMM [5] to characterize the effect of each single error type on the magnetic field. We have considered an undulator with 15 periods and calculated the signature for each error type [6]. We define the signature as:

$$\Delta B = \tilde{B} - B_0 \tag{1}$$

where B_0 is the ideal field and $\tilde{B}$ is the field where only one of the errors at the time has been applied. We have calculated both fields with FEMM [5].

3.1. Characterization of the signatures

Depending on the error type, different curves fits the signatures. In the following list, we present the considered analytic signature functions:

- a sinusoidal function fits the error on the groove width and on the pole width (Fig. 2(a))
- a Gaussian function fits the pole height and the shift in the horizontal winding center (Fig. 2(b))
- the derivative of a Gaussian function fits the shift in the vertical winding center (Fig. 2(c))

The error value relates linearly to the amplitude of the signature [6] and the maximum $\frac{\Delta K}{K}$. We have simulated the field of the undulator for different error values to find the slope of the linear relation. We have extracted the absolute values of peak fields B_{peak} and their correspondent location from the field profiles. The difference between the consecutive field extremes locations gives us the half period length $\frac{\lambda_u}{2}$. So, we can get $\frac{K}{2} = 93.4 \cdot |B_{peak}| \cdot \frac{\lambda_u}{2}$ and finally $\frac{\Delta K}{K}$ is calculated as:

$$\frac{\Delta K}{K} = \frac{\frac{K_0}{2} - \frac{K}{2}}{\frac{K_0}{2}}. \tag{2}$$

Error type	Allowed error size range [μm]
groove width	±10
pole width	±10
vertical winding package position	±20
pole height	±20

Table 1: Mechanical tolerances defined for the pre-series module S-PRESSO.

where $\frac{K_0}{2}$ is calculated from the ideal field and $\frac{K}{2}$ is the maximum undulator parameter halved of the field with the error. Fig. 3 shows the linear relation found between the $\frac{\Delta K}{K}$ and the error size.

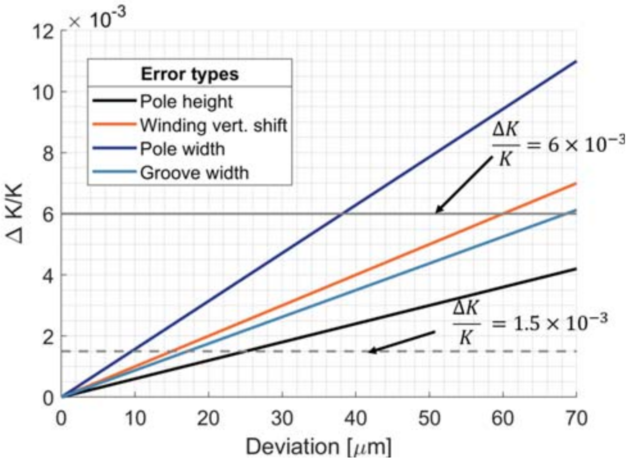

Figure 3: Dependence of the undulator parameter relative deviation respect to the error value. The dashed horizontal line shows the $\frac{\Delta K}{K}$ imposed as RMS deviation of the Gaussian distribution used for the GENESIS simulation study in [3]

4. The Montecarlo simulation

We have performed a Montecarlo simulation to characterize the effect of mechanical errors all along the SCU on the magnetic field. For this study, we consider 2 m long undulator with 131 periods and $\lambda_u = 15\,\mathrm{mm}$. We apply at each half-period length a random deviation on the groove and pole width, pole height and a vertical shift on the winding center. The tolerances for S-PRESSO (table 1) define the domain in which the error values can vary. The error values are extracted randomly from the uniform distribution defined in this domain. We preferred to use errors distributed within a uniform distribution because this choice is more conservative and represents the worst case scenario, compared to a truncated Gaussian distribution. Then, we generate the signature for each error for every half-period length based on the relation found in Fig. 3. All the signatures are summed up to get the total signature to be applied on the magnetic field from the ideal undulator (without mechanical errors). This field is generated using SPECTRA [7].

We have generated 50 different signatures representing 50 different undulators with mechanical errors. Fig. 4 shows the undulator parameter distribution for each period for all the 50 undulators.

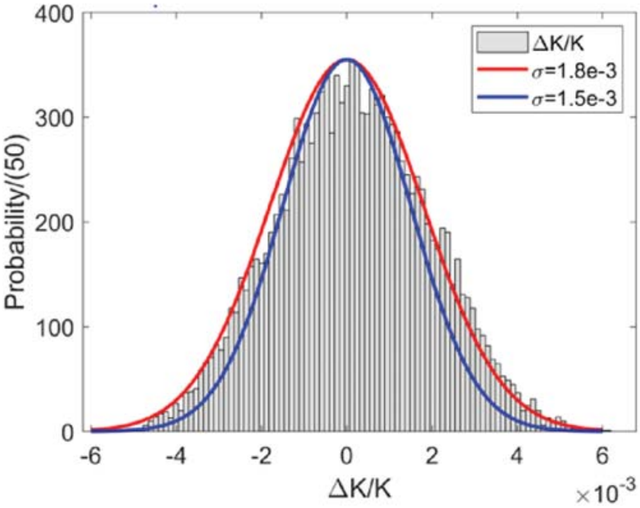

Figure 4: Distribution of the values $\Delta K/K$ of the half periods for the 50 undulators simulated using the errors generated from the Montecarlo method.

The $\Delta K/K$ has the shape of a Gaussian with a standard deviation of 1.8×10^{-3}. In Fig. 4 we show the Gaussian distribution with an RMS distribution of 1.5×10^{-3} which is equivalent to the one used for the GENESIS simulations described in the previous section.

5. Correction scheme

The RMS deviation of 1.8×10^{-3} is above the wished 1.5×10^{-3}. However, we have considered the worse scenario of a uniform distribution of the single mechanical errors within the given range of table 1. In addition, the period considered in this study is 15 mm, while the final design of the afterburner considers a period length of 18 mm, which requires less tight tolerances.

If the tolerances of table 1 cannot be satisfied, we propose as a correction scheme shimming coils placed on two consecutive grooves on both yokes sides Fig. 5. A wire of 0.25 mm diameter is considered for the shimming and a maximum of 10 power supplies with a maximum current of 10 A might be applied. FEMM simulations have shown that such shimming coils with a current of 10 A enable a correction of the $\Delta K/K = 1.6 \times 10^{-2}$.

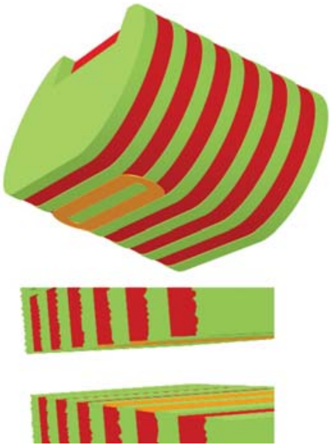

Figure 5: Shimming scheme

6. Conclusion and Outlook

GENESIS simulations show that to ensure FEL degradation does not exceed 5% we must allow a maximum RMS deviation of the $\Delta K/K = 1.5 \times 10^{-3}$ for undulators with a period length of 15 mm.

The mechanical errors responsible for the introduction of errors in the magnetic field come either from the machining of the yoke (pole height, width and groove width) or from the winding procedure (horizontal and vertical shift in the winding package center). We have characterized their effect on the magnetic field.

Table 1 shows the tolerances defined for S-PRESSO. We have simulated the effect of multiple errors present on the SCU at the same time by means of a Montecarlo study. We have extracted the error value for each error type from an uniform distribution defined in the interval identified in table 1 . The deviation on the $\Delta K/K$ has resulted equal to $= 1.8 \times 10^{-3}$, which is above the target value foreseen by the GENESIS simulations. However, we would like to remark that the assumption of a uniform distribution for the error distribution is the worst-case scenario. In addition, the study presented assumes a 15 mm period length undulator, but the final value for the afterburner is 18 mm. With a larger period length, the tolerances are less tight. As an outlook, we are planning to update the Montecarlo study for an undulator period length of 18 mm and to consider in addition the long-range mechanical errors that can affect the undulator field.

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