TOLERANCE STUDY ON THE GEOMETRICAL ERRORS FOR A PLANAR SUPERCONDUCTING UNDULATOR

V. Grattoni*, S. Casalbuoni, B. Marchetti, European XFEL, Schenefeld, Germany

Abstract

At the European XFEL, a superconducting afterburner is considered for the SASE2 hard X-ray beamline. It will consist of six undulator modules. Within each module, two superconducting undulators (SCU) 2 m long are present. Such an afterburner will enable photon energies above 30 keV. A high field quality of the SCU is crucial to guarantee the quality of the electron beam trajectory, which is directly related to the spectral quality of the emitted free-electron laser (FEL) radiation. Therefore, the effects of the SCU's mechanical imperfections on the resultant magnetic field have to be carefully characterized. In this contribution, we present possible mechanical errors affecting the undulator structure, and we perform an analytical study aimed at determining the tolerances on these errors for our SCUs.

INTRODUCTION

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

Errors in the field of the SCU can degrade the FEL performance. Deviations in the pole height or width, groove width and a vertical shift in the winding package cause errors in the magnetic field B and in the undulator period length λ_u. Consequently, also the undulator strength K is affected as it depends linearly on the undulator field and period length: $K \simeq 0.934B[\mathrm{T}]\lambda_u[\mathrm{cm}]$.

The strategy used in our study is the following: we quantify the impact on the undulator strength of the identified errors individually. Then, we perform a Montecarlo simulation to generate several undulator fields with all the errors types to investigate how the undulator strength is affected. Finally, we compare the $\Delta K/K$ resulting from the defined mechanical tolerances with the $\Delta K/K$ found to keep the FEL power degradation below 5% of the emitted power in absence of undulator errors for an SCU line with $\lambda_u = 15$ mm.

This study integrates our previous one published in [3] including an undulator period $\lambda_u = 15$ mm. This time we have considered a $\lambda_u = 18$ mm, which is the final wavelength chosen for the SCU afterburner modules.

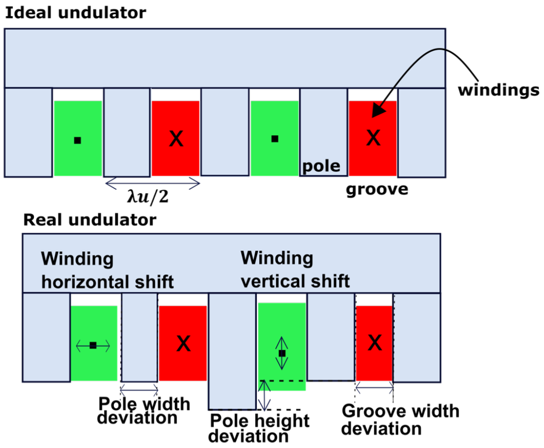

Figure 1: Top: ideal undulator. Bottom: undulator with mechanical deviations.

MECHANICAL ERRORS ON THE SCU

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 wire is wound with alternating direction in consecutive grooves. Two consecutive poles and the grooves following the poles define the undulator period length λ_u. The machining of the yoke introduces deviations from the design value of the pole height or width and on the groove width. The error on the pole or groove width causes a deviation from the nominal period length. 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 [4] 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 [5]. 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 [4].

Characterization of the Signatures

Depending on the error type, different functions have been used to fit the signatures. In the following list, we present the considered analytic signature functions:

- a sinusoidal function has been used to fit the error on the groove width and on the pole width (Fig. 2(a))

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[*] vanessa.grattoni@xfel.eu

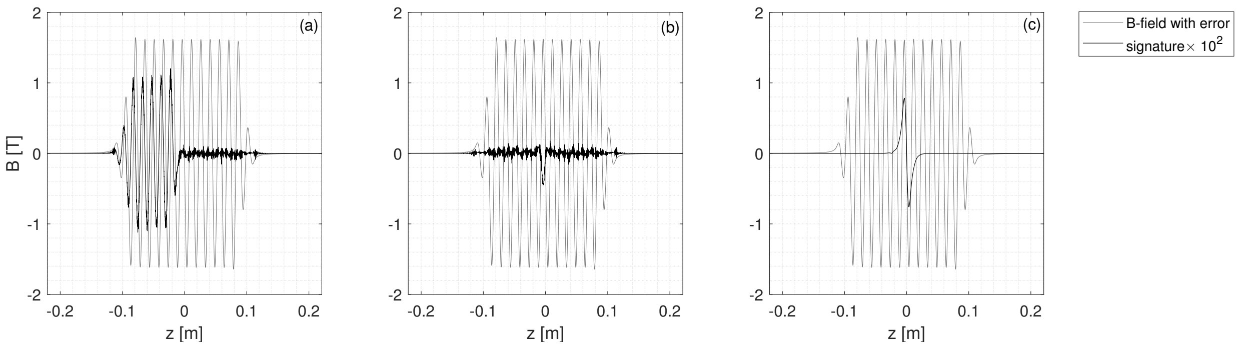

Figure 2: Signatures for (a) groove width error of 30 µm; (b) pole height error of 50 µm; (c) winding package vertical shift of 50 µm.

- a Gaussian function has been used to fit the pole height and the shift in the horizontal winding center (Fig. 2(b))
- the derivative of a Gaussian function has been used to fit the shift in the vertical winding center (Fig. 2(c))

The error value relates linearly to the amplitude of the signature [5] 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 peak field 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:

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

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. Figure 3 shows the linear relation found between the $\frac{\Delta K}{K}$ and the error size.

Table 1: Mechanical Tolerances Defined for the Pre-series Module S-PRESSO

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

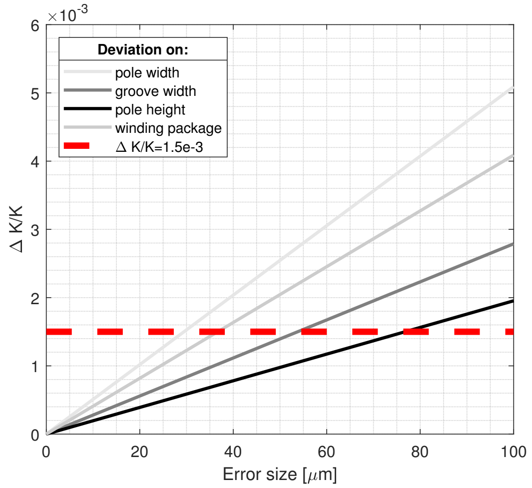

Figure 3: Dependence of the undulator parameter relative deviation respect to the error value. The dashed horizontal line shows the $\frac{\Delta K}{K}$ imposed as RMS deviation of the Gaussian distribution used for the GENESIS simulation study in [7].

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 221 half periods lengths and $\lambda_u = 18$ 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. 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 [6].

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

The $\Delta K/K$ has the shape of a Gaussian with a standard deviation of 1.56×10^{-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 that were done for a SCU undulator line with $\lambda_u = 15$ mm using

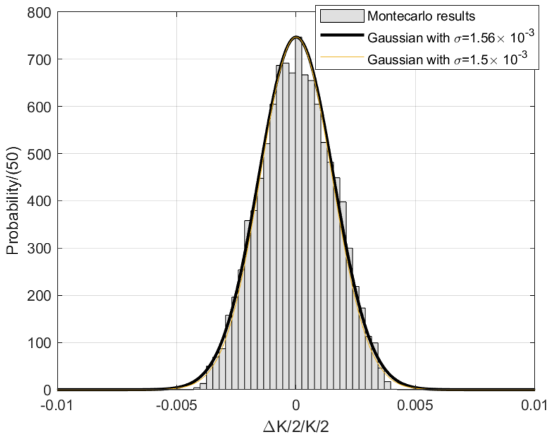

Figure 4: Distribution of the values $\Delta K/K$ of the half periods for the 50 undulators simulated using the errors generated from the Montecarlo method.

the electron beam parameters from the European XFEL [7]. We are updating the study in GENESIS to get the RMS $\Delta K/K$ for a SCU afterburner with $\lambda_u = 18$ mm.

For the Montecarlo simulation, we have considered the worse scenario of a uniform distribution of the single mechanical errors within the given range of table 1.

CORRECTION SCHEME

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 $\Delta K/K = 1.6 \times 10^{-2}$.

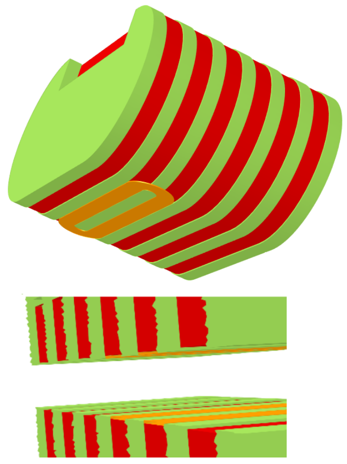

Figure 5: Shimming scheme.

CONCLUSION AND OUTLOOK

GENESIS simulations show that to prevent SASE-FEL degradation below 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. Simulations for a period length of 18 mm are ongoing and we expect that the RMS deviation of the $\Delta K/K$ to limit the FEL degradation below 5% are less stringent.

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 . We have found an RMS $\Delta K/K$ equal to 1.56×10^{-3}, which is 4% larger than the value found in the GENESIS simulations for a SCU FEL line with $\lambda_u = 15$ mm. the GENESIS simulations show a reduction in the FEL performance of 4% with an RMS $\Delta K/K = 1.5 \times 10^{-3}$. However, we would like to remark that the assumption of a uniform distribution for the error distribution is the worst-case scenario and we expect a less stringent RMS $\Delta K/K$ for the simulations that will be performed with $\lambda_u = 18$ mm. As an outlook, we are planning to consider in addition the long-range mechanical errors that can affect the undulator field.

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