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Analysis of the error budget for a superconducting undulator SASE line at European XFEL

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Abstract. European XFEL is investing in the development of superconducting undulators (SCUs) for future upgrade of its beamlines. SCUs made of NbTi, working at 2 K, with a period length of 15 mm and a vacuum gap of 5 mm allow covering a range between 54 keV and 100 keV. The effect of mechanical errors in the distribution of the undulator parameter K along the undulators is more relevant for working points at lower photon energy, which are obtained using a higher magnetic field in the undulator. In this article we investigate the effect of error distribution in the K-parameter for a working point at 50 keV photon energy obtained injecting an electron beam with 16.5 GeV energy from the XFEL linear accelerator in a undulator line composed by SCUs with 1.6 T peak magnetic field.

1. Introduction

The application of SCUs for generating X-ray radiation in FELs is a promising field for two main reasons. The use of high magnetic peak field combined with shorter undulator period length promises excellent performances in terms of radiation flux in the hard X-ray region. Moreover they allow wider tunability of the radiation wavelength for a constant electron beam energy.

The advancement of SCU technology has a strategic importance for the future development of the European XFEL facility. The extension of the energy range of the radiation towards higher values would fully exploit the high electron energy beam capability of the accelerator [7]. The energy available in the soft X-ray beamlines can be enhanced as well by the SCU technology in future facility upgrades. Finally this development can be considered complementary to the study on the upgrade of the XFEL linac for continuous wave (CW) operation [4]. CW operation at European XFEL is considered possible only with reduced electron beam energy. Specifically the electron beam energy will be limited to about 7 GeV, while the present maximum value is 17.5 GeV. Using SCU-technology with short undulator periods it is possible to cover the same photon energy range as presently done with the permanent magnet undulators operated with higher electron beam energy.

For all those reasons a project for the realization of a SCU afterburner for the SASE2 line is being set-up [6, 10]. In this article we will present first evaluations on the tolerances of the magnetic field in the undulator to allow high quality FEL performances and some considerations on the tolerable misalignment errors. The study has been conducted considering self-amplified-spontaneous-emission (SASE) on a line constituted exclusively by SCU modules and a photon energy of 50 keV obtained using undulators with 15 mm long period and electron beam energy of 16.5 GeV.

2. Beamline layout and working point

We choose to work with SCUs made of NbTi, working at 2.2 K, with a period length of 15 mm and a vacuum gap of 5 mm. If we consider operation with 17.5 GeV electron beam energy and maximum magnetic field $\mathrm{B_{max}} = 1.625$ T, obtained with 2 K temperature margin, the energy range of the emitted photons will be between 54 keV and 100 keV.

For the study of the tolerances on the magnetic field of the undulator, we choose to consider a beam energy of 16.5 GeV and we look at the emission of radiation at 50 keV, which corresponds to operation with high magnetic peak field value, $B_0 = 1.58\,T$. For such magnetic field, the undulator parameter is $\mathrm{K_0} = 2.212$, where $\mathrm{K_0} = \frac{\mathrm{e}}{2\pi\mathrm{mc}}\,\mathrm{B_0}\lambda_\mathrm{u} = 0.9336\,\mathrm{B_0}\,[\mathrm{T}]\,\lambda_\mathrm{u}\,[\mathrm{cm}]$.

The present concept for the lattice under consideration is represented in Figure 1. In particular we would like to point out that:

- We assume to operate with a cryomodule containing two undulator segments interleaved with a phase shifter [8].
- We assume to use the same design for the intersections as presently used in the rest of the SASE2 beamline, which is operated with permanent magnet undulators. In those intersections phase shifters, quadrupoles and beam diagnostics are present.
- We assume that the presence of correction coils inside the cryostat and steerers in the intersections will allow perfect alignment of the beam transverse position offset and angle at the entrance of each undulator module with respect to the magnetic axis of the undulator.

Moreover in our numerical study we have considered an ideal beam distribution having constant current and longitudinal slice beam parameters (emittance and energy spread). The working point for the beam parameters and an estimation of the expected FEL properties are shown in Table 1.

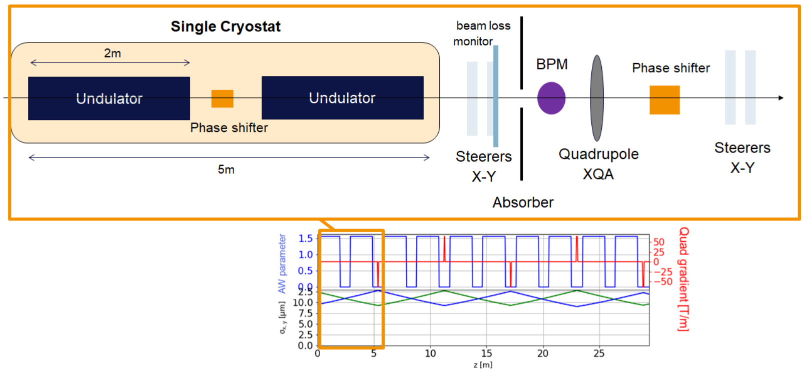

Figure 1. On top: sketch of half-cell of the undulator lattice implemented in the FEL simulations. On the bottom: example of matched beam spotsize $\sigma_{x,y}$ for given settings of the focusing gradients of undulators and quadrupoles in the beamline.

3. Simulations

3.1. Effect of random errors of the undulator parameter K

We run numerical simulations using Genesis 1.3 v.2 [1] and Ocelot [12], with the same approach of reference [11].

We generate local K values for the poles of the undulator segments using a random error generator which produces a distribution with Gaussian shape, RMS amplitude $\Delta\mathrm{K_{RMS}}$ and mean value $\mathrm{K} = \mathrm{K_0}$.

Table 1. Overview of the expected FEL performance considering an ideal flat-top beam distribution with constant slice parameters. The values have been calculated using the FEL estimator integrated in Ocelot [12].

Parameter	**20 pC**	**250 pC**
Electron beam energy	16.5GeV	16.5GeV
Electron bunch length	4fs	50fs
Slice normalized emittance	0.2μm rad	0.4μm rad
Slice energy spread	1.8MeV	3.1MeV
β_x/β_y avg.	20m	20m
λ_R	2.47968e-11m	2.47968e-11m
ρ_{1D}	4.28e-4	3.4e-4
$\rho_3 D$	3.51e-4	1.9e-4
Gain length 1D	1.61m	2.03m
Gain length 3D	1.96m	3.63m
Saturation energy	178μ J	1164μ J
Saturation power	4.4e10W	2.3e10W

After having generated the distribution of the K values along the complete line, we tune artificially the local mean value of the K of each module in order to match the resonant value K_0. This procedure is equivalent to perform a local tuning of the current of the undulator segment in presence of mechanical errors and/or misalignments in the coils.

The values of the correction coils up and downstream each module are set such that the calculated first and second field integrals are equal to zero. As a result of such corrections, the trajectory of the tracked electron beam in the intersections is perfectly aligned to the magnetic axis of the quadrupoles. Inside the undulators the trajectory of the electron beam performs some local excursion from the ideal one due to the different values of K at each magnet pole. Such excursion has only few μm amplitude, nevertheless causes a dephasing between the radiation field and the electrons, which is corrected by adjusting the configuration of the phase shifters.

For each set of input parameters we have repeated simulations averaging over 50 shots of SASE pulses.

Table 2. Power degradation expected from the presence of errors in K. The degradation parameter has been calculated at the saturation length.

Input parameters	**FEL power degradation parameter**
Reference: $\epsilon_\mathrm{n} = 0.2\,\mu\mathrm{m\,rad}$, $\Delta\mathrm{E} = 1.8\,\mathrm{MeV}$	$---$
$\Delta\mathrm{K_{RMS}/K} = 0.0015$, $\epsilon_\mathrm{n} = 0.2\,\mu\mathrm{m\,rad}$, $\Delta\mathrm{E} = 1.8\,\mathrm{MeV}$	$\mathrm{D_{z=60\,m}}$: 96 %
Reference: $\epsilon_\mathrm{n} = 0.3\,\mu\mathrm{m\,rad}$, $\Delta\mathrm{E} = 2.6\,\mathrm{MeV}$	$---$
$\Delta\mathrm{K_{RMS}/K} = 0.0015$, $\epsilon_\mathrm{n} = 0.3\,\mu\mathrm{m\,rad}$, $\Delta\mathrm{E} = 2.6\,\mathrm{MeV}$	$\mathrm{D_{z=80\,m}}$: 96 %

Figure 2 shows the result of the simulation performed for different electron beam parameters: transverse emittance and energy spread.

We can define a parameter to quantify the FEL power degradation due to K-errors of the

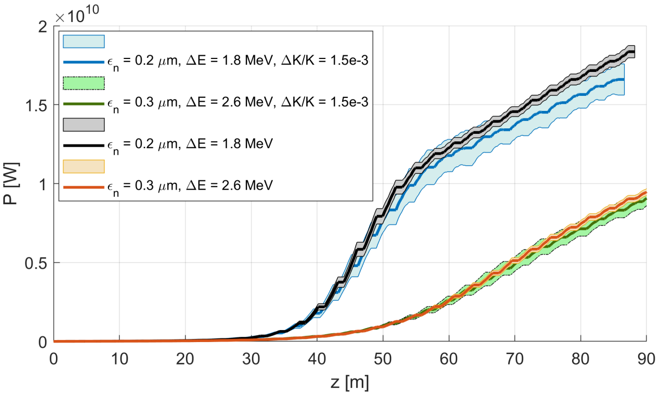

Figure 2. Output of FEL simulations: mean power along the undulator beamline corresponding to different electron beam transverse normalized emittance ϵ_n and energy spread ΔE. The curves have been obtained averaging on 50 SASE pulses. The standard deviation of the average values of the curve is shown as shaded area. Simulations with and without errors in the K parameters of the undulator have been performed.

undulator:

$$D_{z=z_0} = \frac{P_{er}(z = z_0)}{P_{ref}(z = z_0)} [\%] \tag{1}$$

where $\mathrm{P_{er}}$ is the value of the mean power at $\mathrm{z = z_0}$ obtained in simulations including the errors in K, and $\mathrm{P_{ref}}$ is the value of the mean power at $\mathrm{z = z_0}$ obtained in reference simulations with constant $\mathrm{K = K_0}$. $\mathrm{z_0}$ is always chosen to be about the saturation length.
In table 2 we summarize the impact of the errors in K on the FEL performances.

The simulations show that, for the chosen value of the error $\Delta\mathrm{K_{RMS}/K = 1.5e^{-3}}$, more than 95% of the mean power with respect to the ideal case can be reached. If the electron beam quality is worse, the effect of the K-errors is similar, for the considered parameters.
We have performed simulations using the code FEMM [2] to check the mechanical errors of the undulator coils corresponding to $\Delta\mathrm{K/K = 1.5e^{-3}}$. The result of such study is presented in [9]. As can be seen in the reference, the tolerances on the groove width, pole width, position of the winding package and pole height of the magnet are found to be realistic and below 50 μm.

3.2. Correlated errors of the undulator parameter K due to misalignment of the SCU-coils

Th misalignment of the undulators in the beamline causes an effective error in the K parameters "experienced" by the electron beam that is correlated with the longitudinal coordinate z along the undulator.
The dominant errors for our setup are:

- The error due to a misalignment of the undulator in the vertical direction. In particular a vertical shift of 50 μm causes a constant error of $\Delta\mathrm{K/K = 2.2e^{-4}}$ along the undulator. This error could anyway be possibly compensated by readjusting the set-point of the current of the SCU.
- The error caused by the rotation of one undulator about the horizontal axis x, which is perpendicular to the main magnetic field component, B_y (yaw error). A misalignment by an angle $\theta = 0.1$ mrad corresponds to a parabolic error distribution, correlated with the longitudinal position in the undulator and having maximum amplitude $\Delta\mathrm{K_{corr}/K = 1e^{-3}}$ at the entrance/exit of the SCU. Such error cannot be fully compensated by the readjustment of the set-point of the current in the SCU and its effect sums up with the random error in K that we have discussed in the previous section.

We have run Ocelot simulations to check if the effect of the mentioned Yaw error is acceptable in terms of FEL lasing performances.

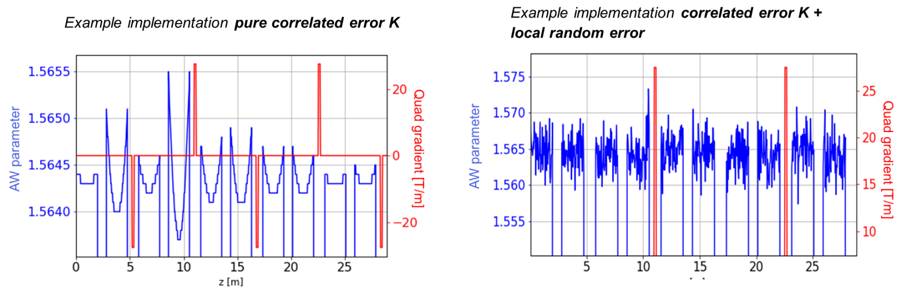

Figure 3. Implementation of correlated error distribution of K in Ocelot, corresponding to the effect of Yaw errors in the alignment of the SCUs. The AW parameter is defined as $K/\sqrt{2}$.

A correlated parabolic error in the K distribution in each SCU as shown on the left side of Fig. 3 has been generated within Ocelot. For each undulator the edges of this function are picked from a random gaussian distribution with RMS $= \Delta \mathrm{K}_{\mathrm{corr}}$. Such correlated error distribution is then summed up with the random K error distribution discussed in the previus section, having $\Delta \mathrm{K}_{\mathrm{rand}}/\mathrm{K} = 1.5\mathrm{e}^{-3}$ (see right side of Fig. 3).
A yaw error $\Delta\theta = 0.1$ mrad corresponds to a parabolic distribution of the correlated error in the undulator having maximum value $\Delta \mathrm{K}_{\mathrm{corr}}/\mathrm{K} = 0.001$ at the entrance/exit of the SCU.
In Fig. 4 the effect of yaw misalignment errors in the mean power along the undulator beamline is shown. For a yaw error $\Delta\theta = 0.1$ mrad, the effect of the correlated error in K is negligible with respect to the effect of the random error from the machining tolerances. As a comparison, we plot also the power curve corresponding to a yaw error $\Delta\theta = 1$ mrad. It can be observed that in this case the radiation production is strongly dumped.

4. Conclusions

We have run simulations to estimate the needed tolerances on the design of the coil for applications of SCUs in future projects at XFEL.
The simulations have been done considering a SASE line composed by SCU modules having a period of 15 mm and a photon energy of 50 keV. Warm intersections with the same design as the ones presently implemented in the SASE2 beamline have been considered.
For the presented working point, an error $\Delta \mathrm{K}_{\mathrm{RMS}}/\mathrm{K} = 1.5\mathrm{e}^{-3}$ has been judged acceptable in terms of degradation of the FEL performances. This value corresponds to tolerances on the manufacturing of the coil which are in the order of few tens of micrometers. Ideally the experimental characterization of the SCU coils after production [3] will demonstrate if shimming procedure is needed to meet the goal tolerances. In case $\Delta \mathrm{K}_{\mathrm{RMS}}/\mathrm{K} > 1.5\mathrm{e}^{-3}$, shimming coils able to correct more than 1% of field error might be added [5].
We have conducted also a study to estimate the effect of misalignment errors of the SCUs in the FEL lasing process. In particular the effect of yaw errors has been included in the simulations. An error of the yaw angle of the undulator of 0.1 mrad has been judged acceptable.

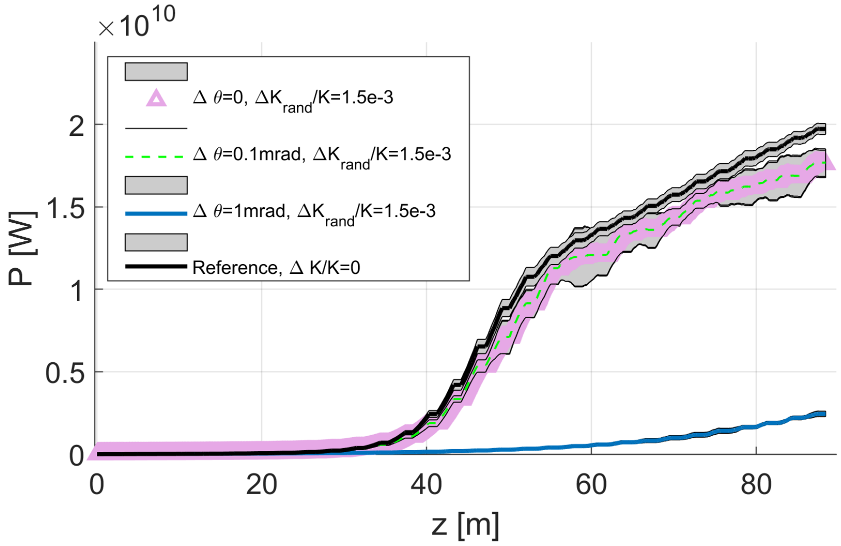

Figure 4. Output of FEL simulations: effect of yaw misalignment errors in the mean power along the undulator beamline for an electron beam with transverse normalized emittance $\epsilon_{\rm n} = 0.2$ μm and energy spread ΔE $=$ 1.8 MeV. The curves have been obtained averaging on 5 SASE pulses. The standard deviation of the average values of the curve is shown as shaded area.

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