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STUDY OF THE TOLERANCES FOR SUPERCONDUCTING UNDULATORS AT THE 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 for 17.5 GeV electron energy. 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 1.58 T peak magnetic field.

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 [1]. 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 [2]. 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 [3]. In this article we will present first evaluations on the tolerances of the magnetic field in the undulator to allow high quality FEL performances. 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.

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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 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 $K_0 = 2.212$, where $K_0 = \frac{e}{2mc} B_0 \lambda_u = 0.9336\, B_0\, [T]\, \lambda_u\, [cm]$.

The present concept for the lattice under consideration is represented in Fig. 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 [4].
- 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.

SIMULATIONS

We run numerical simulations using Genesis 1.3 v.2 [5] and Ocelot [6], with the same approach of reference [7].

We generate local K values for the poles of the undulator segments using a random error generator which produces a

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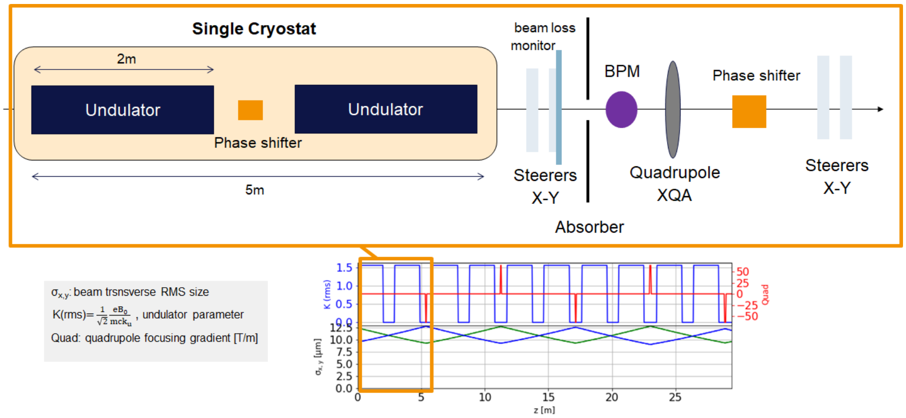

Figure 1: On top: sketch of half-cell of the undulator lattice implemented in the FEL simulations. On the bottom: example of matched beam spotsize $\sigma_{x,y}$ for given settings of the focusing gradients of undulators and quadrupoles in the beamline.

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 [6].

Parameter	20 pC	250 pC
Electron beam energy	16.5 GeV	16.5 GeV
Electron bunch length	4 fs	50 fs
Slice normalized emittance	0.2 µm rad	0.4 µm rad
Slice energy spread	1.8 MeV	3.1 MeV
β_x/β_y avg.	20 m	20 m
λ_R	2.47968×10^{-11} m	2.47968×10^{-11} m
ρ_{1D}	4.28×10^{-4}	3.4×10^{-4}
$\rho_3 D$	3.51×10^{-4}	1.9×10^{-4}
Gain length 1D	1.61 m	2.03 m
Gain length 3D	1.96 m	3.63 m
Saturation energy	178 µJ	1 164 µJ
Saturation power	4.4×10^{10} W	2.3×10^{10} W

distribution with Gaussian shape, RMS amplitude ΔK_{RMS} and mean value $K = K_0$.

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 imperfections 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.

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 undulator:

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

where P_{er} is the value of the mean power at $z = z_0$ obtained in simulations including the errors in K, and P_{ref} is the value of the mean power at $z = z_0$ obtained in reference simulations with constant $K = K_0$. 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 $\Delta K_{RMS}/K = 1.5e^{-3}$, 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.

We have performed simulations using the code FEMM [8] to check the tolerances in the machining of the undulator coils corresponding to $\Delta K/K = 1.5e^{-3}$. We have consid-

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: ϵ_n = 0.2 µm rad, ΔE = 1.8 MeV	− − −
$\Delta K_{RMS}/K$ = 0.0015, ϵ_n = 0.2 µm rad, ΔE = 1.8 MeV	$D_{z=60\,m}$: 96%
Reference: ϵ_n = 0.3 µm rad, ΔE = 2.6 MeV	− − −
$\Delta K_{RMS}/K$ = 0.0015, ϵ_n = 0.3 µm rad, ΔE = 2.6 MeV	$D_{z=80\,m}$: 96%

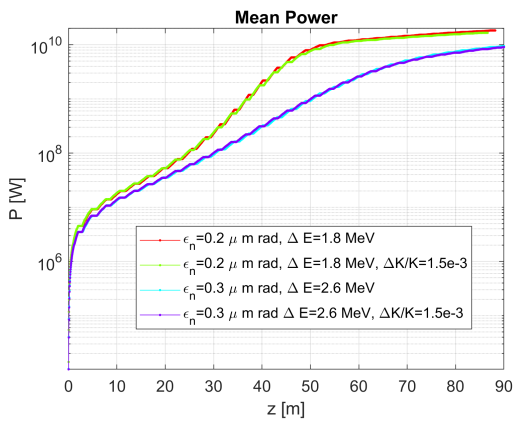

Figure 2: Output of FEL simulations: mean power along the undulator beamline corresponding to different electron beam transverse normalized emittance ϵ_n and energy spread ΔE. The curves have been obtained averaging on 50 SASE pulses. Simulations with and without errors in the K parameters of the undulator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

ered that the main source of mechanical errors come from the machining of the pole, the groove and how precisely is positioned the center of the winding package in the groove. Each parameter of the coil has been varied while keeping the other ones constant and equal to the design value. This procedure allows to find the sensitivity of the K value to the precision of each varied parameter.

The following boundaries have been estimated:

- Precision of the pole height ±25 µm;
- Precision of the pole width ±10 µm;
- Precision of the groove width ±15 µm;
- Precision of the horizontal position of the winding ±15 µm;
- Precision of the vertical position of the winding ±15 µm.

Further studies foresee the combined variation of all parameters.

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 $\Delta K_{RMS}/K = 1.5e^{-3}$ 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 [9] will demonstrate if shimming procedure is needed to meet the goal tolerances. In case $\Delta K_{RMS}/K > 1.5e^{-3}$, shimming coils able to correct more than 1% of field error might be added [3].

Further studies including working points with higher beam charge, detailed evaluation of the wakefields and alternative designs for the intersections are foreseen in the near future.

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