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DEPENDENCE OF THE VUV-FEL PERFORMANCE AT THE TESLA TEST FACILITY ON MAGNETIC FIELD ERRORS

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ABSTRACT

The VUV FEL, which is in its design stage at DESY, is a SASE device which is driven by a 1 GeV superconducting linac. In this paper, the performance of the 25 m long undulator, is studied. Results of simulations, including magnetic peak-field errors, are presented. Dependence of the performance on these errors is discussed.

1. Introduction

In designing a VUV-FEL, much effort is spent in reducing the electron beam energy spread and emittance. As one aims at shorter wavelengths, the phase space volume of the electron beam has to become smaller. For a SASE FEL, the undulator needs about 1000 periods. In this case the cumulative effect of magnetic field errors becomes another issue to take into account. During the past decade, both analytical and numerical studies have shown that two important parameters which determine the FEL performance are the phase of the electron with respect to the ponderomotive potential, as well as the beam wander, i.e., the deviation of the electron beam from the undulator axis [1-7]. The first quantity determines the energy exchange between electrons and the field, the second determines the transverse overlap between electron beam as a whole and the radiation field.

The different error sources, such as variation in undulator wavenumber or random tilt of the poles, generating small undesirable magnetic field contributions in both transverse and longitudinal directions, are assumed to be either negligibly small, or are assumed to be well described by an effective random variation of the main peak field of the planar structure. The aim of this paper is to determine the influence of phase and overlap for the TTF-FEL parameters on the gain as well as to establish some general idea within what distance the electron beam has to remain from the optical axis, including the motion due to the FODO-lattice used to keep the beam confined within the specified radius of 57 μm . The design of the undulator with a superimposed FODO-lattice is studied in separate papers [8-9].

This paper is organized as follows. In section 2, some comments will be made on the influence of the error in magnetic peak field. The next section results of simulations for different error distributions are shown. In the last section the results are discussed and first estimations on tolerances are given.

2. Influence of magnetic field errors

From FEL physics, it is well known that two important quantities determine to large extent the FEL performance. One is the resonance condition, i.e., the phase of the electrons with respect to the ponderomotive potential, the second is the overlap between electron beam and field. The ponderomotive phase is approximated by

$$\psi \approx \psi_0 + \left(k_u - \frac{k_s}{2\gamma_0^2} \right) z - \frac{k_s}{2\gamma_0^2 k_u} \Delta\psi$$

$$\text{with } \Delta\psi(z) = k_u \int_0^z (\gamma_0 \beta_x)^2 dz', \quad (1)$$

where k_u and k_s are the undulator and radiation wavenumber, respectively, γ_0 and β_x are the energy and transverse electron velocity normalized to the speed of light. Using $\langle \psi' \rangle = 0$ to determine the resonant wavelength results in the following resonance condition

$$\lambda_s = \frac{\lambda_u}{2\gamma_0^2} \left(1 + \frac{\langle \Delta\psi \rangle}{\pi N_u} \right). \quad (2)$$

Table 1: Parameters of the TTF VUV-FEL

Electron beam	
Energy	1 GeV
Peak current	2500 A
Normalized rms emittance	2π mm mrad
rms energy spread	0.1 %
External β -function	3 m
rms beam size in the undulator	$57 \mu\text{m}$
Undulator	
Type	Planar
Period	27.3 mm
Peak magnetic field	0.497 T
Magnetic gap	12 mm
Undulator module length	4.4 m
Effective undulator length	25 m
FODO-period	1.2 m
Quadrupole strength	4 T/m
Radiation	
Wavelength	6.4 nm

Figure 1: Normalized power versus rms phase-shake in case of an undulator field error per period after the first undulator module. Calculations have been performed in the one-dimensional limit, i.e., without FODO-lattice. Parameters as in Table 1.

With the resonant wavelength given by Eq. (2), we are now ready to calculate the phase shake. Its rms value is defined as the phase at the magnetic poles including errors minus the phase in case of ideal magnetic field squared and summed over all poles (see for example Ref. 5). With the definition of phase as given by Eq. (1), the ideal ψ is zero on

the poles. Thus, the rms phase shake is

$$\sigma_\psi = \sqrt{\frac{1}{2N_u} \sum_{n=1}^{2N_u} \psi_n^2}, \quad (3)$$

where ψ_n is the phase evaluated on the poles. Poles are labeled by their appropriate number up to $2N_u$, with N_u the number of undulator periods. In case of a non-ideal undulator, the derivative of β_x depends on the error of the n -th pole. Because the integral up to the n -th pole does not vanish, β_x depends all previous magnetic peak-field errors. Therefore, the electron beam trajectory may substantially deviate from the optical axis. Similar to the phase-shake, we also define

$$\sigma_x = \sqrt{\frac{1}{2N_u} \sum_{n=1}^{2N_u} x_n^2}, \quad (4)$$

where x_n is the second field integral evaluated on the magnetic poles, i.e., $x(z) = \int \beta_x(z') dz'$. In order to describe a realistic undulator, one has to take into account the possibility to 'tune' the matching sections that set the first and second field integral equal to zero. A cos-field is assumed with constant peak field in case of an ideal undulator. Matching is achieved by starting and ending with quarter-periods instead of half. In all calculations it is assumed that the field amplitude of these two poles are adjusted such that first and second field integrals over the whole undulator field are equal to zero. The FODO-lattice is not taken into account in these adjustments.

3. Results of simulations

In this section, the model is applied to the TTF VUV-FEL (see Table 1 for details). Simulations have been performed with TDA3D [10-11].

Results given in Figs. 1 and 2 are obtained without FODO-lattice. The emittance is taken equal to zero. All other parameter are as in Table 1. In order to distinguish between phase shake, σ_ψ , and electron beam wander, σ_x , the normalized power ($P_{\text{out}}/P_{\text{in}}$) shown in Fig. 1 is obtained by using an error per undulator period instead of an error per half-period. Thus, the field integral per period is always zero and, consequently, the electron beam remains on axis. Of the two phenomena studied in this paper, only phase-shake can become large in this case. In

order to get an rms phase-shake of the order of 1 radian for an undulator module of 4.4 m, as shown in Fig. 1, the field-amplitude error had to be increased to as much as 4%. As can be seen, up to 0.5 rad, there is only a few percent decrease in power.

Figure 2: Normalized power versus rms phase-shake (a) and versus electron beam wander (b) in case of an undulator field error per half-period after the first undulator module. All remaining parameters as in Fig. 1.

In Fig. 2, errors are chosen per half period. Therefore, the electron beam can wander off-axis in this case. In all calculations, the rms field-amplitude error is 0.5%, which is believed to be feasible. Fig. 2a shows again the normalized power versus rms phase shake. As can be seen, the power reduction is much larger than in the case with an error per period. The scatter of the points is much larger than in Fig. 1. In Fig. 2b, the normalized power versus beam wander is shown. The dotted line is a Gaussian fit. As can be seen, the phase shake is not the principle parameter which determines the FEL

performance in this case. It is dominated by the wander of the beam (see for example Ref. 4).

In calculations so far, the FODO-lattice was not taken into account. In case of an ideal undulator, i.e., without any errors, now including a FODO-lattice, the influence of electron beam mismatch is studied first. By giving the beam an initial transverse offset, it performs an oscillation throughout the whole undulator, thus reducing the overlap between electron beam and radiation field.

Figure 3: Normalized power versus initial beam offset. No undulator errors are included. Period of the FODO-lattice is 1.2 m.

In Fig. 3, the normalized power at the exit of one undulator module is shown for different values of the initial offset. Note that the normalized power in this case does not exceed 21, compared to 42 in the previous figures. This power reduction is caused by the non-zero emittance and focussing of the electron beam. The figure shows that the power reduction due to an initial offset can be approximated by $\exp(-X_0^2/2\sigma_b^2)$, where σ_b is the electron beam radius.

In Fig. 4, the performance of the FEL is shown including magnetic field errors and the FODO-lattice. It has been assumed the the focusing structure is ideal. Errors in this structure will be studied in a future paper. As can be seen, the results are similar to those obtained without focusing. The case without errors gives a normalized power of approximately 21, as in Fig. 3. With a σ_x of $10\mu\text{m}$, the reduction 10%. We would like to stress that the value for σ_x has been calculated with Eq. (4), using the on-axis magnetic field, which is equivalent to neglecting the FODO-lattice. It does give, however, the deviation with respect to the ideal undulator.

In the TTF-FEL, we aim for four steering stations per module. This should result in an overlap which

is large enough not to have a large gain reduction. According to Ref. 4, assuming a gain length of approximately 1.4 m (or 50 periods), a peak field error of 0.5% and steering stations every 1.1 m, we find $W = 0.08$, and a gain reduction of less than 2% (see Eq. (7.32) in Ref. 4).

4. Discussion and conclusions

In case of the TTF-FEL, the dominant effect of magnetic field errors is the wander of the electron beam. Phase-shake with a perfectly aligned electron beam only gives a minor reduction in gain by a few percent per undulator module, whereas beam wander for the same rms-field error can give a gain-reduction by as much as an order of magnitude, if no additional steering is provided within the module. Calculations including the FODO-lattice show that oscillations may not exceed $10\text{ }\mu\text{m}$ of maximum excursion (about $0.2\sigma_b$), giving a gain reduction of 10%. With the 4 planned steering stations per module, the gain reduction is no more than a few percent.

We would like to stress that in the results presented in this paper, only the first undulator section has been taken into account. If the electron beam is perfectly matched at any section entrance, these results also hold for the five remaining ones, because the errors in the different sections are independent. The main difference between the first and all remaining sections is, however, that the beam is not prebunched in these calculations. In order to calculate all remaining sections, we intend to modify TDA3D such that it can describe the modular setup of the TTF-FEL. To our understanding, however, the first undulator section will be the most crucial one, because the radiation field has to startup from noise.

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Figure 4: Normalized power versus electron beam wander in case of an undulator field error per half-period after the first undulator module including the FODO-lattice with a period of 1.2 m. All remaining parameters as in Fig. 1.

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