Optimum β-function for phase I of the TESLA Test Facility FEL at DESY

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Abstract

The undulator of the TESLA Test Facility Free Electron Laser (TTF-FEL) has been optimized for the radiation wavelength of 6 nm and an electron beam energy of 1 GeV [1]. First experiments are planned at a reduced energy and a radiation wavelength of approximately 70 nm. The undulator length available for these tests is only half of the final length. Although the undulator length needed for a smaller beam energy is much shorter, the so-called 'beam saucaging', i.e. the variation of the β-function due to discrete FODO lattice, increases length needed to reach saturation. Furthermore, the beam quality, especially the difference between overall energy spread and emittance compared to the same quantities within a cooperation length, is still under discussion. In order to achieve an optimum performance over a wider range of electron beam parameters and photon wavelengths, the undulator should be slightly modified for these tests. In this paper, the influence of emittance and energy spread, as well as the wavelength dependence has been studied to obtain a device that is widely tuneble and easier to align.

1 introduction

The goal of the TTF-FEL is to supply future users with VUV radiation, possibly in the range between 6 and 120 nm. It will operate as a single pass device starting from noise, based on so-called Self Amplified Spontaneous Emission (SASE) [2, 3]. The electron beam will be supplied by a low emittance photo cathode gun and accelerated by a high-gradient superconducting accelerator. In order to get the desired current of 2.5 kA, the electron bunches will be compressed in three stages. The radiation will be produced in an undulator with a superimposed alternating gradient (FODO) focusing structure. In order to test these components at an early stage and prove the SASE principle in this wavelength range, phase I will be performed with only three accelerating modules in place ($E_b < 390\,\mathrm{MeV}$), two bunch compressors and half of the undulator (consisting of three modules).

Simulations performed at a beam energy of 300 MeV have shown, that even in the case that all parameters are as predicted, the radiation will not reach saturation within the three undulator modules. In view of the uncertainty in many of the beam parameters and the startup from noise, one should carefully look into the possibility of changing the undulator design in order to take into account all possible situations.

For phase II, at an electron beam energy of 1 GeV, the electron beam has an average β-function of 3 m with a variation of ± 0.5 m. The average value of the β-function scales linear with energy, but the variation is constant (in first approximation). Therefore, the relative change in β increases from ± 20 % at 1 GeV to ± 50 % at 300 MeV. This large variation increases the saturation length, an increase which depends on the electron beam energy as well as the beam emittance. In the remainder of this report, simulations have been performed with TDA3D, the only simulation code that takes this effect into account fully [4, 5]. Because we are interested in the influence of electron beam quality on the optimum β-function and on the wavelength range that can be achieved for a given FODO structure, the next section will discuss the dependence of saturation length on the quadrupole gradient of the FODO lattice and beam emittance. Although many FODO parameters could be considered, thus increasing the parameter space under investigation, in the present stage of the project only minor changes, within given technical limitations, to the design have been considered. In addition, for two optimum quadrupole gradients, the wavelength dependence is investigated.

2 Results of simulations

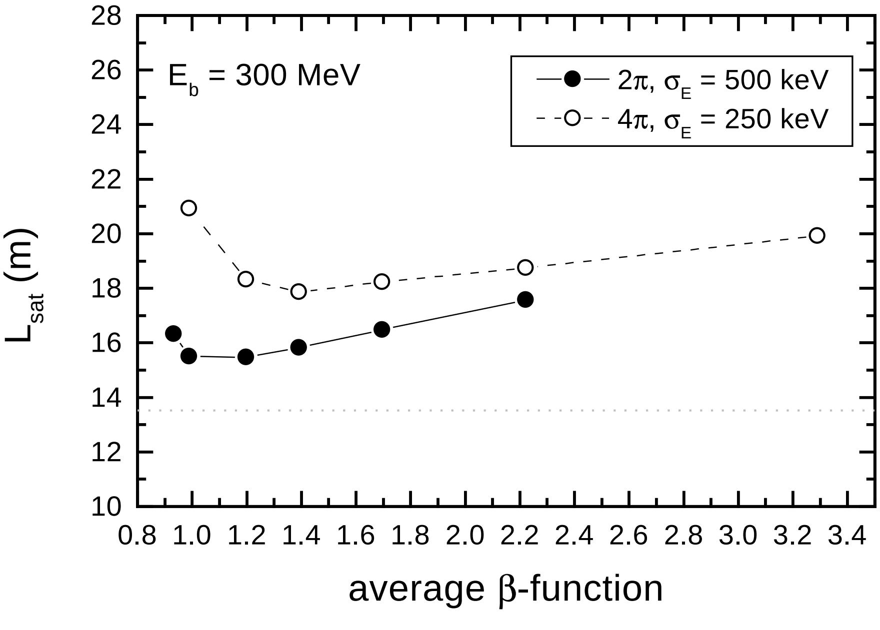

Figure 1: *The saturation length at a radiation wavelength of 70 nm for different values of the average β-function. The solid line represents an electron beam with an emittance of 2π and an energy spread of 500 keV and the dashed line 4π and 250 keV.*

The optimum β-function depends on the value of the emittance. At the nominal beam energy of 300 MeV, corresponding to a radiation wavelength of 70 nm, the quadrupole gradient has been varied from 25 T/m to 5 T/m in order to determine the optimum value of the average β-function. The length of the quadrupoles and the distance between them remains unchanged. Hence this is relatively easy to accomplish, but it would require a remeasuring and retuning of all quadrupoles in case one decides to change the values from phase I to phase II of the project. The beam parameters have been chosen equal to the present nominal values, $\epsilon_n = 2\pi$ and $\sigma_E = 500\,\mathrm{keV}$, and alternative values, $\epsilon_n = 4\pi$ and $\sigma_E = 250\,\mathrm{keV}$. Compared to phase II of the project, the first one corresponds to a two times larger longitudinal emittance, the second one to a two times larger transverse emittance. Results are shown in Fig. 1. The solid line, corresponding to the assumed beam parameters so far, gives a minimum saturation length for an average β-function of approximately 1 m, which is close to the present design. The quadrupole gradient required is between 20 and 15 T/m (design value is 18.3 T/m). For the larger emittance, the optimum β-function shifts to 1.4 m, corresponding to 12.5 T/m. As can be seen in Fig. 1, changing the quadrupole gradient from 18.3 T/m to 12.5 T/m hardly increases the saturation length for the first parameter set (solid line), namely from 15.5 to 16 m. For the gradient of 18.3 T/m, the increase in saturation length for the 4π mm mrad electron beam increases from 18 to 20 m, a much larger change.

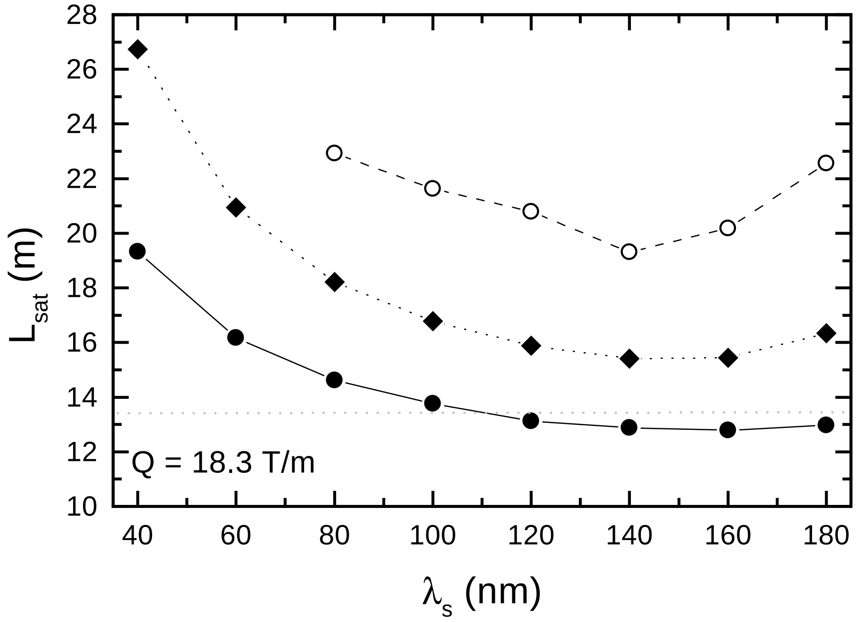

Figure 2: *Saturation length at different radiation wavelengths for a quadrupole strength of 18.3 T/m. The solid line represents an electron beam with an emittance of 2π and an energy spread of 500 keV, the dashed line4π and 500 keV and the dotted line 4π and 250 keV. The undulator length is 13.5 m.*

There are two additional advantages to use a smaller quadrupole gradient.

- Due to a smaller quadrupole gradient and thus a larger β-function, the electron beam radius increases. Therefore, the sensitivity to magnetic errors becomes smaller. For 300 MeV, the second field integral one has to achieve before errors start to decrease the gain increases from 10 to 12 Tmm^2. In case of an emittance of 4π, this value is even larger and thus the sensitivity to errors smaller by a factor of 1.4.

- The so-called saucaging of the electron beam (variation of the β-function due the discrete FODO-lattice) becomes smaller. $\beta_{\rm max}/\beta_{\rm min}$ reduces from 3 to 2 at 300 MeV. Therefore, the FODO lattice is stable over a larger electron beam energy range, e.g. for wavelengths up to 400 nm (120 MeV beam energy). Because the saturation length usually decreases for larger wavelengths, one can go down in energy further in order to achieve saturation within the three available undulator modules in phase I.

The effect of magnetic field errors for phase I parameters has been studied before [6]. The remainder of this report is dedicated to the study of the wavelength dependence of the saturation length and radiation power for the two different values of the quadrupole gradient that gave the minimum saturation length at 70 nm.

Fig. 2 shows the saturation length as a function of radiation wavelength for a quadrupole gradient of 18.3 T/m. The solid line corresponds to an electron beam emittance of 2π mm mrad and an energy spread of 500 keV. Saturation is reached within the three undulator modules (indicated by the dotted line at 13.5 m) for all wavelengths exceeding 110 nm. The minimum saturation length of 12.8 m is reached at 160 nm. Beyond this wavelength, the saturation length increases again due to the large value of saucaging ($\beta_{\rm max}/\beta_{\rm min} \geq 4.7$).[1] The dotted curve shows similar results for an electron beam with $\epsilon_n = 4\pi$ mm mrad and 250 keV energy spread. The power does not saturate within the three available modules, the minimum saturation length being 15.4 m at a radiation wavelength of 140 nm. The dashed curve represents an electron beam with $\epsilon_n = 4\pi$ mm mrad and 500 keV energy spread. For these electron beam parameters, the minimum saturation length is 19.3 m, again at 140 nm.

The fact that saturation is not reached within three modules is in itself not crucial for the proof of principle. However, in view of uncertainties, it is important not to loose too much power in order to be sure that one is well within the exponential gain regime. Fig. 3 shows the power that is reached at the end of the three undulator modules. The most pessimistic case ($\epsilon_n = 4\pi$ mm mrad and 500 keV energy spread) is not shown in this figure. The power level reached in this case is more than two orders of magnitude below saturation, even for the minimum saturation length. The power of the 2π electron beam is constant for wavelengths larger than 100 nm, which approximately corresponds to saturation. For the 4π electron beam, the maximum power is approximately a factor of 4 below saturation. This value is very sensitive to field errors. If saturation would have been reached, this sensitivity is much smaller. For example, if the saturation length of the 2π beam increases from 13 to 14 m (e.g. at 160 nm), the power drops only by some 30%. For the 4π beam this increase in saturation length by 1 m means a reduction in power by a factor 2 to 4. The wavelength with the smallest saturation length, i.e. the largest power at the end of the

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[1] The average value of β increases when the variation in β becomes too large

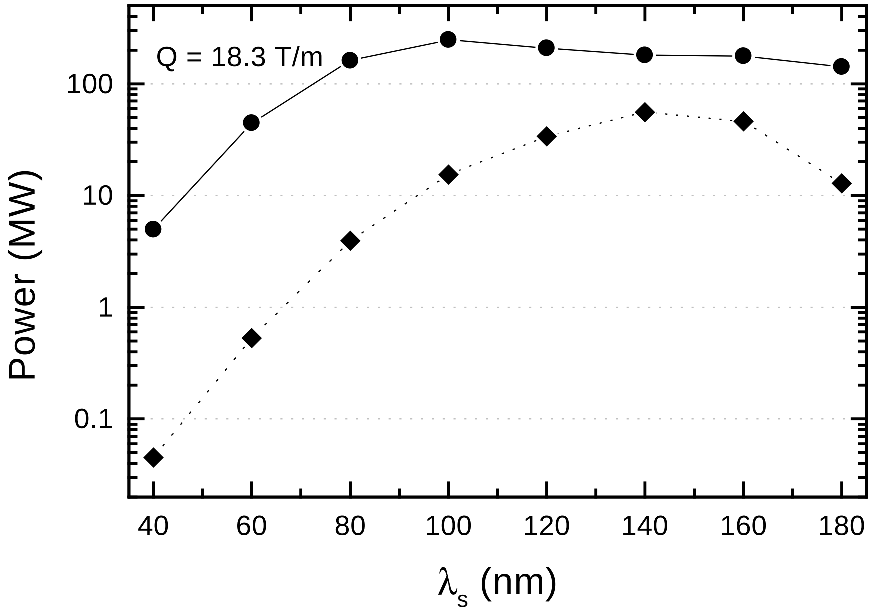

Figure 3: *Radiation power at the undulator exit for different radiation wavelengths for a quadrupole strength of 183 T/m. The solid line represents an electron beam with an emittance of* 2π *and an energy spread of 500 keV and the dotted line* 4π *and 250 keV.*

undulator, has the largest gain and therefore an increase by one meter results in the largest reduction in power.

The situation looks entirely different for the same FODO lattice but with a gradient of 12.5 T/m, as can be seen in Fig. 4. The same three curves are shown. The best case, corresponding to an electron beam with an emittance of 2π, reaches saturation for all wavelengths exceeding 120 nm, a small change compared to the situation in Fig. 2, where saturation was reach for all wavelengths exceeding 110 nm. Because of the much smaller saucaging ($\beta_{\mathrm{max}}/\beta_{\mathrm{min}} \leq 2.3$), the saturation length continues to decrease for larger wavelengths. The minimum corresponds to 12 m at 180 nm. Beyond this point, no simulations have been performed. In the worst case, with an emittance of 4π and an energy spread of 500 keV, the minimum saturation length has been reduced by approximately 2 m. The most important difference is, however, that for an electron beam with an emittance of 4π and an energy spread of 250 keV, the power saturates within three undulator modules for all radiation wavelengths larger than 140 nm. The minimum saturation length in this case is close to 180 nm.

The consequence for the power at the undulator exit can been seen in Fig. 5. For the worst beam parameters studied (not shown in this graph) the maximum power, obtained at a radiation wavelength of 160 nm, increases approximately by an order of magnitude compared the case with stronger focusing. For the two cases shown, the power exceeds 100 MW for wavelengths larger than 110 nm.

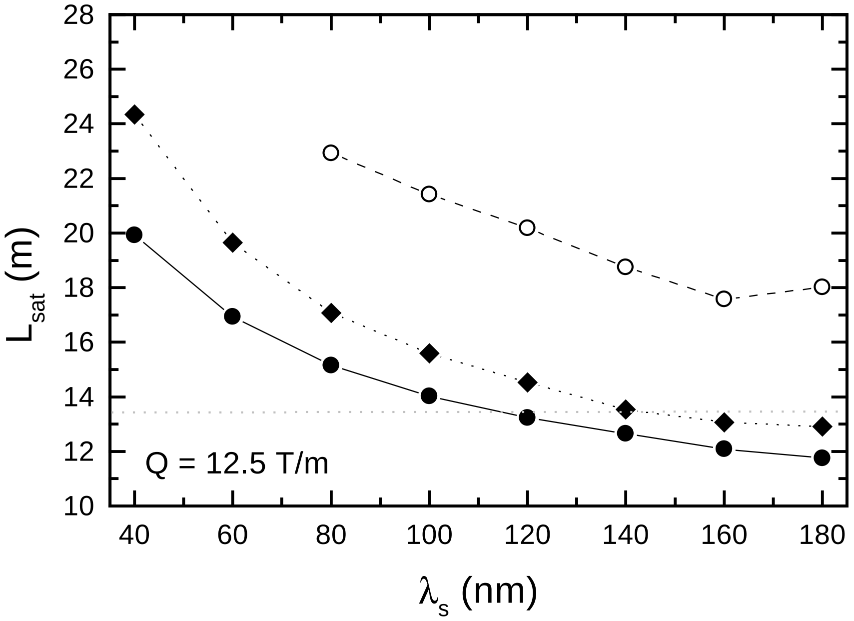

Figure 4: *Saturation length at different radiation wavelengths for a quadrupole strength of 12.5 T/m. The solid line represents an electron beam with an emittance of* 2π *and an energy spread of 500 keV, the dashed line*4π *and 500 keV and the dotted line* 4π *and 250 keV. The undulator length is 13.5 m.*

3 Conclusion and Discussion

One can say in general that a quadrupole gradient of 12.5 T/m is a better value than 18.3 T/m for phase I of the TTF-FEL, given the uncertainties in the beam parameters at this moment. For the design values of the electron beam parameters, the gain reduction is negligible compared to a gradient of 183 T/m, but if the emittance is larger than predicted, this gradient still guarantees that saturation can be reached at a longer wavelength. Because the saucaging is much smaller at a given beam energy due to a smaller phase advance per FODO cell the focusing structure is more stable. As a consequence, the saturation length decreases for wavelengths up to 180 nm. Furthermore, the undulator is less sensitive to magnetic field errors.

Because saturation is only possible at radiation wavelengths exceeding 120 nm, one should consider changing the wavelength for the SASE proof of principle experiment to this value. First simulations of the collimation systemneeded to protect the undulator have shown that it is possible with this reduced focusing strength to protect the undulator for all energies between 200 and 500 MeV [7]. In view of the sensitivity of the diagnostics equipment, which is designed to operate between 50 and 120 nm, the best choice for the proof of principle tests is at the longest wavelength, i.e. at 120 nm, corresponding to an electron beam energy of 230 MeV. This is well within the range of acceptance of all equipment and gives the best quarantee to reach saturation during the proof of principle experiment.

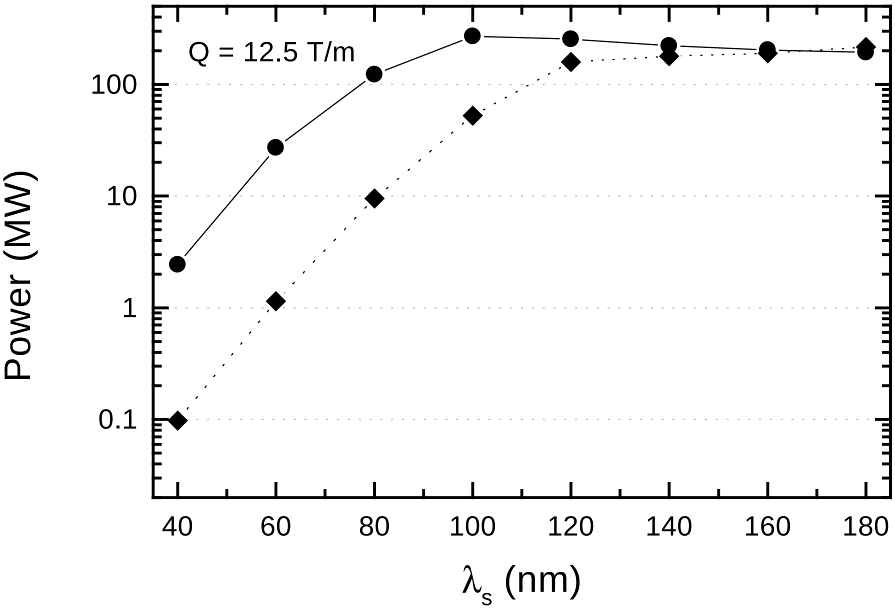

Figure 5: *Radiation power at the undulator exit for different radiation wavelengths for a quadrupole strength of 12.5 T/m. The solid line represents an electron beam with an emittance of* 2π *and an energy spread of 500 keV and the dotted line* 4π *and 250 keV.*

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