SENSITIVITY STUDY OF A TAPERED FREE-ELECTRON LASER

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Abstract

The output power of a free-electron laser (FEL) can be greatly enhanced by tapering the undulator line. In this work, a sensitivity study of a tapered FEL is presented. The study is conducted using the numerical simulation code GENESIS and a taper optimization method. Starting from a possible case for the future X-ray FEL at the MAX IV Laboratory in Lund, Sweden, a number of parameters are varied systematically and the impact on the FEL power is investigated. These parameters include the electron beam's initial energy, current, emittance, energy spread, as well as the seed radiation power.

INTRODUCTION

In a single-pass free-electron laser (FEL), the technique of undulator tapering involves the decrements in the deflection parameter a_w along the undulator line, thereby maintaining the resonance condition as the electrons lose energy to the radiation. This can increase the output power and the energy extraction efficiency, as has been demonstrated by experiments at the LLNL [1] and the LCLS [2].

The effectiveness of this technique relies on the proper optimization of the tapering profile $a_w(z)$. Two methods are the multidimensional scanning method by Jiao et al. [3] and the GINGER self-design taper algorithm [4] based on the Kroll-Morton-Rosenbluth (KMR) formalism [5]. In a previous work [6], we presented another method based on a modification of the KMR formalism and demonstrated, with numerical simulations, its higher efficiency of energy extraction than the GINGER algorithm.

Utilizing this method of taper optimization, we conduct a sensitivity study to determine the impact of various parameters on the power of a tapered FEL. The results shall provide insights into the development of an X-ray FEL at the MAX IV Laboratory [7], which is part of the laboratory's long-term strategic plan. The plan includes an extension of the MAX IV linear accelerator to 4–6 GeV, enabling the production of hard X-ray.

METHOD

Sensitivity Study

We carry out the sensitivity study using the numerical simulation code GENESIS [8] in the steady-state mode. The starting point is a possible case for the future X-ray FEL at the MAX IV Laboratory, with main parameters as shown in Table 1. We use this as the reference case for the purpose of our sensitivity study.

Table 1: Main Parameters for the Reference Case

Parameter		Value
Electron beam energy	E	4 GeV
Beam current	I	4 kA
Normalized emittance	$\varepsilon_{x,y}$	0.4 mm mrad
Average beta	$\bar{\beta}$	20 m
Energy spread	σ_E/E	1×10^{-4}
Undulator period	λ_w	20 mm
Radiation wavelength	λ	4 Å
Seed radiation power	P_{in}	5 MW

Based on the reference case, we vary five parameters systematically, one at a time. The parameters are the electron beam's energy, current, emittance, energy spread and the seed radiation power. For each parameter value, we apply our taper optimization method, so as to obtain the highest possible FEL power at the end of a 200-metre undulator line. Finally, we examine the impact that the variation of each parameter has on the FEL power.

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Taper Optimization

The taper optimization method used in this sensitivity study is the Modified KMR Method, which has been elucidated in a previous work of ours [6]. The method considers a reference particle with phase-space coordinates (ψ_R, γ_R) subject to the following constraints:

$$\gamma_R(z) = \sqrt{\frac{\lambda_w}{2\lambda}[1 + a_w^2(z)]}$$

$$\psi_R(z) = gz \text{ for some } g > 0.$$

The energy γ_R is always on resonance throughout the undulator line, while the phase ψ_R is made to increase linearly with distance z along the undulator line at some desired gradient g. Imposing these constraints on the particle's equation of motion results in a taper profile $a_w(z)$. In numerical simulations, we scan over different values of g to obtain the maximum FEL output power.

RESULTS AND DISCUSSIONS

Sensitivity to Beam Energy

The initial energy of the electron beam is 4 GeV in the reference case. We examine the effects of increasing the energy from 4 GeV to 5, 6 and 7 GeV. For each energy, we apply the taper optimization method to maximize the final FEL power at $z = 200$ m. The resulting FEL power curves and the corresponding taper profiles are shown in Fig. 1. The optimum g-values resulting from the taper optimizations are specified in the figure legend.

The reference case, with initial beam energy 4 GeV, produces a final FEL power of 1.6 TW. Upon increasing the initial beam energy, the FEL power shows a higher growth

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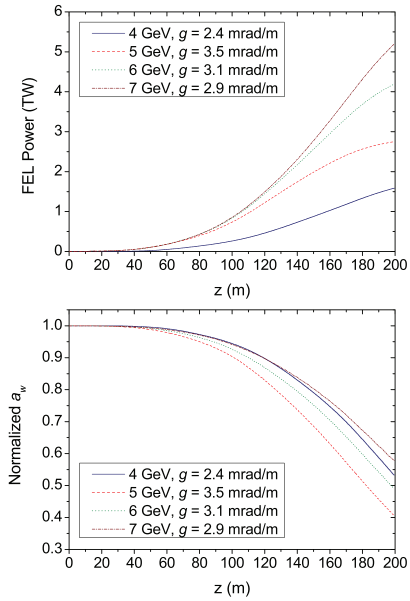

Figure 1: The FEL power curves (top) and the corresponding taper profiles (bottom) for different initial energies of the electron beam. In all the taper profiles, the a_w parameter is normalized to its initial value.

rate, hence a larger final value at $z = 200$ m (see Fig. 1). For every 1-GeV increase in the initial beam energy, there is at least an 1-TW increase in the final FEL power. In particular, an increase of initial beam energy from 4 GeV to 6 GeV results in an increase of final FEL power by 1.6 times.

Sensitivity to Beam Current

The initial current of the electron beam is 4 kA in the reference case. We vary the current around the reference-case value, from 3.0 kA to 5.5 kA at intervals of 0.5 kA. The FEL power curves and the corresponding taper profiles are shown in Fig. 2.

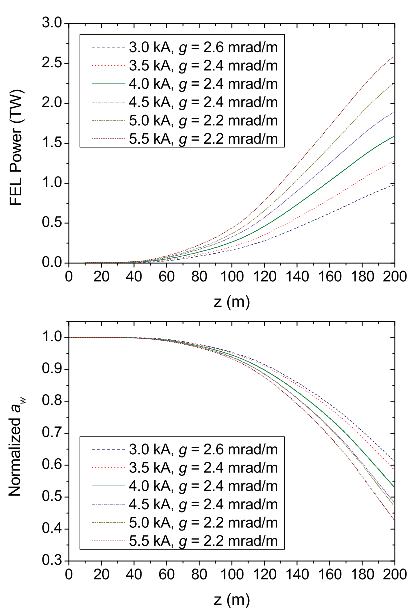

Figure 2: The FEL power curves (top) and the corresponding taper profiles (bottom) for different initial currents.

As seen in Fig. 2, a higher initial current results in a more rapid growth of FEL power. Also, the final FEL power at $z = 200$ m increases almost linearly with the initial current.

Sensitivity to Emittance

The initial emittance of the electron beam is 0.4 mm mrad (for both the x- and y-directions) in the reference case. We vary the emittance around the reference-case value. In particular, we decrease it to 0.2 and 0.3 mm mrad, and increase it to 0.6, 0.8 and 1.0 mm mrad. The FEL power curves and the corresponding taper profiles are given in Fig. 3.

The results show that a lower initial emittance yields a more rapid growth of FEL power. Also, the final FEL power at $z = 200$ m increases almost quadratically with the initial emittance. Reducing the initial emittance from 0.4 mm mrad to 0.2 mm mrad doubles the final FEL power.

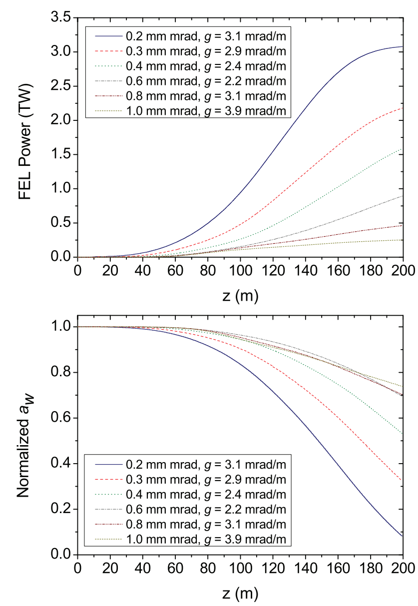

Figure 3: The FEL power curves (top) and the corresponding taper profiles (bottom) for different initial emittances.

Sensitivity to Energy Spread

The initial relative energy spread of the electron beam is 1×10^{-4} in the reference case. We examine the effects of increasing the value to 5×10^{-4}, as well as decreasing the value to 5×10^{-5} and 1×10^{-5}. The FEL power curves and the corresponding taper profiles are shown in Fig. 4.

There are two observations. First, increasing the energy spread from the reference-case value to 5×10^{-4} reduces the final FEL power almost by half. Second, decreasing the energy spread from the reference-case value has no appreciable impact on the FEL power.

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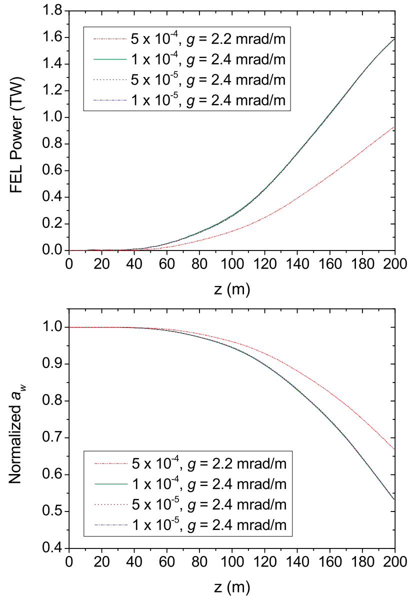

Figure 4: The FEL power curves (top) and the corresponding taper profiles (bottom) for different initial energy spreads. Note the overlapping of the curves for energy spread values 1×10^{-4}, 5×10^{-5} and 1×10^{-5}.

Sensitivity to Seed Power

The seeding of an FEL can be achieved by various methods [9], of which one example for hard X-ray FELs is self-seeding [10]. In this subsection, we study the sensitivity of the FEL performance to the seed radiation power, regardless of the seeding method.

In the reference case, the seed power is 5 MW. We examine the effects of changing the seed power to the following values: 50 kW, 500 kW, 50 MW and 500 MW. The resulting FEL power curves and the corresponding taper profiles are shown in Fig. 5.

Upon varying the the seed power, the FEL power curves exhibit the expected behaviours in the region of initial exponential growth (see inset of Fig. 5). With a higher seed power, the initial exponential growth and the initial saturation of FEL power occur within a shorter distance z down the undulator line. The higher is the seed power, the higher is the FEL power at the initial saturation.

While the seed power has a strong influence on the initial saturation power, its impact on the final FEL power at z = 200 m is relatively small (see Fig. 5).

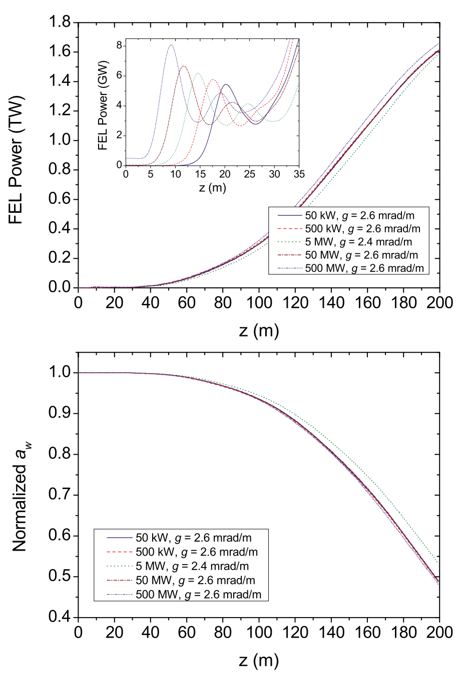

Figure 5: The FEL power curves (top) and the corresponding taper profiles (bottom) for different seed powers. The inset shows a magnification of the power curves for $z < 35$ m.

Taper Optimization

In each taper optimization, we scan over g for an optimum value that maximizes the final FEL power at z = 200 m, where g is the gradient of the linearly increasing phase $\psi_R(z) = gz$ of the reference particle. This subsection summarizes some general observations regarding the taper optimizations.

In general, a larger g leads to more rapid power growth beyond the initial saturation. However, the final saturation occurs at a lower power and at a smaller z. In contrast, a smaller g leads to slower power growth beyond the initial saturation. However, the final saturation occurs at a higher power and at a larger z, which is often beyond the undulator line simulated. The phase gradient g therefore serves as an independent adjustment knob for the final saturation power and the final saturation length of a tapered FEL. The optimum value of g depends on the length of the undulator line and the electron beam parameters.

From the sensitivity results presented in the previous subsections, we can also examine the dependence of the optimum g-value on the various parameters. First, the optimum g-value is largely unaffected by the seed power. Second, it remains the same for initial energy spread values below the reference-case value. Third, it decreases almost linearly with the initial beam current.

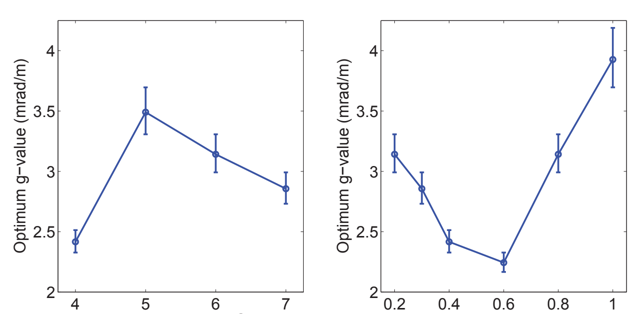

Figure 6: The dependence of the optimum g-values on the initial beam energy (left) and emittance (right).

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However, it is worth taking a closer look at the dependence on the initial beam energy, as well as the initial emittance. As seen in Fig. 6, the optimum g-value has a local maximum at some initial beam energy and a local minimum at some initial emittance. The significance behind these turning points is unknown. Further investigation is needed to understand the physical meaning behind these g-dependences.

CONCLUSION

We have presented a sensitivity study on a tapered FEL, based on a reference case for the future X-ray FEL at the MAX IV Laboratory [7]. Using of the numerical simulation code GENESIS [8], we apply the Modified KMR Method [6] to optimize the taper profile $a_w(z)$ in a 200-metre undulator line. In this method, the phase gradient g of the reference particle acts as an independent adjustment knob for the final saturation length and the final saturation power.

We have examined the dependence of the FEL output power on the initial beam energy, current, emittance, energy spread and the seed power. The results show that final FEL power increases with the initial beam energy and current, but decreases with the emittance. Meanwhile, the initial energy spread and the seed power have very little influence on the final FEL power.

Beyond this work, we shall further our sensitivity study by considering the effects of break sections in the undulator line, which are required for beam focusing and diagnostics. We shall also explore the possibility of fine-tuning our taper optimization method by considering quadratic or cubic functions for the reference particle's phase $\psi_R(z)$.

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