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Optimization of power output and study of electron beam energy spread in a Free Electron Laser oscillator

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Abstract

Design of a multi-stage depressed collector for efficient operation of a Free Electron Laser (FEL) oscillator requires knowledge of the electron beam energy distribution. This knowledge is necessary to determine the voltages of the depressed collector electrodes that optimize the collection efficiency and overall energy conversion efficiency of the FEL. The energy spread in the electron beam is due to interaction in the wiggler region, as electrons enter the interaction region at different phases relative to the EM wave. This interaction can be simulated well by a three-dimensional simulation code such as FEL3D. The main adjustable parameters that determine the electron beam energy spread after interaction are the e-beam current, the initial beam energy, and the quality factor of the resonator out-coupling coefficient. Using FEL3D, we study the influence of these parameters on the available radiation power and on the electron beam energy distribution at the undulator exit. Simulations performed for $I = 1.5\,\mathrm{A}$, $E = 1.4\,\mathrm{MeV}$, $L = 20\%$ (internal loss factor) showed that the highest radiated output power and smallest energy spread are attained for an output coupler transmission coefficient $T_\mathrm{m} \cong 30\%$. © 2001 Published by Elsevier Science B.V.

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1. Introduction

Good electron beam transport along the beamline of a Free Electron Laser (FEL) oscillator is essential in order to enable efficient energy exchange between the beam electrons and the electromagnetic wave inside the interaction region. Good transport is particularly important in electron beam energy recovery schemes such as a depressed collector in an Electrostatic Accelerator FEL (EA-FEL) [1–3]. At the entrance to the interaction region all the electrons have very nearly the same energy. In passing through the interaction region electrons may lose or gain a different amount of energy from the electromagnetic wave, depending on their entrance phase; consequently electrons have a large energy spread at the interaction region exit. Since the beam energy spread is generated by the nonlinear interaction process taking place in the resonator, it should be considered in the design of the FEL resonator. The resonator parameters (losses, output coupling coefficient) should be optimized for attaining both maximum output power emission and minimum energy spread [4,5].

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In this paper, we investigate the electron beam energy spread after the interaction region of the Israeli Tandem FEL [3] using our simulation code FEL3D [6,7]. The results will be used to optimize FEL operation and to determine the most efficient depressed collector voltages [8]. The study led us to the determination of the resonator parameters that provide highest output power and smallest electron energy spread. For the Tandem FEL, the optimal transmission coefficient of the resonator output coupler is $T_{\mathrm{m}} \cong 30\%$.

2. Resonator losses and power out-coupling

Our goal in this study is to find optimal operating conditions for an FEL oscillator. The desired optimization is primarily with regard to the output radiation power of the device. Another parameter of importance is the energy spread of the electron beam after the interaction region. This parameter determines the overall power efficiency that can be obtained in FELs with energy retrieval. In particular it affects the design of a multistage collector in an Electrostatic Accelerator FEL [8].

The model used for this study is depicted in Fig. 1. It is assumed that a single transverse mode $C(z)E(x, y)\exp(jk_z z)$ develops in the interaction region and is amplified along the wiggler. The resonator feedback loop is represented symbolically as a ring cavity, but can be generalized to an arbitrary shape. The output coupling mirror placed at the wiggler exit couples a power fraction T_{m} externally.

$$P_{\mathrm{out}} = T_{\mathrm{m}} P(L_{\mathrm{w}}). \tag{1}$$

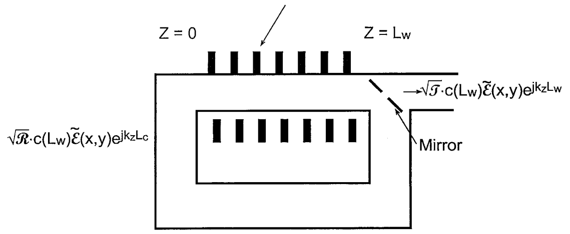

Fig. 1. A schematic of an FEL oscillator.

We lump all the internal losses, including mirror losses, ohmic losses on the waveguide walls, and diffraction losses, into one loss factor in the feedback loop.

Thus

$$P_{\mathrm{loss}} = L(1 - T_{\mathrm{m}})P(L_{\mathrm{w}}) \tag{2}$$

and the power feedback into the wiggler entrance after one round-trip is

$$P(0) = RP(L_{\mathrm{w}}) \tag{3}$$

where R is the round-trip power reflectivity factor

$$R = (1 - L)(1 - T_{\mathrm{m}}). \tag{4}$$

If the gain factor of the FEL, G, satisfies in the small signal (linear) regime the oscillation condition

$$GR > 1 \tag{5}$$

then any input signal $P(0)$ at the wiggler entrance will be amplified in each feedback round trip until the FEL is driven into saturation. At this point, the nonlinear gain G drops till Eq. (5) turns into an equality. The power output at steady state can be written in terms of the radiation power extracted from electron beam $\Delta P = P(L_{\mathrm{w}}) - (P(0))$ using Eqs. (1) and (2)

$$P_{\mathrm{out}} = T_{\mathrm{m}}/(1 - R)\Delta P. \tag{6}$$

3. Simulation of electron beam energy spread and output power in our Tandem FEL

We used our simulation codes to determine optimal parameters for the operation of the Tandem FEL [3]. On one hand, we are interested in obtaining maximum output power from the oscillator, and on the other hand, we would like to have minimal electron beam energy spread after the interaction region (for efficient energy retrieval).

The main degree of freedom we have for optimizing the oscillator performances is the mirror reflectivity T_{m}. Eq. (1) may suggest that increasing T_{m} increases the output power; however, it would also tend to decrease R and $P(L_{\mathrm{w}})$, and would eventually break the oscillation condition (5), stopping oscillation altogether. On the other hand, decreasing T_{m} increases R and $P(L_{\mathrm{w}})$,

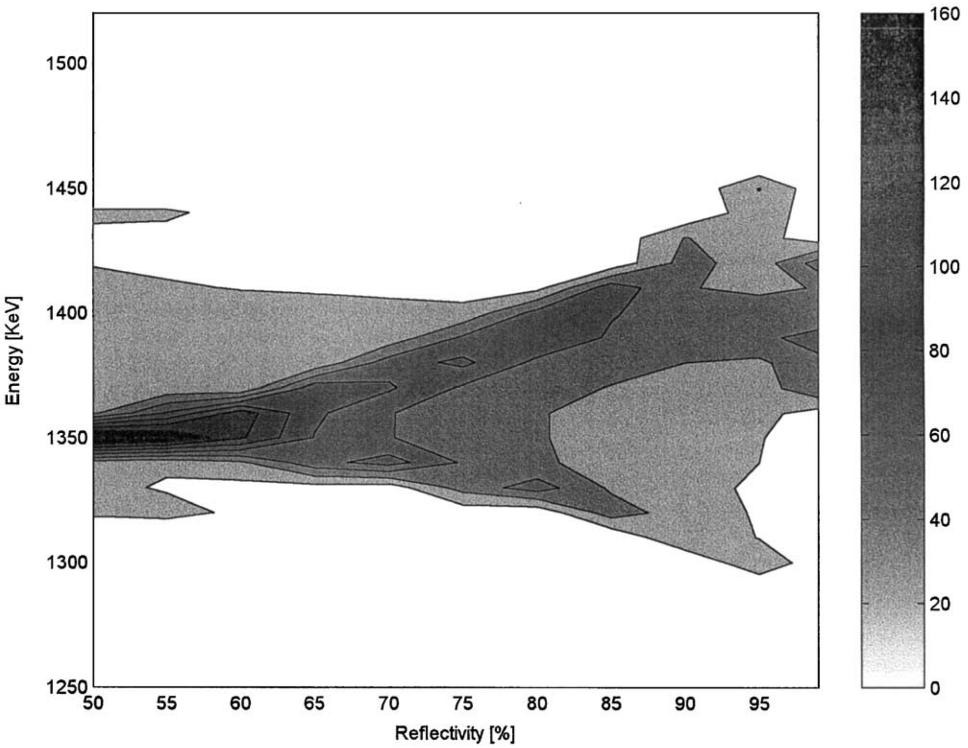

Fig. 2. Electron beam energy spread as function of the resonator reflectivity R (the gray scale indicates the number of electrons per energy interval).

but less power P_{out} couples out (Eq. (1)). Furthermore, considering a finite loss factor L, when T_m grows, the power loss (2) becomes significant relative to the output power (1), and the internal efficiency drops. Clearly, for a given L there must be an optimal value of $0 < T_m < 1$ for which P_{out} is maximal [9]. At the same time, since decreasing T_m drives the FEL deeper into saturation, it also tends to increase the e-beam energy spreads. Therefore, there should be an optimal value of T_m for which the beam energy spread is minimal.

Clearly, the optimization of the FEL oscillator design is a nonlinear problem that requires the use of a nonlinear computer code for simulation of the electron beam interaction with the resonator radiation field at saturation. For this purpose we use our code FEL3D [6,7], which simulates the oscillation buildup process in the FEL by solving exactly the FEL amplifier in each transversal along the wiggler, and, after each round trip, resetting the initial condition according to Eq. (3) (see Fig. 1). The signal frequency is chosen as the one having maximum small signal gain and minimum threshold for oscillation (5). This process is repeated until steady- state (saturation) is reached. For any given overall round-trip reflectivity value R, the operating point of the oscillator is fully determined. This includes full determination of the radiation power distribution inside the resonator (specifically $P(0)$, $P(L_w)$) and the distribution of the wasted electron beam energies. Note that these parameters are not dependent separately on T_m and L, only implicitly through (4).

Figs. 2–5 display the oscillator optimization study results for the parameters of the Israeli FEL given in Table 1 of Ref. [3]. Fig. 2 presents a map of the e-beam energy distribution after interaction, given as a function of the round trip reflectivity parameter R. The diagram indicates that excessive energy spread happens for large R as the FEL oscillator is driven deep into saturation. To keep the energy spread small, we

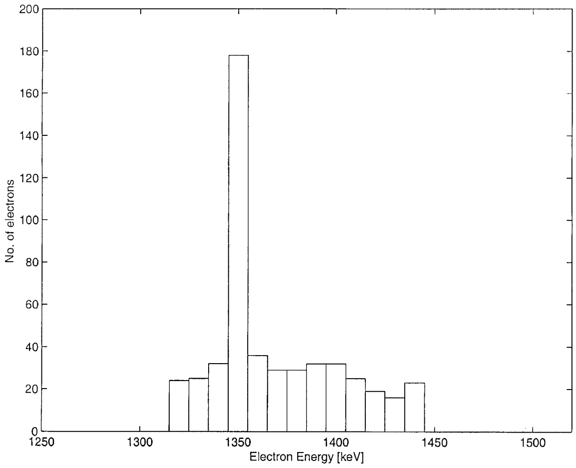

Fig. 3. Electron energy distribution at minimal electron energy spread conditions ($R = 50\%$).

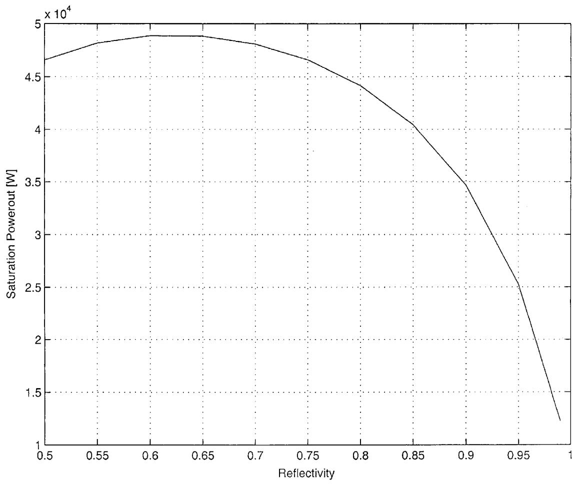

Fig. 4. The total power extracted from the e-beam ΔP and the power at the end of the resonator $P(L_w)$ as a function of the resonator reflectivity R.

will keep $R < 60\%$. Fig. 3 displays the energy distribution for $R = 50\%$ (near oscillation threshold).

Fig. 4 displays the saturation power at the end of the wiggler as a function of the resonator round trip reflectivity R. This curve was obtained by running FEL3D up to the saturation level for the parameters of Table 1 and changing values of R.

The output power of the FEL for a given T_m can be directly calculated from the curve of Fig. 4 using Eq. (1). In practice, usually the loss factor is

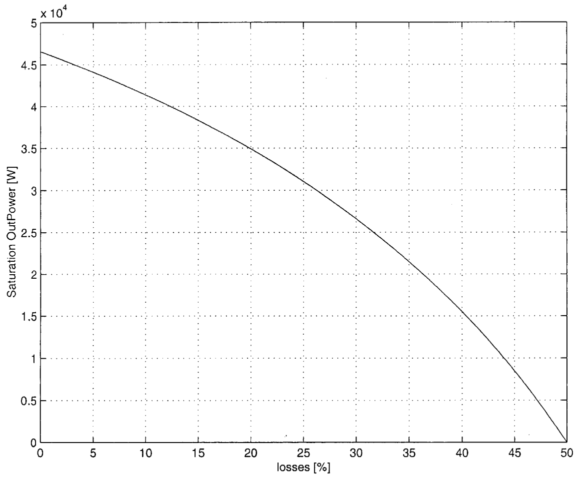

Fig. 5. The FEL output power P_{out} as a function of the out-coupling parameter of the resonator T_m, for different internal loss values L.

an uncontrollable given parameter and only T_m can be varied, either in the design stage, or (if the output coupler is controllable) in real time. For this reason, we provide a set of curves, useful for determining the maximum output power of the FEL oscillator for given loss factor parameter values.

From Fig. 5 we conclude that for an expected internal loss factor $L = 20\%$, maximum output power at the level of 35 kW is expected to be achieved with mirror transmission $T_m = 25-37\%$. Fortunately, the beam energy spread is smallest in the partially overlapping region $R = 55-65\%$ ($T_m = 20-30\%$). This overlapping region would therefore be the optimal operation regime of the FEL oscillator.

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