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Blau, J.

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Simulations of high-power free electron lasers with strongly focused electron and optical beams

J. Blau, V. Bouras, A. Kalfoutzos, G. Allgaier, T. Fontana,
P.P. Crooker, W.B. Colson*

Physics Department, Naval Postgraduate School, 833 Dyer Road, Monterey, CA 93943, USA

Abstract

A high-power free electron laser (FEL) is being designed in collaboration with Jefferson Laboratory, University of Maryland and Advanced Energy Systems, using short Rayleigh-length resonators to increase the spot size at the mirrors and hence avoid mirror damage. A short Rayleigh length implies a very small optical mode waist in the center of the cavity. It may be desirable to strongly focus the electron beam as well, to improve overlap with the intense optical fields in the interaction region. Three-dimensional simulations are used to study the effects of varying the electron beam radius and angular spread to enhance FEL gain and efficiency. The effects of off-axis shifting and tilting of the electron beam are also studied.

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1. Introduction

At the Naval Postgraduate School, we are designing a high-power free electron laser (FEL) for ship defense, in collaboration with Jefferson Laboratory, University of Maryland and Advanced Energy Systems [1]. A short Rayleigh-length resonator has been proposed to increase the spot size at the mirrors, and hence reduce mirror damage [2]. The Rayleigh length Z_0 is defined as the distance over which the optical mode doubles in area; in our simulations we normalize

it as $z_0 = Z_0/L$, where L is the undulator length. A typical FEL has $z_0 = 0.3$, while the proposed high-power FEL has $z_0 = 0.03$. This implies a nearly concentric cavity with a very small optical mode waist [3]. A slight misalignment of the electron beam, either an offset or a tilt, could conceivably reduce the overlap between the electrons and the optical mode in the center of the undulator, resulting in less gain and efficiency.

A given accelerator has a fixed normalized beam emittance, $\varepsilon_n = \gamma r_e \theta_e$, where γ is the Lorentz factor, r_e is the electron beam radius, and θ_e is the electron beam angular spread. In most FEL experiments, r_e and θ_e are “matched” so that the beam profile does not change significantly over the length of the

*Corresponding author. Tel.: +1-831-656-2765; fax: +1-831-656-2834.

E-mail address: colson@nps.navy.mil (W.B. Colson).

undulator [4]. For a typical Rayleigh length, a matched electron beam optimizes overlap with the optical mode. However, in a short Rayleigh length FEL, the electron beam could be focused with external magnets (decreasing r_e and increasing θ_e), optimizing overlap with the intense optical fields in the center of the undulator, and thus enhancing the gain and efficiency.

2. High-power FEL design parameters

The FEL design calls for a 185 MeV electron beam with a peak current of 3.2 kA, and bunches of length 0.1 mm at a repetition rate of 750 MHz. This corresponds to a dimensionless current density of $j = 210$. The average beam current is 0.8 A, so the electron beam carries 148 MW of average power. To obtain 1 MW of output power, the FEL extraction efficiency must be at least 0.7%. The normalized beam emittance is $\varepsilon_n = 8$ mm mrad, and the beam radius is $r_e = 0.14$ mm. The undulator consists of $N = 20$ periods, each of length $\lambda_0 = 3$ cm, for a total length of $L = 60$ cm. The optical wavelength is $\lambda = 1$ μ m. The optical cavity is $S = 12$ m long, with $\sim 70\%$ power transmission per pass. To reduce the power load on the mirrors, we have proposed a very short Rayleigh length of $Z_0 = 1.8$ cm. In that case, the optical mode waist radius is only $W_0 = 0.1$ mm, hence the requirement to carefully align the electron beam. The experimental design tolerances assume the beam will be aligned to within 0.01 mm of the undulator axis, with a tilt of no greater than 20 μ rad.

3. Simulation methods

To study this FEL, we use a three-dimensional simulation in x , y , and t , including the effects of diffraction and optical mode distortion [5]. The undulator is oriented along the z -axis, with the magnets normal to the y -axis. The simulation uses dimensionless coordinates: longitudinal lengths in z are divided by the undulator length L , transverse lengths in x and y are divided by $(L\lambda/\pi)^{1/2}$, and angles are divided by $(\lambda/\pi L)^{1/2}$.

The electrons are given an initial spread in positions (x, y) and angles (θ_x, θ_y) determined by the beam emittance and focusing. They can also be given an offset in position or angle, to study the effects of beam misalignment. As the electrons pass through the undulator, in addition to their fast wiggling motion in the xz -plane, they also undergo slower betatron oscillations in the yz -plane [4] described by

$$y = (y_0 + \Delta y)\cos(\omega_\beta(\tau - \tau_\beta)) + \frac{\theta_{y0} + \Delta\theta_y}{\omega_\beta}\sin(\omega_\beta(\tau - \tau_\beta)).$$

In this equation, the beam misalignment is described by an offset y_0 and a tilt θ_{y0} , while the beam emittance is described by a random position shift Δy and a random angular shift $\Delta\theta_y$. The dimensionless betatron frequency is given by $\omega_\beta = 2\pi NK/\gamma$. The dimensionless time $\tau = z/L$ corresponds to the electron's position along the undulator axis, and τ_β is the position where the electron beam is focused to its minimum size. If the electron beam is tilted but not shifted ($y_0 = 0$, $\theta_{y0} \neq 0$), then τ_β also corresponds to the position about which the beam is tilted.

In the longitudinal direction, the electrons evolve in phase space according to the FEL pendulum equation [4]. An electron's phase velocity is given by $v = L[(k + k_0)\beta_z - k]$, where $k = 2\pi/\lambda$ is the optical wave number, $k_0 = 2\pi/\lambda_0$ is the undulator wave number, and $\beta_z = v_z/c$. If the electron is injected off-axis by a distance y and at an angle θ_y , its phase velocity is reduced by $\Delta v = -(\omega_\beta^2 y^2 + \theta_y^2)$.

The optical wavefront evolution is described by the parabolic wave equation [4]. Appropriately shaped mirrors are placed at each end of the optical cavity. One of the mirrors is partially transmitting, with energy loss per pass determined by Q_n . The optical wavefront is started with an initial Gaussian profile, and evolves over many passes until a steady-state mode is obtained, and the extraction efficiency is calculated using $\eta = -\Delta\bar{v}/4\pi N$, where $\Delta\bar{v}$ is the shift in average electron phase velocity due to the FEL interaction.

4. Simulation results

Fig. 1 shows the simulation results for steady-state efficiency η versus initial phase velocity v_0 , for three values of normalized electron beam shift, $y_0 = 0, 0.4$, and 0.6 . In each case, the efficiency steadily increases as the phase velocity increases, with a sharp drop-off just after the peak, corresponding to the value of v_0 where the FEL gain drops below threshold.

Fig. 2 summarizes the results of many simulations, with the electron beam shift varied from $y_0 = 0$ to 1 in steps of 0.1. At each of these values of y_0 , the initial phase velocity v_0 was varied to determine the peak efficiency $\hat{\eta}$. The normalized beam shift that corresponds to 0.1 mm is indicated by an arrow on the horizontal axis at $y_0 = 0.23$.

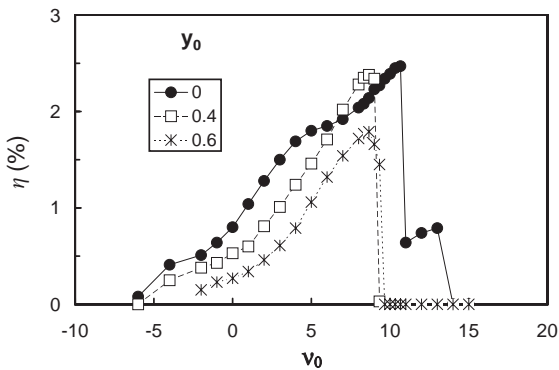


Fig. 1. Single-pass extraction efficiency η versus initial phase velocity v_0 , for three values of normalized electron beam offset y_0 .

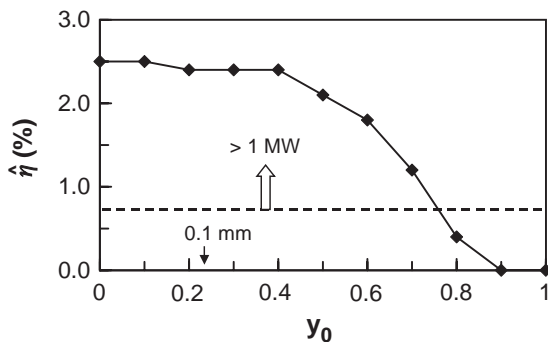


Fig. 2. Peak single-pass extraction efficiency $\hat{\eta}$ versus normalized electron beam offset y_0 .

The required efficiency to achieve the 1 MW goal is indicated by a dashed line at $\eta = 0.7\%$. The peak efficiency steadily decreases as the beam is further offset from the undulator axis, but remains above the MW goal for $y_0 < 0.8$, well beyond the design tolerance of 0.01 mm which corresponds to normalized value $y_0 = 0.02$.

Fig. 3 shows the simulation results for steady-state efficiency η versus initial phase velocity v_0 , for three values of normalized electron beam tilt, $\theta_{y0} = 0, 4$, and 6 , about the center of the undulator, $\tau_\beta = 0.5$. As before, the efficiency increases up to a peak, and then drops off sharply at the value of v_0 where the FEL gain falls below threshold. As the tilt angle is increased, the optimum value of v_0 increases.

Fig. 4 summarizes the results of many simulations, showing the peak efficiency $\hat{\eta}$ versus tilt

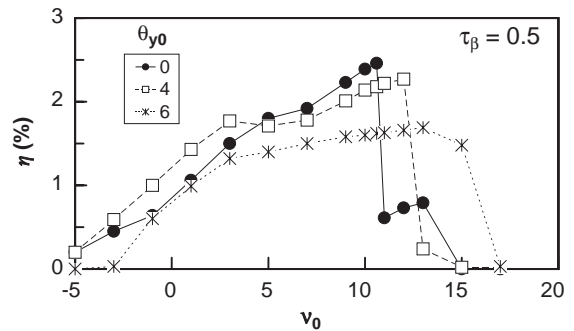


Fig. 3. Single-pass extraction efficiency η versus initial phase velocity v_0 , for three values of normalized electron beam tilt θ_{y0} through the center of the undulator ($\tau_\beta = 0.5$).

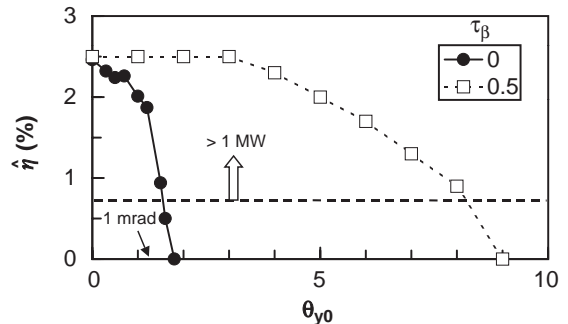


Fig. 4. Peak single-pass extraction efficiency $\hat{\eta}$ versus normalized electron beam tilt θ_{y0} at the beginning of the undulator ($\tau_\beta = 0$) and through the center of the undulator ($\tau_\beta = 0.5$).

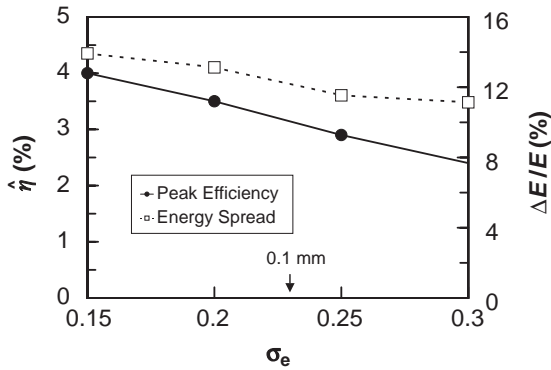


Fig. 5. Peak single-pass extraction efficiency $\hat{\eta}$ and induced energy spread $\Delta E/E$ versus normalized electron beam radius σ_e .

angle θ_{y0} , for an electron beam tilted at the beginning of the undulator ($\tau_\beta = 0$) and at the middle of the undulator ($\tau_\beta = 0.5$). The normalized tilt angle that corresponds to 1 mrad is indicated by an arrow on the horizontal axis at $\theta_{y0} = 1.4$. Of course, the FEL operation is more sensitive to beam tilt at the beginning of the undulator, but in both cases the efficiency remains above the MW goal well beyond the design tolerance of 20 μ rad (normalized angle $\theta_{y0} = 0.03$).

All of the results presented so far have used a matched electron beam. We have also studied electron beam focusing, by varying the electron beam waist radius, while keeping the total current and emittance fixed. Fig. 5 shows the simulation results for peak efficiency $\hat{\eta}$ versus normalized electron beam radius $\sigma_e = r_e(\pi/L\lambda)^{1/2}$ at the electron beam waist, focused at the middle of the undulator, $\tau_\beta = 0.5$. The normalized beam radius that corresponds to 0.1 mm is indicated by an

arrow on the horizontal axis at $\sigma_e = 0.23$. The largest value shown, $\sigma_e = 0.3$, corresponds to a matched beam for the parameters of this experiment. As σ_e is reduced by focusing the beam, the peak efficiency increases far beyond the needed value of 0.7%. This indicates that it may be possible to reduce the average current and still obtain the goal of 1 MW output power.

Also shown in Fig. 5 is the induced energy spread (full-width) in the electron beam due to the FEL interaction, $\Delta E/E$. The energy spread needs to be kept below 15% to facilitate beam recirculation; the figure shows that the spread increases from 11% to 14% as the beam is focused from $\sigma_e = 0.3$ to 0.15.

Acknowledgements

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