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SIMULATIONS OF THE JEFFERSON LAB FEL USING THE NEW ELECTROMAGNETIC WIGGLER [*]

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Abstract

After successfully lasing at 10 kW of average power at a wavelength of 6 μm, a new electromagnetic wiggler has been installed at Jefferson Lab, which will be used to achieve high power at shorter wavelengths. Wavefront propagation simulations are used to predict system performance for weak-field gain and steady-state extraction, as the bunch charge, pulse length, electron beam radius, Rayleigh length, and mirror output coupling are varied.

INTRODUCTION

In 2004, the free electron laser (FEL) at Jefferson Lab successfully lased at 6 μm, with an average power of 10 kW [1]. For that demonstration, they used an undulator with a period of 20 cm. This year, they have installed a new electromagnetic undulator, with a period of 8 cm [2]. This enables them to operate at wavelengths as short as 1 μm. It also allows them to study new effects, such as a short-Rayleigh length optical cavity [3].

This paper presents the results of research using simulations to study the effects of varying system parameters such as the electron beam bunch charge, pulse length, and beam waist radius, and the Rayleigh length and output coupling of the optical cavity. We also consider the effects of system misalignments, including shifting or tilting the mirrors and the electron beam.

SIMULATION METHOD

In this research, we use a three-dimensional, multimode simulation in (x, y, t), which solves the self-consistent Lorentz force and Maxwell wave equations. We start with a fundamental Gaussian mode in weak fields, and follow the wavefronts as they interact with the electrons and evolve to steady-state over many passes through the optical cavity, and we determine the weak-field gain and steady-state extraction. The latter is defined as the ratio of the output optical power to the initial electron beam power.

A recent improvement to our simulations incorporates an expanding coordinate system, which follows the light as it propagates from the ends of the wigglers all the way out to the mirrors with a fixed grid size [4]. This allows us to simulate realistic cavity lengths, as well as short-Rayleigh length optical cavities.

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FEL PARAMETERS

These simulations are based on the following set of parameters corresponding to the FEL operating conditions near the end of July 2005 [5]. The electron beam energy is $E_b = 111$ MeV, with a bunch charge of $q = 0.135$ nC, and a pulse duration of $t_b = 0.4$ ps. The transverse emittance is $\epsilon_n = 15$ mm-mrad, and the longitudinal emittance is $\epsilon_l = 80$ keV-ps. The undulator period is $\lambda_0 = 8$ cm, with $N = 29$ periods for a total length of $L = 2.3$ m. The rms undulator parameter is $K = 0.55$. This configuration produces light at a wavelength of $\lambda = 1.1$ μm. The optical cavity is $S = 32$ m long, with a Rayleigh length of $Z_0 = 0.9$ m, and 4% outcoupling corresponding to quality factor $Q_n = 25$.

SIMULATION RESULTS

Figure 1 shows the results of a series of simulations varying the electron bunch charge over a range from $q = 0.1$ nC

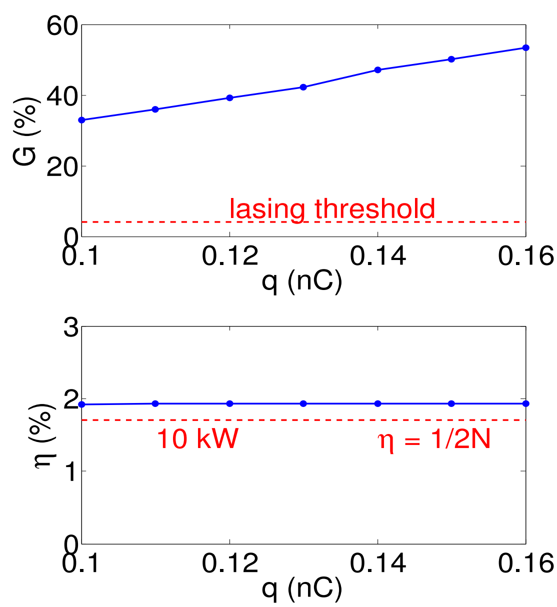

Figure 1: Weak-field gain G and steady-state extraction η versus electron bunch charge q. The gain increases linearly with q, while the extraction is constant. The minimum gain for lasing and the minimum extraction to achieve 10 kW output power are indicated by dashed red lines.

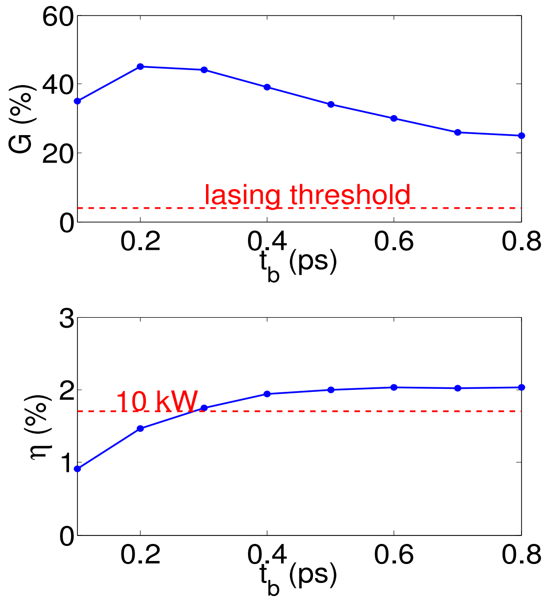

Figure 2: Weak-field gain G and steady-state extraction η versus electron pulse duration t_b. The output power is above 10 kW for $t_b > 0.3$ ps.

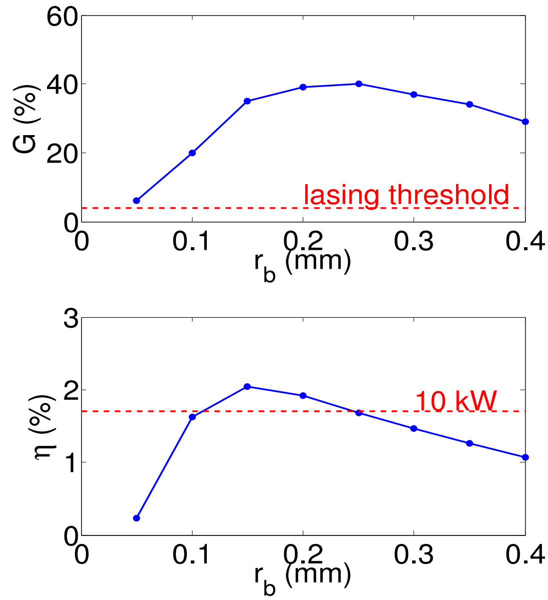

Figure 3: Weak-field gain G and steady-state extraction η versus electron beam waist radius, r_b. The optimum radius is $r_b \approx 0.2$ mm.

to 0.16 nC. As expected, the gain increases linearly with bunch charge; for the entire range, it is well above the lasing threshold, indicated by the dashed red line at $G = 4\%$. The extraction is not affected by the bunch charge; for all the cases it is $\eta = 1.9\%$, above the requirement for 10 kW output power, indicated by the dashed red line at $\eta = 1.7\%$. That is the same value that one would obtain from the simple FEL theory, $\eta = 1/(2N)$.

Figure 2 shows the results of simulations varying the electron pulse duration from $t_b = 0.1$ ps to 0.8 ps. The bunch charge and longitudinal emittance are held constant, so a shorter pulse implies higher peak current and increased energy spread. Notice again that the gain is well above the lasing threshold for the entire range, although it peaks at $t_b \approx 0.2$ ps. The extraction drops off for short pulses, due to the increased energy spread, but as the pulse duration increases above 0.3 ps, the goal of 10 kW output power is achieved. Note that these simulations do not include pulse slippage effects, so in reality the gain and extraction would likely drop off even more rapidly for short pulses.

Now we consider varying the electron beam radius, while holding the bunch charge and transverse emittance constant. Thus, a smaller beam radius corresponds to higher peak current and increased angular spread. Figure 3 shows the simulation results varying the beam radius from $r_b = 0.05$ mm to 0.4 mm. The gain and extraction drop off rapidly for narrower beams, since the corresponding increased angular spread reduces overlap with the optical mode, as depicted in the top part of Fig. 4. For broader beams, the gain and extraction also decrease because of reduced overlap with the intense optical mode in the center of the cavity, as shown in the bottom part of Fig. 4. Note that the length scales on the axes in this figure are not the same; the horizontal axis is $L = 2.3$ m long, while the vertical axis is only 9 mm wide.

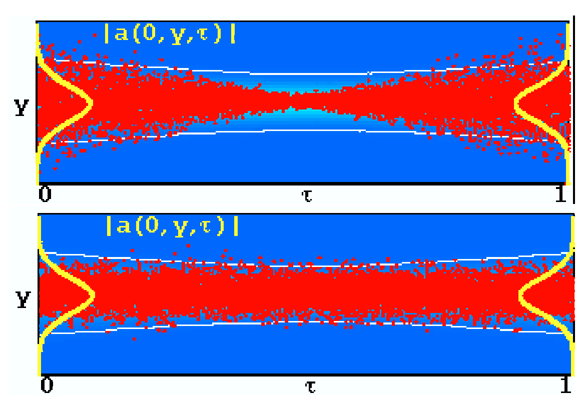

Figure 4: Simulation output showing a cross-section of the optical field amplitude $|a(y,\tau)|$ over a single pass through the undulator, with red dots representing sample electrons, for a narrow electron beam with waist radius $r_b = 0.1$ mm (top), and a broad electron beam with $r_b = 0.4$ mm (bottom). The yellow curves depict the optical mode profile $|a(y)|$ at the beginning ($\tau = 0$) and end ($\tau = 1$) of the undulator. The white line represents 5% of the peak optical field amplitude $|a|$.

Next we look at varying the Rayleigh length. Figure

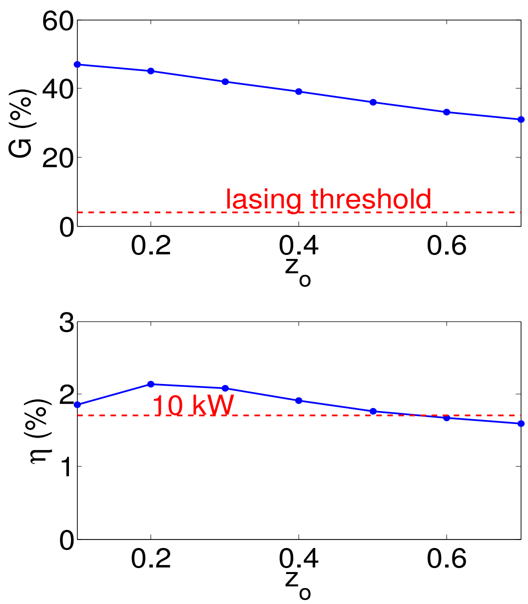

Figure 5: Weak-field gain G and steady-state extraction η versus normalized Rayleigh length, $z_0 = Z_0/L$. The gain increases as the Rayleigh length decreases; the optimum extraction is at $z_0 \approx 0.2$.

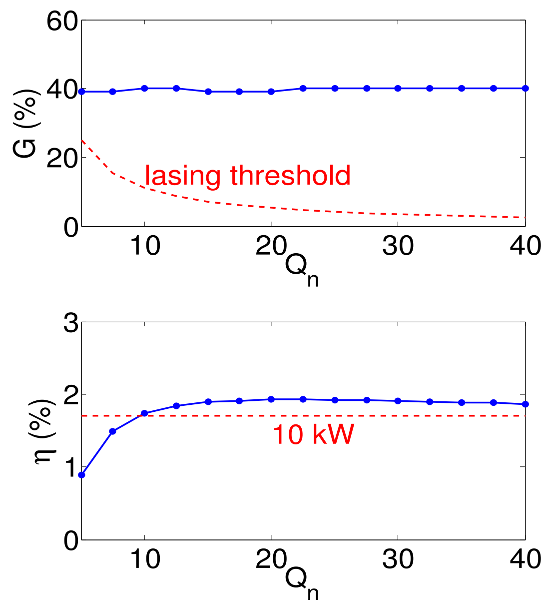

Figure 6: Weak-field gain G and steady-state extraction η versus resonator quality factor, Q_n. The output power is greater than 10 kW for $Q_n > 10$.

5 shows the simulation results, varying the normalized Rayleigh length, $z_0 = Z_0/L$, from 0.1 to 0.7. The Rayleigh length for a typical FEL is $z_0 \approx 0.4$, but our research has shown that there is an advantage to using a smaller value: not only is the optical intensity on the mirrors reduced, but also the FEL interaction is enhanced, yielding more gain and extraction [3]. As z_0 is reduced, the gain increases linearly; we believe this is due to optical mode distortion which occurs even in moderate-gain FELs [6]. However, as z_0 is reduced, the extraction eventually drops off, because with $Q_n = 25$, the steady-state gain in strong fields is only 4%,and there is very little mode distortion. Our simulations predict that the optimum Rayleigh length for this FEL is $z_0 \approx 0.2$.

Next, we consider varying the mirror output coupling. Figure 6 shows the results of simulations varying the quality factor $Q_n = 1/(\text{outcoupling})$ from 5 to 40. As expected, the weak-field gain is constant, but the extraction increases as Q_n grows up to about 20, as the FEL saturates in stronger optical fields. For larger values of $Q_n > 20$, the extraction levels off and even begins to drop slightly. However, these simulations do not include multiple longitudinal modes, which could allow the saturation power and the extraction to continue growing for larger values of Q_n.

We have also studied the effects of tilting and shifting the optical cavity and the electron beam. Cold-cavity theory predicts that for a nearly-concentric resonator such as this, a very small mirror tilt will cause a large tilt in the optical mode, [7, 8] but our simulations show that the gain medium (the electron beam) tends to keep the optical mode aligned, so that it overlaps the electron beam at the ends of the undulator, as show in Fig. 7.

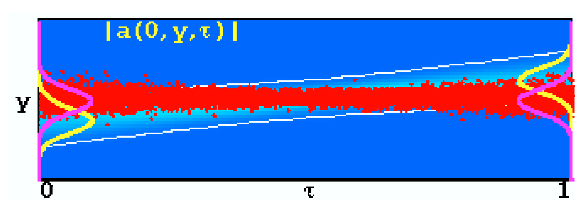

Figure 7: Simulation output showing a cross-section of the optical mode $|a(y,\tau)|$ over a single pass through the undulator, with red dots representing sample electrons, for an output mirror tilt of $\theta_m = 6\ \mu$rad. The yellow curves depict the optical mode profile $|a(y)|$ at the beginning ($\tau = 0$) and end ($\tau = 1$) of the undulator, and the purple curves depict the fundamental mode profile for no mirror tilt.

Figure 8 shows the simulation results for tilting the output mirror over a range from $\theta_m = 0\ \mu$rad to $8\ \mu$rad. As the mirror is tilted, the gain drops off steadily, but is above threshold for $\theta_m < 8\ \mu$rad. The extraction, however, is fairly constant up to about $4\ \mu$rad, before it begins to drop off, and the output power remains above 10 kW for $\theta_m < 5\ \mu$rad. This is well beyond the value that the mirrors can be held to with active alignment [9].

A similar result is obtained for shifting the output mirror. The gain remains well above threshold, and the output power above 10 kW, for a mirror shift $\Delta y_m < 75\ \mu$m.

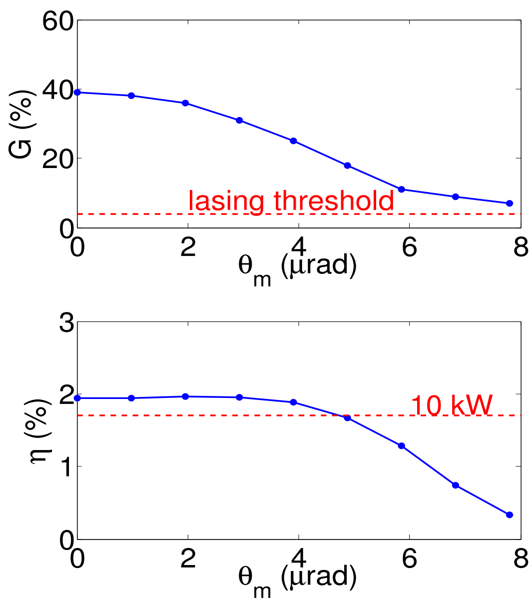

Figure 8: Weak-field gain G and steady-state extraction η versus output mirror tilt, θ_m. The output power is greater than 10 kW for $\theta_m < 5$ μrad.

Finally, we consider the effects of tilting and shifting the electron beam. When we tilted the electron beam about the center of the cavity, the optical mode did not follow the electron beam. The gain and extraction began to drop off as the overlap was reduced, but the output power remained above 10 kW for a beam tilt less than 0.75 mrad. When we shifted the electron beam off-axis, we observed that higher-order modes began to develop, as shown in Fig. 9. This effect has been observed in previous research [10]. However, the simulations predict that the total output power still remains above 10 kW for an electron beam shift less than 0.5 mm. These values for electron beam tilt and shift are well beyond the range that beams can be controlled experimentally [11].

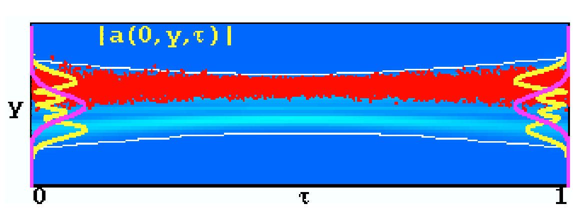

Figure 9: Simulation output showing a cross-section of the optical field amplitude $|a(y,\tau)|$ over a single pass through the undulator, with red dots representing sample electrons, for an electron beam shifted off-axis 0.9 mm. Note the presence of higher-order modes in the yellow curves, which depict the optical mode profile $|a(y)|$ at each end of the undulator.

CONCLUSIONS

The results of this research show that Jefferson Lab should be able to obtain over 10 kW of optical power at 1.1 μm with this FEL configuration, assuming there are no unforeseen problems with the optics or other system components. Simulations show the gain and extraction are quite sensitive to the electron beam radius; improving the beam emittance would reduce this sensitivity. Our simulations also indicate that the gain and extraction could be enhanced by reducing the Rayleigh length to a normalized value of around 0.2, which would have the important added benefit of reducing the power intensity on the mirrors. We have also established theoretical tolerances for misalignments of the cavity mirrors and the electron beam, and shown that these are well beyond what can be achieved experimentally.

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