SIMULATIONS OF HIGH POWER-FEL AMPLIFIERS*

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Abstract

FEL amplifier simulations have been updated and parallelized, and system vibration effects have been added. The simulations are used to study proposed high-power amplifier FELs at LANL and BNL. We look at the single-pass gain and output power, including the effects of wiggler tapering, electron beam pinching, and shifting and tilting of the electron beam.

INTRODUCTION

At the Naval Postgraduate School over the past several years, we have made significant changes to our simulations of FEL oscillators, including an improved light propagation method using expanding coordinates [1], cavity and electron beam stability effects [2], better diagnostics such as optical mode analysis [3], and parallelizing the codes to run on a cluster computer. These same improvements have now been incorporated into our FEL amplifier simulations. In this paper, we discuss the results of using these simulations to study several existing and proposed high-power FEL amplifiers at Brookhaven and Los Alamos National Labs. We look at the effects of tapering the undulator, as well as shifting, tilting, and focusing of the electron beam. We consider how each of these affect the single-pass gain, energy extraction, and optical beam quality.

SIMULATION METHOD

We represent the optical field using a Cartesian coordinate system, following the amplitude and phase at each (x, y) grid point as it evolves through the undulator. The initial field has a Gaussian transverse profile, focused at the beginning of the undulator. The electron and optical pulse lengths are assumed to be much longer than the slippage distance $N\lambda$, where N is the number of undulator periods and λ is the optical wavelength. We use a large number of sample electrons, with an initial position and angular distribution determined by the transverse emittance, and an initial energy spread determined by the longitudinal emittance. To study stability effects we can include an initial shift or tilt in the electron beam, and we can also adjust the beam focus position along the undulator.

At each time step within the undulator, the electrons evolve according to the Lorentz force equation, including betatron focusing. The optical field evolves self-consistently according to Maxwell's wave equation. At the end of the undulator, the field is propagated to the first optical element using an expanding coordinate system [1] to handle the large scale change due to diffraction.

In our simulations, we use dimensionless parameters, with longitudinal lengths normalized to the undulator length L, transverse lengths normalized to $\sqrt{L\lambda/\pi}$, and time normalized to L/c, where c is the speed of light. Graphical output from the simulations shows the evolution of the optical field, bunching of the electrons in phase space, and the structure of the optical wavefront at the end of the undulator and at the first optical element.

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SIMULATION RESULTS

Brookhaven SDL FEL

At the Source Development Lab (SDL) at Brookhaven National Lab (BNL), they have an FEL amplifier based on the NISUS undulator [4], with $N = 256$ periods, each $\lambda_0 = 3.9$ cm long, for a total length $L = N\lambda_0 \approx 10$ m. The undulator parameter is $K_{rms} = 0.78$. The electron beam has an energy of 102 MeV, with a bunch length of 1 ps and a bunch charge of 0.35 nC. The optical wavelength is $\lambda = 0.79$ μm, and the distance to the first optic is 20 m.

Figure 1 shows results from a simulation of this FEL. On the top, a cross-section of the dimensionless optical field amplitude $|a(y)|$ is represented as it evolves from the be-

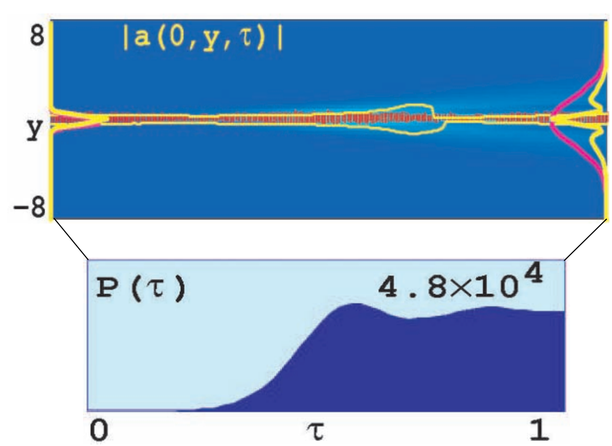

Figure 1: Simulation results for the SDL FEL with no taper. On the top is the evolution of the amplitude profile $|a(y)|$, as described in the text. On the bottom is the evolution of the dimensionless optical power $P(\tau)$ from the beginning ($\tau = 0$) to the end ($\tau = 1$) of the undulator. The maximum value of the power is indicated in arbitrary units.

ginning (dimensionless time $\tau = 0$) to the end ($\tau = 1$) of the undulator. The narrow yellow contour line marks the $1/e$ value of the field amplitude at each time step, while the bold yellow curves on the left and right plot the field profile at $\tau = 0$ and $\tau = 1$. A few sample electrons are shown in red. The simulation predicts high gain, $G \approx 1000$, which leads to optical mode distortion and guiding [5]. Without the gain medium, the field would maintain a Gaussian profile and diffract out to a large radius, as shown in purple on the right; the actual field profile shown in bold yellow is much narrower and distorted. The simulation predicts an extraction of $\eta = 0.6\%$ (extraction is defined as the ratio of the output optical power to the input electron beam power). In the actual experiment, an extraction of about 0.4% was measured. The difference is likely due to pulse slippage effects, which are not included in the simulation.

The lower half of Fig. 1 shows the power saturating about halfway down the undulator, so we consider tapering the magnetic field to enhance the extraction. Figure 2 shows the simulation results with a linear taper rate $\Delta K/K \approx -5\%$ over the last 2.4 m of the undulator. Now the power continues growing, and the extraction is increased to $\eta = 1.2\%$. The final electron phase space on the lower left shows about half of the electrons trapped in closed orbits [5]. The electron phase ζ roughly corresponds to the position of an electron within an optical wavelength, while $\nu = d\zeta/d\tau$ is the phase velocity. The induced spread in phase velocities $\Delta\nu$ translates to an electron beam energy spread $\Delta E/E = \Delta\nu/4\pi N = 3.7\%$, compared to 2.5% for the untapered case. The final optical wavefront $|a(x, y)|$ at the output mirror is shown in the lower right.

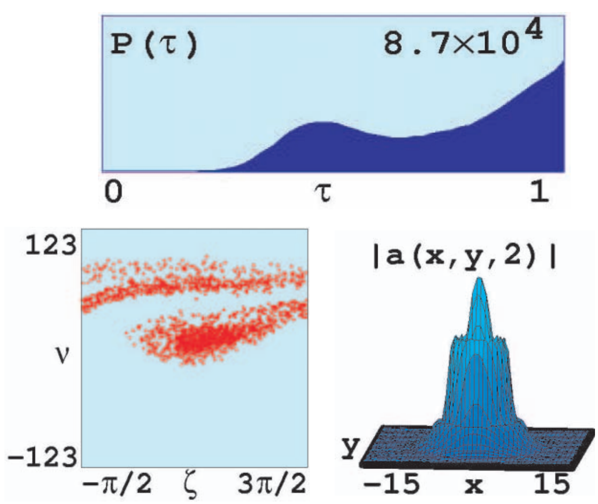

Figure 2: Simulation results for the SDL FEL with a -5% taper rate over the last 2.4 m of the undulator. On the top is the evolution of the optical power, $P(\tau)$. On the lower left is the final electron phase space as described in the text, with sample electrons shown in red. On the lower right is the final optical wavefront, $|a(x, y)|$, at the output mirror.

Another factor of two improvement in extraction could be achieved by starting the taper earlier at $\tau_s = 0.5$, near the onset of saturation for the untapered FEL. Figure 3 shows the results of many simulations, plotting extraction η versus phase acceleration δ for this latter case. The phase acceleration [5] is related to the undulator taper rate by

$$\delta = -4\pi N \frac{K^2}{1+K^2} \frac{(\Delta K/K)}{1-\tau_s}. \tag{1}$$

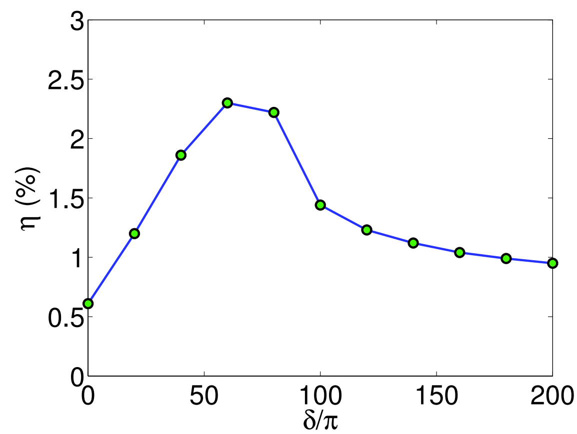

Figure 3: Extraction η versus phase acceleration δ for the SDL FEL, with a linear taper over the last 5 m of the undulator. The maximum extraction $\eta = 2.3\%$ is achieved for $\delta = 60\pi$, which corresponds to $\Delta K/K \approx -7\%$.

Figure 4 shows the results of simulating the SDL FEL with a taper rate of -7% over the last 5 m of the undulator, corresponding to the peak extraction value of 2.3% in Fig. 3. The optical power $P(\tau)$ grows significantly in the second half of the undulator, and the phase space plot shows good bunching. The induced energy spread is 5%.

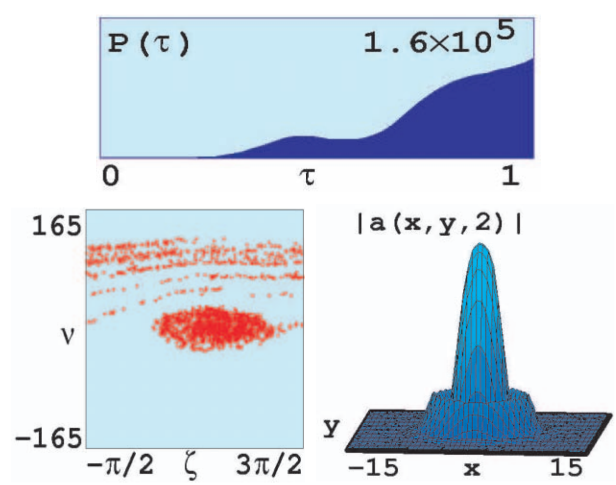

Figure 4: Simulation results for the SDL FEL, with a -7% taper rate over the last 5 m of the undulator.

Brookhaven proposed FEL

Another high-power amplifier FEL has been proposed at BNL [6]. This system would use an 80 MeV electron beam with a bunch length of 2.8 ps and a bunch charge of 1.4 nC. The undulator would have $N = 120$ periods, each $\lambda_0 = 3.25$ cm long, for a total length $L = 390$ cm, with $K_{rms} = 0.7$. The optical wavelength would be $\lambda = 1\ \mu$m, with the first optic at a distance of 27 m.

Figure 5 shows simulation results for this FEL. Again we see guiding of the optical field (top), and the power is near saturation at the end of the undulator (center). The simulation predicts gain $G \approx 800$ and corresponding extraction $\eta \approx 1\%$; the design goal for this system is $\eta = 0.25\%$. In the lower left, the electron phase space shows bunching, and an induced electron beam energy spread of 3.5%. In the lower right, the final optical wavefront has a nearly top-hat shape.

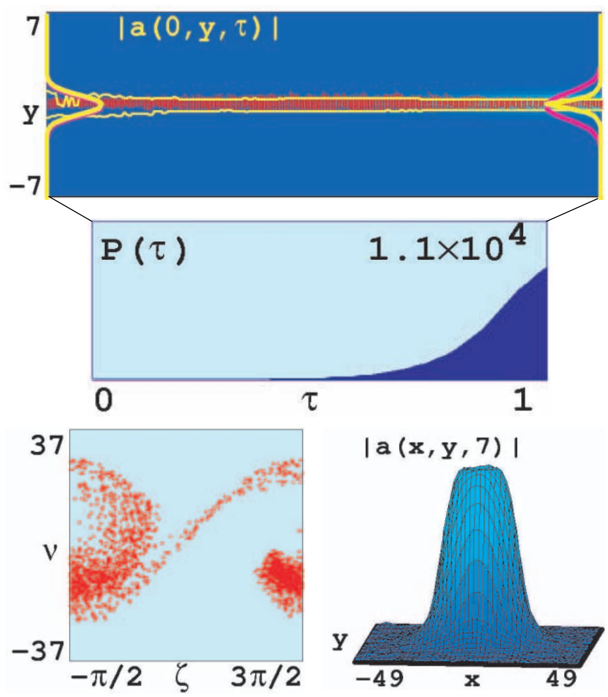

Figure 5: Simulation results for the proposed BNL FEL.

We also studied electron beam stability effects for this system. Figure 6 shows the results of many simulations, with the electron beam shifted off-axis in the plane of the undulator magnetic field. The extraction drops as the beam is shifted, but the design goal of $\eta = 0.25\%$ is still achieved for $y_0 < 1.2$ mm, about 5 times the electron beam radius ($r_b = 0.25$ mm, indicated on the graph). Figure 7 shows how guiding enables the optical mode to follow the shifted electron beam over about half of a betatron oscillation, for a beam shift of $y_0 = 1$ mm.

Figure 8 shows the effect of tilting the electron beam about the center of the undulator. The simulations predict that the system can tolerate a beam tilt of $\theta_y \approx 0.9$ mrad, well beyond the beam angular spread of $\Delta\theta = 0.1$ mrad.

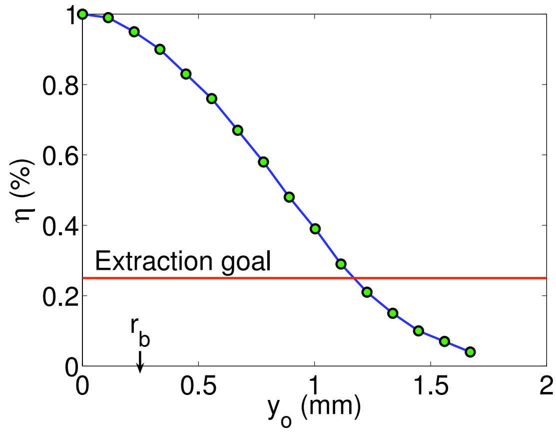

Figure 6: Extraction η vs. electron beam shift y_0 for the proposed BNL FEL. The extraction goal is exceeded for all values of $y_0 < 1.2$ mm, well beyond a typical experimental tolerance of $\approx 50\ \mu$m, and much greater than the electron beam radius $r_b = 0.25$ mm.

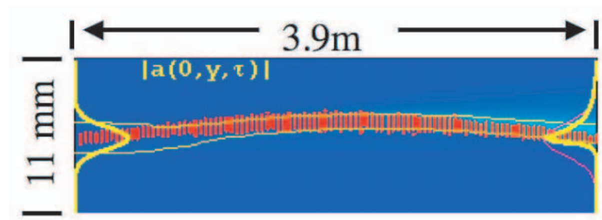

Figure 7: Optical field evolution for the proposed BNL FEL. Initial conditions are chosen so that the electron beam (shown in red) is shifted off-axis by $y_0 = 1$ mm at the center of the undulator. Betatron focusing bends the beam back towards the axis at the ends of the undulator. The horizontal and vertical axis scales are quite different, as indicated. Notice how guiding enables the optical mode (narrow contour line) to follow the electron beam as it shifts off axis.

Again, this is due to the guiding effect, as shown in Fig. 9. Our simulations predict good extraction for electron beam shifts x20 and tilts x100 greater than the experimental tolerance of existing FELs [7].

Los Alamos proposed FEL

At Los Alamos National Lab (LANL), they have proposed a somewhat different design for a high-power FEL amplifier [8]. This system would use an 81 MeV electron beam with a bunch length of 1 ps and a bunch charge of 1 nC. The undulator would have $N = 110$ periods, each $\lambda_0 = 2.18$ cm long, for a total length of $L = 240$ cm, with $K_{rms} = 1.2$. The optical wavelength would be $\lambda = 1.05\ \mu$m, with the first optic at a distance of 24 m.

Our simulations of this design predict that it would achieve a gain of $G \approx 240$, corresponding to extraction of $\eta = 0.74\%$, with induced energy spread of about 5%.

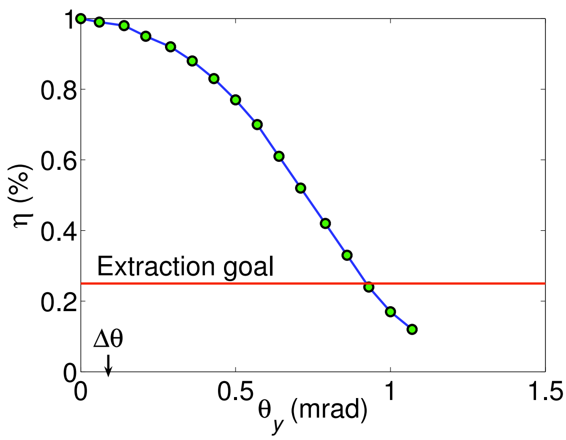

Figure 8: Extraction η vs. electron beam tilt θ_y for the proposed BNL FEL. The extraction goal is obtained for all values of $\theta_y < 0.9$ mrad, well beyond a typical experimental tolerance of 10 μrad, and much greater than the electron beam angular spread, $\Delta\theta = 0.1$ mrad.

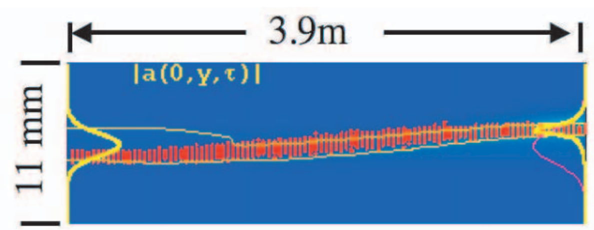

Figure 9: Optical field evolution for the proposed BNL FEL. Initial conditions are chosen so that the electron beam is tilted by $\theta_y = 0.9$ mrad at the center of the undulator. The tilt appears exaggerated due to the different horizontal and vertical scales. Notice that the optical mode (narrow yellow contour line) follows the tilted electron beam (red).

However, the design goal for this system is $\eta = 1.2\%$. We find that by tapering the undulator, $\Delta K/K \approx -18\%$ over the last 40 undulator periods, they could increase the gain to $G \approx 500$ and the extraction to $\eta = 1.7\%$, while only inducing an energy spread of about 6%.

We studied stability effects for the LANL amplifier design; our simulations predict that it will still achieve the desired extraction with beam shifts up to 0.4 mm, or beam tilts up to 0.4 mrad. These results are again well beyond the experimental tolerance of existing FELs.

We also tried varying the electron beam focus for this FEL. Figure 10 is a plot of the extraction versus the beam focus position, τ_β. The peak extraction $\eta \approx 1.9\%$ is at $\tau_\beta = 0.15$ or 0.75, rather than at $\tau_\beta = 0.5$ as one might expect. This is due to the betatron motion of the electrons, in both cases focusing the beam near the end of the undulator, where the tapering enhances the extraction. This "scalloped" shape of the electron beam, as seen in the inset plots in Fig. 10, leads to focusing of the optical wavefront at the undulator exit, thus allowing it to rapidly diffract afterwards, which should reduce the intensity at the first optic.

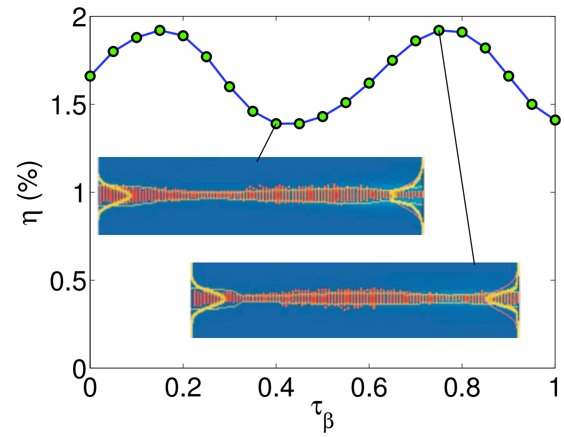

Figure 10: Extraction η vs. electron beam focus position τ_β for the proposed LANL FEL. The inset plots show the evolution of the electron beam and the optical mode at $\tau_\beta = 0.4$ (top) and $\tau_\beta = 0.75$ (bottom).

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