Gain and efficiency enhancement by a multicomponent wiggler free-electron laser

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A multicomponent wiggler scheme is presented as a possible solution to the problems associated with start up and saturation of a tapered wiggler free-electron laser oscillator: low small-signal gain and large shift of the output radiation frequency with input power. Optimization of the scheme is analyzed and it is shown that appropriate wiggler configurations can be found that enhance by an order of magnitude the small-signal gain and eliminate the shift in radiation frequency with input power.

Recently, there has been a large research effort towards the development of the free-electron laser (FEL) as a high average power source of infrared and visible electromagnetic radiation.[1–4] It has been demonstrated theoretically that the inherently low efficiency of a FEL at high input power ($P \gtrsim 1$ MW) and small output wavelengths ($\lambda_s \leq 10.6\ \mu$m) can be increased by appropriately tapering the wiggler field.[2,3] In this form, an efficient FEL amplifier could be obtained. A number of experiments are in progress to validate this theory.[4,5]

The enhanced gain of a high power FEL with a tapered wiggler, however, peaks at a given input power for which the taper is optimum; it decreases at other input powers.[6] Further, the output radiation frequency at which the gain is maximum as well as the gain spectrum width changes as a function of input power for a given taper.[7–9] Thus, a tapered wiggler free-electron laser (TWFEL) becomes less attractive as an oscillator. In this Communication we discuss how these unwanted oscillator characteristics might be eliminated by substituting the tapered wiggler by a more complex, multicomponent wiggler (MCW) configuration.[6,7,10]

The MCWFEL is based on the physical principles of both the TWFEL and the constant (untapered) wiggler free-electron laser (CWFEL). In a constant wiggler, the electron beam is injected with an energy (γ_{inj}) *above* the resonant energy (γ_R) in order to obtain maximum net deceleration of the electrons. γ_R is the energy associated with the phase velocity of the ponderomotive potential formed by the wiggler and radiation fields. In a TWFEL, the wiggler is tapered to vary with γ_R, in such a way that there is a resonant particle whose phase stays stationary all through the interaction length and a maximum number of electrons can be trapped in the ponderomotive potential well. The rate of deceleration in γ_R is proportional to the square root of the input power $P_s^{1/2}$; hence, for a given taper, there will be only one radiation power that is optimum (P_s^{op}). The optimum $\gamma_{\text{inj}} = \gamma_{\text{inj}}^{\text{op}}$ at this power is equal to γ_R to maximize the number of trapped electrons. For radiation powers smaller than the optimum, the closed orbits open up and the particles remain untrapped. Energy extraction can occur if the average energy relative to γ_R increases at a slower rate than the decrease in γ_R due to the wiggler taper. This, in turn, requires $\gamma_{\text{inj}}^{\text{op}} < \gamma_R$. For a practical oscillator γ_{inj} remains fixed and therefore, as the power in the cavity increases, the output frequency shifts in such a way to "reaccommodate" the resonant energy so that the difference $\gamma_{\text{inj}} - \gamma_R$ has the optimum value for maximum gain. For any taper $\Delta = \Delta B_w / B_w$, the fractional change in the wiggler field B_w, there is an optimum power for maximum gain operation, and this power increases with Δ^2 and decreases with the interaction length.[2] In addition, for any Δ the gain spectrum shifts as a function of increasing power with larger shifts occurring for larger tapers.

In the MCWFEL oscillator scheme, a number of wiggler components are utilized in such a way that each component operates at its own optimum power and either is transparent or enhances the performance of other components at other powers. In addition, in order to reduce the gain spectrum width, the various wiggler components are chosen with different wavelengths λ_w and amplitudes B_w, and separated by proper amounts of drift space in such a way that γ_R is different for each component and $\gamma_{\text{inj}} = \gamma_{\text{inj}}^{\text{op}}$ in each section.

The simplest MCW combination is a two-component one consisting of a CW followed by, or following, a tapered wiggler (TW). Since $\gamma_{\text{inj}}^{\text{op}} > \gamma_R^{\text{CW}}$, but $\gamma_{\text{inj}}^{\text{op}} \simeq \gamma_R^{\text{TW}}$, λ_w and B_w are chosen in such a way that $\gamma_R^{\text{CW}} < \gamma_R^{\text{TW}}$. The small-signal gain is enhanced by the constant wiggler section. If the CW is located before the TW, the electrons can be "bunched" in phase space at the end of the CW. The optimum bunch phase depends on the taper.[2] Thus, in order to introduce the electrons in the TW in a proper phase at high powers, a very small drift space ($\lesssim \lambda_w$) is required. On the other hand, if the CW is located after the TW, due to the very low small-signal gain of the TW, no bunching occurs in the electrons before entering the CW for low input powers and the CW is transparent to high powers.

In addition, the large-signal gain can be enhanced by a system similar to an optical klystron.[6,7,11–13] That is, a large drift space where the electrons bunch as they free stream can be added between the CW and TW components to increase the number of trapped electrons for the TW operation. The drift length necessary to achieve electron bunching is calculated as the length that it takes particles separated in energy by $\delta\gamma/\gamma$ and in space by half a radiation wavelength to come together. This length is $L_D = \lambda_s \gamma^2/[2(\delta\gamma/\gamma)]$, where $(\delta\gamma/\gamma)$ is induced by the synchrotron rotation in the ponderomotive potential. The drift length L can be substituted by a dispersion magnet which produces an "effective drift distance" proportional to L^3 and therefore permits to enhance the gain with shorter devices.[7,13]

In order to obtain quantitative confirmation of these ideas, they were numerically investigated utilizing the TRW one-dimensional code that includes diffraction effects of the input Gaussian optical beam and finite electron beam emittance.[6] The basic features of this code are similar to those utilized to describe the characteristics of the CW and TWFEL.[2,14] The numerical results presented here utilize the optimum parameters of the TRW experiment[4]: $\lambda_s = 10.6\ \mu$m, electron beam energy $E_b \simeq 25$ MeV, electron beam peak current $I \simeq 40$ A, electron beam radius $r_e \simeq 2.25$ mm $\simeq$ photon beam waist r_p, total interaction length $L \leq 4$ m, effective energy spread (square) $\Delta\gamma/\gamma = 0.5\%$, and $a_w = (eB_w\lambda_w/2\pi mc^2) \simeq 0.98$. Figure 1 shows the gain spectrum obtained for a simple $L = 4$ m tapered wiggler FEL for different input powers. The large taper is required to obtain sufficiently high gain ($> 8\%$) at 500 MW (for smaller tapers the gain peaks at smaller cavity powers). For $P_s < 1$ MW the gain is below 5% with a wide spectrum, $\Delta\omega/\omega > 4\%$.

In order to test the MCW idea, we first simulated a 3-m two-component wiggler as illustrated in Fig. 2. In that figure and the following figures, $\Delta a_w/a_w$ represents the fractional change in a_w through the wiggler. Case (1) corresponds to a 1-m CW followed by a 2-m TW separated by a 1-cm phase adjustment section, and the order of the components is inverted for case (2). The parameters are chosen in such a way that $\gamma_R^{CW} < \gamma_R^{TW}$ and $\gamma_{inj} = \gamma_R^{TW}$ is optimum for the whole system. The exact parameters utilized in the simulation are indicated in the figure. The taper utilized, $\Delta = 20\%$, would correspond to an optimum power of 500 MW for a simple TW with $L = 2$ m and of 100 MW if $L = 3$ m. The gain curve (gain versus power, at fixed γ) for the simple TWFEL is also shown in Fig. 2. The effect of the 1-m CW section in case (1) is to increase the small-signal gain over that of a simple 3-m TWFEL by a factor larger than 10. At very high powers ($P > 500$ MW) the system behaves as a simple 3-m TW of $\Delta = 20\%$. The gain at 100 MW is enhanced by a factor of almost 2 and the optimum power now occurs at 50 MW. For case (2), the small-signal gain is also increased by almost a factor of 10, however, for very high powers the system behaves as a simple 2-m TWFEL.

In case (1), the initial CW acts as a buncher section of the TW and the optimum power of this device is smaller than that of a 3-m TW for the same taper Δ. For very high powers, the bucket size is sufficiently large that the increase in bunching does not play an important role and the whole system behaves as a 3-m TWFEL. For case (2), the CW is practically transparent to high powers and all the gain is determined by the 2-m TW. The dip in the curve is due to the fact that this system essentially behaves like two separate components and the optimum power of the 2-m TW is at those high powers for which the CW gain curve is already very small. Obviously, several possibilities can be suggested to obtain a monotonically decreasing gain curve with sufficient

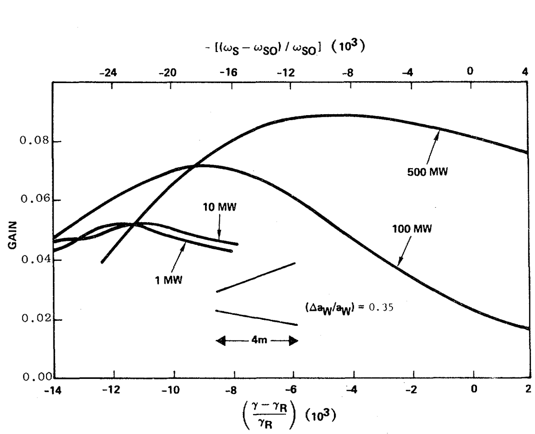

FIG. 1. Gain spectrum for different input powers—TWFEL.

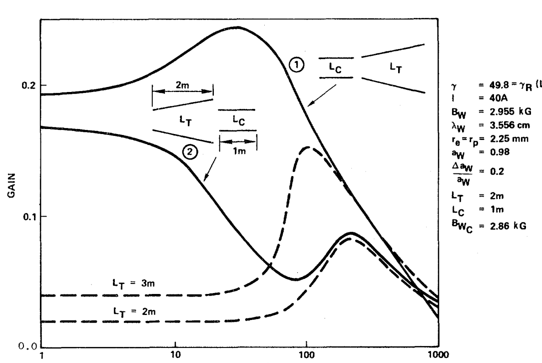

FIG. 2. Multicomponent FEL (MCFEL) gain vs input power for a two-component wiggler FEL. Dashed lines are gain curves for simple TWFEL's.

gain at high powers. For example, a system similar to (2) with a very small taper ($\Delta \sim 1\%$ or so) for the first section will decrease by a very small amount the small-signal gain but will increase the gain at the dip. Another possibility is to consider the effect of drift sections in the high-signal gain.

In order to test the optical klystron idea for a TWFEL, a three-component wiggler (CW, drift space, TW) was simulated, as shown in Fig. 3. In this figure the results obtained for a short prebuncher CW section ($L_C = 15$ cm) followed by an $L_D = 1$-m drift section and by a 3- and a 2-m TW section, respectively, are compared with those of simple 3- and 2-m TWFEL's whose P_s^{op} occur at 100 and 500 MW, respectively. The three-component wiggler comparison is then made on the basis of where the P_s^{op} occurs. A comparison with a simple TWFEL of $L = 4$ m with P_s^{op} at 500 MW can be made by utilizing Fig. 1. The lengths L_C and L_D were chosen to maximize the bunching at high power. The gain and efficiency are enhanced at P_s^{op} by a factor of almost 2. This enhancement will not be effective if the potential well is full from the beginning; in that case the particles bunched in phase space will spread in energy beyond the well.

As a final demonstration of the possibilities of a MCW system for FEL oscillators, a four-component system was simulated as illustrated in Fig. 4. Essentially, a prebuncher (CW plus drift section) was added to the case (2), of Fig. 2. In addition, the taper was decreased to 13% corresponding to an optimum power of the simple 2-m TW near 100 MW, coincident with the optimum power of a simple 3-m TW with $\Delta = 0.20$. In this system the small-signal gain is further enhanced by utilizing the whole initial 3 m as a prebuncher and drift space for the final 1-m CW section. Note that the small-signal gain is 60% compared to 20% in Fig. 2 and less than 3% for the single 3-m TW. The high-signal gain is increased over that of a 3-m taper due to the prebuncher; however, this

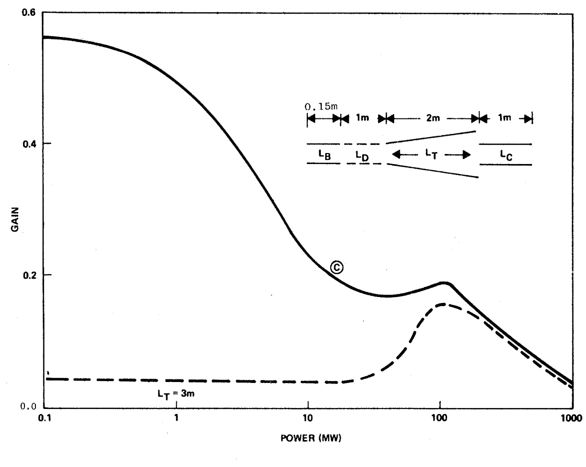

FIG. 4. Multicomponent FEL gain vs input power for a three-component wiggler with drift space; same parameters as Fig. 3 except $\Delta = 0.133$, $\gamma = \gamma_R(L_B) = \gamma_R(L_T)$. Dashed line is gain curve for a simple TW with $L_T = 3$ m.

increase is less than a factor of 2 due to the initial energy spread (0.5%) of the electron beam. In addition, the whole gain curve has an almost (except for the small bump at a 100 MW) monotonically decreasing characteristic. The case shown in Fig. 4 has a total single pass efficient $\eta \simeq 3\%$ at $P \simeq 600$ MW which is assumed to be the saturation power for a cavity loss of 5%.

More important than to show plain gain enhancement is to look at the improvement in the gain spectrum. Comparison between Figs. 1 and 5 shows the decrease (with respect to that of a simple $L = 4$ m TWFEL) in the spectrum width for small signals, the increase of the maximum gain peak, and the almost negligible shift in the peak for the MCW of total $L = 4$ m. This is due to flexibility of choosing different γ_R for the different sections of the MCW.

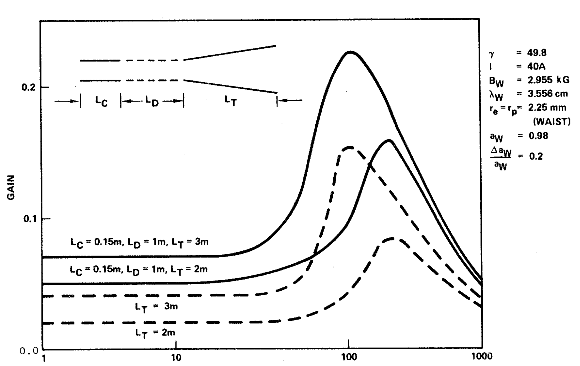

FIG. 3 Multicomponent FEL gain vs input power for a TW with prebuncher (two components with drift space). Dashed lines are gain curves for simple TWFEL's.

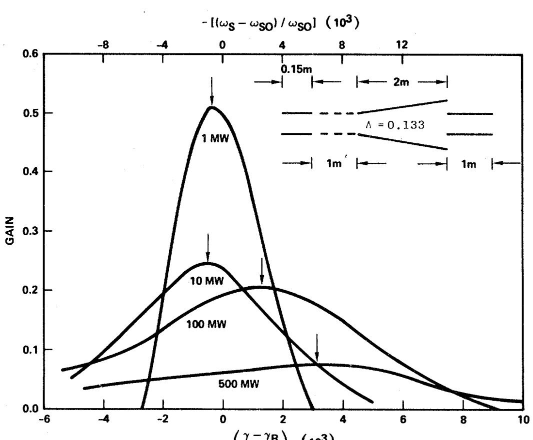

FIG. 5. Multicomponent FEL gain spectrum for different input powers.

These results can be optimized further by utilizing a very small taper wiggler instead of the CW. The number of photon passes calculated to obtain saturation at 600 MW, assuming an injected power of 1 MW, was 90 for the case shown in Fig. 4. It should be noted that the total length of the MCWFEL can be reduced by utilizing a dispersion magnet instead of a drift section.

Although we have presented here specific numerical examples, the use of appropriate CW and drift sections will enhance the gain and efficiency and decrease the gain spectrum width of *any* TWFEL. The appropriate length and Δ for each section is determined by calculating the length necessary to produce an energy modulation $\Delta\gamma$ and the bunching drift length L_D for different input powers, the taper for optimum power at P_s^{op} for the *total* effective length and by arranging the sections so that $\gamma > \gamma_R^{\mathrm{CW}}$ at low powers and $\gamma = \gamma_R^{\mathrm{TW}}$ at $P \sim P_s^{\mathrm{op}}$.

In conclusion, we have analyzed the main characteristics that determine the gain and gain spectrum versus power curves for different tapers and developed a scheme that permits the operation of the FEL as an oscillator, at very high powers. The scheme MCWFEL increases the small-signal gain by a factor larger than 10, provides a smooth gain curve, and decreases or eliminates the possibility of frequency chirp due to nonoptimum electron beam energy injection.

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