High-Efficiency Extraction of Microwave Radiation from a Tapered-Wiggler Free-Electron Laser

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We have substantially increased the output power and extraction efficiency of a free-electron laser operating at 34.6 GHz by tapering the wiggler magnetic field. In the exponential-gain regime, the laser exhibited a measured gain of 34 dB/m. With a 50-kW input signal, the amplifier saturated in 1.3 m with a 180-MW output signal. By using a taper that brought the magnetic field at the end of the wiggler down to 45% of its initial (peak) value, we increased the output signal to 1.0 GW. This corresponds to an extraction efficiency of 34%.

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The free-electron laser (FEL) produces coherent radiation at a frequency which is strongly dependent on the electron beam energy[1]:

$$\lambda_s \approx (\lambda_w/2\gamma^2)[1+\tfrac{1}{2}(eB_w\lambda_w/2\pi mc)^2], \tag{1}$$

where λ_w and B_w are the period and peak magnetic field strength of the applied wiggler field, and γ is the electrons' Lorentz factor. As the beam radiates and loses energy, the electrons fall out of resonance with the ponderomotive well formed by the electromagnetic wave and the applied wiggler field. The transfer of energy from the electron beam to the electromagnetic wave then ceases, and the amplifier saturates. Beyond the saturation point the phase of the electrons oscillates with respect to the ponderomotive well, and the electrons alternately give energy to and take energy from the radiation field. However, the radiation power is never higher than at saturation. Previous experiments indicated saturated power levels to be on the order of 5%–10% of the initial beam power.[2] The oscillatory behavior of the radiation as a function of the wiggler length is a manifestation of the synchrotron motion of the electrons in the ponderomotive well.[3]

In order to prevent the FEL from saturating, either the wiggler period or the wiggler field can be tapered[3,4] in such a manner that the resonance condition given by Eq. (1) remains satisfied for many electrons as the electrons lose energy. It is then possible to extract considerably more energy from the electron beam, as we demonstrate here.

The electron laser facility[5] (ELF) at Lawrence Livermore National Laboratory (LLNL) is ideally suited for investigating the performance of a tapered-wiggler amplifier. ELF is a single-pass FEL amplifier operating in the microwave regime ($f = 34.6$ GHz). The input signal is provided by a conventional microwave source: a pulsed magnetron which generates a 550-ns-wide, 100-kW microwave pulse. This signal is matched into the interaction region by waveguide tapers and a screen reflector (which is transparent to the relativistic electron beam). Half (3 dB) of the magnetron power is lost in matching into the interaction region. Therefore, our input signal for the amplifier is actually 50 kW. The interaction region is a 3×10-cm^2 stainless-steel waveguide and is excited in the TE_{01} mode, for which the electric field is in the wiggle plane of the electrons. The stainless-steel wall ensures good penetration of the pulsed magnetic field.

The plane-polarized wiggler is 3 m long and has a constant 9.8-cm period. The wiggler field is produced by an array of air-core, pulsed solenoids. The rise time of the wiggler field is 600 μs. Each two periods of the wiggler is energized by its own power supply; thus, the wiggler magnetic field profile can be varied in two-period intervals. In addition, the input and output periods are tailored to provide a good match for the electron beam onto the axis of the FEL. The wiggler field intensity can be varied from 0 to 5 kG.

The planar wiggler field provides strong vertical focusing ($k_{\beta V} = 0.22$ cm^{-1}). Horizontal focusing through the wiggler is done with external, horizontally focusing quadrupoles ($k_{\beta H} = 0.04$ cm^{-1}). As can be seen from the horizontal and vertical betatron wave numbers, the vertical focusing is about 25 times stronger than the horizontal focusing. No solenoidal focusing is present in the interaction region.

ELF utilizes the electron beam provided by the experimental test accelerator[6] (ETA) which is capable of producing a 4.5-MeV, 10-kA electron beam. The accelerator produces a 30-ns-wide beam pulse and can operate at 1 Hz, although in these experiments we operate at $\frac{1}{2}$ Hz. Because of the highly chromatic nature of the beam transport to the wiggler and energy variation through the pulse, we lose the leading and trailing edges of the beam pulse resulting in a 10–20-ns-long pulse in the FEL. For the experiments described here, the accelerator operated at 3.5 MeV in order to match the 34.6-GHz resonance in the operating range of the wiggler magnet. The ETA injector used a field-emission cathode[7] which provided a 4-kA electron beam. An emittance filter was used to reduce the current and emittance of the beam injected into the wiggler (beam brightness is conserved). The normalized beam brightness[5] was 2×10^4 A/(cm rad)^2, which is a factor of 2 better than the beam brightness used in previously reported experiments. We typically passed 850 A through the 3-m-long wiggler.

The effective length of the wiggler can be varied by setting of the appropriate coil currents to give the resonance field B_w over the desired length; the other coil currents are then reduced to 40% of the peak current, providing approximately $0.4B_w$ for the rest of the wiggler. The reduced wiggler field serves to transport the electron beam out of the interaction region to a current monitor at the end of the wiggler without contributing to the effective length of the FEL.

The output signals from the amplifier were injected into a large vacuum chamber (4-ft diam×8 ft long) where the fundamental (TE_{01}) signal was reduced by 41 dB through diffraction. The signal was further attenuated by directional couplers and variable attenuators to a level at which it could be measured by conventional crystal detectors. Low-pass and band-pass filters were used to ensure that we were only measuring the ampified (in band) signal.

In order to study the dependence of FEL performance on the wiggler length, we started with a 1-m-long uniform wiggler and determined the amplifier output as a function of wiggler magnetic field. At 1 m the amplifier is not saturated, and therefore the peak of the detuning curve (microwave power P_μ vs B_w) can be found. For the 3.5-MeV electron beam, the amplifier gain is maximum at a peak wiggler field of 3.72 kG. Using this value for the resonant wiggler field, we examined the FEL power as a function of wiggler length. The dependence of amplifier output on wiggler length in an untapered wiggler is illustrated in Fig. 1. The microwave signal grows exponentially through the first 1.3 m at a rate of 34 dB/m. Extrapolating the amplified signal back to the origin would indicate that we are only injecting 5 kW into the amplifier and not 50 kW. This order-of-magnitude difference can be ascribed to launching losses: Only one-third of the input electric field (one-ninth of the power) couples into the growing mode. The rest of the injected signal couples to decaying or oscillating modes.

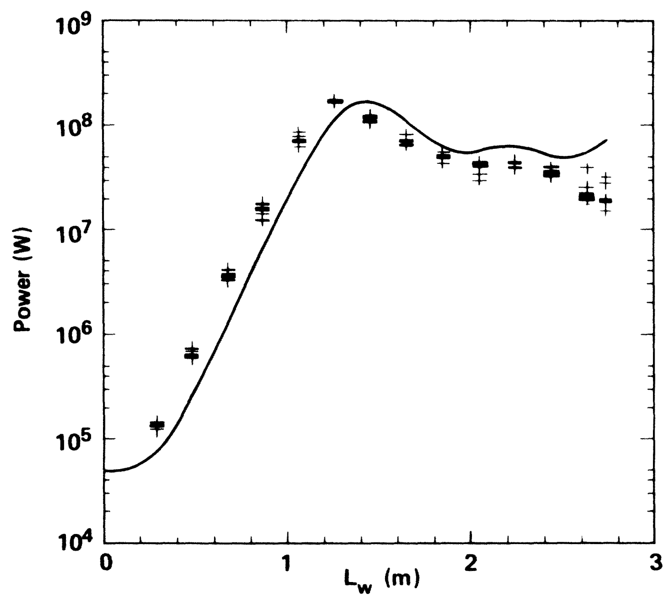

FIG. 1. Amplified signal output as a function of wiggler length for uniform (flat) wiggler. Crosses indicate experimental values and the solid line is the result of numerical evaluation.

The amplifier saturates at a wiggler length of 1.3 m. The output power at this point is 180 MW. The power in the injected electron beam is 3.0 GW, yielding an efficiency of 6%, which is comparable to the 5% measured in the previous experiments.[2] As the wiggler length is increased beyond saturation, the amplified signal oscillates with a period of approximately 1 m. The synchrotron wave number in the absence of longitudinal space charge forces is given by[3]

$$k_{\text{synch}} = (e^2 E_s B_w / \gamma_r^2 m^2 c^3)^{1/2}, \tag{2}$$

where E_s is the peak electric field of the radiation. Evaluating this expression for the parameters of our experiment gives a synchrotron period of 0.8 m, in reasonable agreement with the measured value. At least some of the $\sim 20\%$ discrepancy can be attributed to longitudinal space-charge effects.

The results of the two-dimensional simulation code FRED[8] are plotted in Fig. 1 along with the experimental results. The code uses all the experimental values and has no free (i.e., fitted) parameters, with the single exception of the precise magnetic field value, which is 7% higher in the simulations. The peak of the detuning curve consistently occurs at a field slightly higher in the simulations than in the experiment; comparison between theory and simulation here is done at the peaks of the detuning curves, rather than at fixed field. In addition, the code takes into account the effects of longitudinal space-charge forces.[9] It is evident that the model predicts the behavior of the FEL quite accurately. However, the simulation shows a shorter synchrotron period and larger-amplitude synchrotron oscillations beyond saturation. The experiment seems to exhibit more detrapping (e.g., reduced bucket size) beyond saturation.

The data shown in Fig. 1 correspond to the power in the TE_{01} mode only. The resonant energy of the TE_{21} mode is only 2% higher than that of the fundamental mode, and measurements reported elsewhere[10] have shown that comparable power ($\sim 50\%$ of the fundamental) is in the higher-order mode.

In order to study the effect of tapering on the FEL, we started with a 1.3-m flat wiggler at resonance. This allows the radiation field to grow to its maximum value prior to saturation. We then varied each subsequent wiggler power supply (two-period segments) to maximize the output signal. The lowest we could reduce the coil current (because the hardware restrictions) was to 40% of the maximum. By the time the wiggler profile was optimized to 2.4 m, the magnetic field at the end was 45% of the maximum field B_w (because of intracoil coupling). The resulting wiggler field is shown in Fig. 2 in terms of the rms dimensionless vector potential

$$a_w = \tfrac{1}{2}\sqrt{2}eB_w\lambda_w/2\pi mc. \quad (3)$$

(In these figures we ignore both the input and output periods, since these are adjusted to match the electron beam onto the equilibrium orbit in the wiggler and do not contribute to the FEL interaction.)

The output radiation power as a function of (tapered) wiggler length is shown in Fig. 3. As can be seen from this figure, the output power increases monotonically beyond the saturation point. The signal increases from 180 MW at saturation to 1.0 GW at 2.3 m. In our experiment, the wiggler field was at its lowest level ($0.4B_{max}$) from 2.4 to 3 m, and therefore the power was the same at these two points. The taper from 1.3 to 2.3 m provides an additional factor of 5.5 (7.5 dB) increase in output power. The efficiency of this tapered-wiggler FEL is 34%. Results of numerical simulations with FRED are plotted with the data in Fig. 3. The numerical simulation indicates that we have trapped $\sim 75\%$ of the electron beam and reduced its energy by $\sim 45\%$. Since the taper optimized the power in the fundamental mode, the power in the TE_{21} mode was virtually unaffected by the taper profile and remained at the same level as in the uniform wiggler. Thus, the output power from the tapered wiggler was nearly all ($\sim 90\%$) in the fundamental mode. Figure 2 also shows the results of an optimum wiggler profile as determined with the "self-design" feature of FRED, in which a single design electron is maintained at constant ponderomotive phase by reducing a_w as the design electron loses energy. Here we chose $\psi_r = 0.40$ and restrained the design electron to be on axis. In doing the computer design, the wiggler was con-

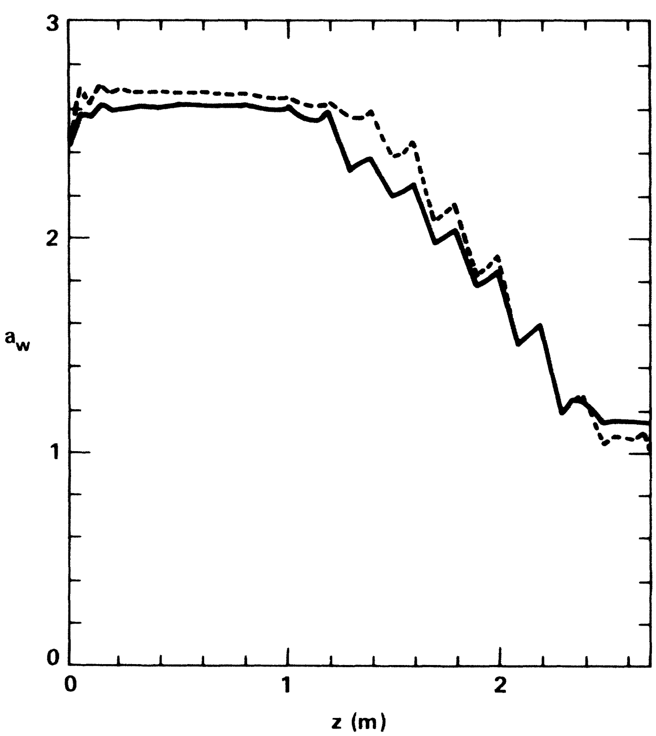

FIG. 2. Optimum wiggler field profile for tapered wiggler. The dashed line corresponds to empirical evaluation and the solid line is the numerical prediction.

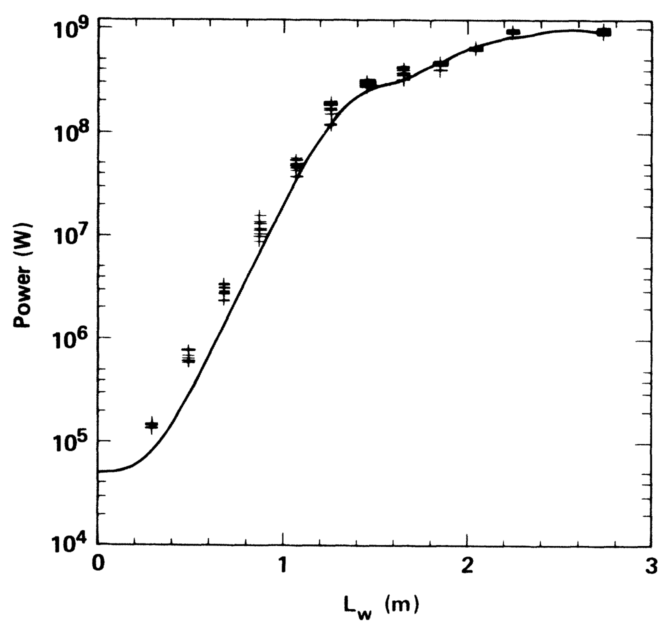

FIG. 3. Amplified signal output as a function of wiggler length for tapered wiggler field. Crosses indicate experimental values and the solid line is the results of the numerical evaluation.

strained so that the current in the wiggler coils could not be lower than 40% of the maximum. It is interesting to note that the profiles determined empirically and numerically are very close, despite the very different tapering procedures.

We have successfully demonstrated that an FEL amplifier can be brought out of saturation by tapering of the wiggler field. A saturated power of 180 MW (6% efficiency) has been increased to 1.0 GW (34% efficiency) by optimizing of the wiggler profile. The two-dimensional numerical simulation has accurately calculated the experimental results even in the nonlinear regime.

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[1]This expression is only approximate for the experiment described here, since we must also take into consideration waveguide effects, space-charge wave effects, and finite emittance.

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