It is obvious that the effect discussed here can be expected also in the case of cyclotron resonance in solid-state materials. It is well known[9] that the effective mass of the electron in some semiconductors (e.g., InSb) is strongly dependent on energy of its excitation, which should cause some shift of cyclotron frequency under action of the strong resonant EM pumping. This effect, being in some sense analogous to the relativistic mass effect, can result in strong hysteresis, if the nonlinear shift of the cyclotron frequency is larger than frequency width of resonant line. The effective mass of the electron m^* in InSb could be as small as $m^* \approx 0.02\ m_0$, which for the case of $H_0 = 100$ kG produces the cyclotron wavelength $\lambda_0 \sim 20\ \mu$m, so that cw radiation of the CO_2 laser will be suitable to excite hysteretic cyclotron resonance.

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Variable-Wiggler Free-Electron-Laser Experiment

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First results are presented of a free-electron-laser experiment that utilizes a tapered wiggler for efficiency enhancement. The spontaneous spectrum and the electron-beam energy loss due to the free-electron-laser interaction are measured and compared with theory. With a 2.25% magnetic field taper, 12% of the electrons were decelerated by 0.6%, corresponding to a gain of 2.7% and an efficiency of 0.07%, which is 10 times higher than that calculated for a zero taper and otherwise identical conditions.

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An efficient free-electron laser (FEL) is a viable source of high-power radiation in the visible regime. It has been shown[1,2] theoretically that the FEL efficiency, inherently low at small wavelengths ($\lambda_s \leq 10.6\ \mu$m), can be increased by appropriately tapering the wiggler field. In this paper, we present the encouraging initial results of the TRW FEL amplifier experiment being performed to prove the validity of this scheme.

A FEL[3] generates stimulated radiation by the interaction of a relativistic electron beam with a rippled magnetic field (wiggler). The wavelength,

λ_s, of the stimulated radiation emitted at an angle θ with respect to the direction of propagation of the electron beam is proportional to the wiggler wavelength λ_w downshifted by a factor proportional to the square of the relativistic electron beam energy ($\epsilon = \gamma mc^2$). For a sinusoidal wiggler of amplitude B_w, we have

$$\lambda_s = \frac{\lambda_w}{2\gamma^2}(1 + a_w^2/2 + \gamma^2\theta^2), \quad a_w = \frac{qB_w}{mc^2}\frac{\lambda_w}{2\pi}. \qquad (1)$$

The operation of a constant-wiggler FEL has been demonstrated in the infrared regime by the Stanford group both by measuring the single pass gain[4] and by operating the FEL as an oscillator.[5] In the tapered-wiggler FEL scheme,[1,2] the electrons are intentionally trapped in the potential well ("bucket") of the axially propagating ponderomotive wave, formed by the interaction of the wiggler field with the radiation field. By adiabatic reduction of the total energy associated with the phase velocity of the ponderomotive well, the trapped electrons are forced to move to a lower energy state. The energy difference is used to amplify the radiation field. In this experiment, the reduction in bucket energy is accomplished by an axial decrease in the wiggler field amplitude. The total efficiency of the process depends on the number of electrons trapped in the bucket and the deceleration efficiency of the "resonant" particle. For example, for optimum experimental parameters, the efficiency is predicted to be more than one order of magnitude larger than for a zero-taper wiggler field.

The layout of the experimental system is shown schematically in Fig. 1. The three major components are electron beam, photon beam, and magnetic wiggler.

The electron beam source is the rf linear accelerator located at the EG & G Santa Barbara Operations. It has an energy range of 1–30 MeV, with 25 MeV being the nominal operating point. Firing at a repetition rate of 60 Hz, the linac produces single beam pulses of 30 ps duration with a 1% full width at half maximum (FWHM) energy spread, 15 A peak current, and an emittance of 4.3π mm mrad. The electron energy analyzer consists of a 45° analyzer magnet and an electron position monitor. Electrons are detected by a single optical polysilicate fiber, wound on a mandrel to form a ribbon of sixty closely spaced loops.[6] One section of this ribbon is placed in the momentum dispersion plane at the end of the vacuum system. The ribbon is oriented at the Čerenkov angle with respect to the electron beam,

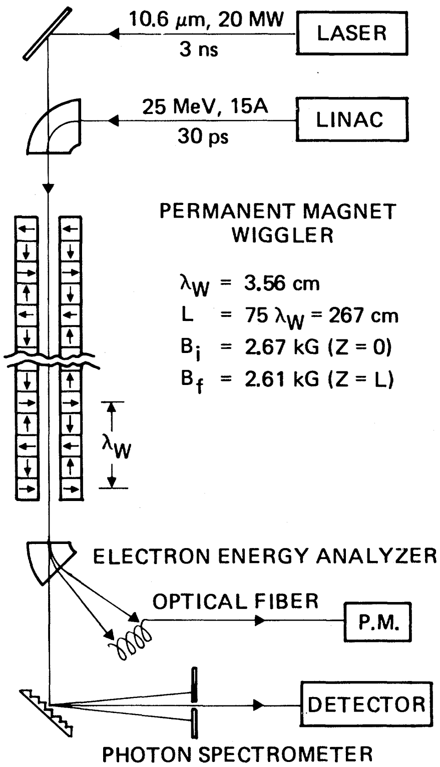

FIG. 1. Block diagram of the experimental system.

and the local fiber axis is perpendicular to the direction of the momentum dispersion. Čerenkov radiation is emitted by each electron as it passes through the fiber, and this light is guided along the fiber to a photomultiplier outside the accelerator shielding. The transit time of light as it traverses the circumference of a loop provides a time delay between photons originating in adjacent loops. The entire energy spectrum can be obtained in a single oscilloscope trace for each beam pulse. The energy-to-time conversion factor is determined by the magnetic transport system, the spacing between loops, and the loop circumference. For this spectrometer, the dispersion is 0.024%/nsec. The resolution of the analyzer is $\Delta E/E = 0.18\%$ or 7.5 nsec. The analyzer signals are sampled, digitized, and stored. Approximately 5000 shots are used to reconstruct one electron spectrum.

The optical system consists of a laser driver, beam propagation optics, and a spectrometer with a detector. The laser beam of 20 MW peak power and 3 nsec FWHM is produced in a two stage CO_2 laser system using an electro-optical switch[7] for pulse-length control. The system is designed to run at high repetition rates to allow the use of signal-averaging techniques.

The tapered wiggler is constant in wavelength ($\lambda_w = 3.56$ cm) but varies axially in field amplitude. It consists of a pair of linear arrays of $SmCo_5$ permanent magnets[8] with the magnetization vectors oriented as shown in Fig. 1. The field at the symmetry axis is given by $B = A\cos(kz) \times \exp(-kh)$. k is the wiggler wave number equal to $2\pi/\lambda_w$, h is the half-separation of the two magnet planes, and A is a factor that depends on the magnet material and geometrical factors. Variation of the field strength is accomplished by making h a function of z. Additional end tapers are necessary for an unperturbed beam propagation.

A measurement of the spectrum of the spontaneous radiation proved to be of extreme importance because it provided the first comparison with the tapered-wiggler FEL theory and was used to tune the electron beam energy. It also demonstrated experimentally the influence of electron emittance on the radiation process and provided a check on the electron-beam steering.

The power radiated into a well-defined solid angle was focused onto and detected by a fast HgCdTe detector. An oscilloscope trace of the total power is reproduced in the inset of Fig. 2. The pulse width of 0.8 nsec corresponds to the 1.3-GHz bandwidth of the detector and is much larger than the estimated 30-ps width. The spectrum was measured with a diffraction grating. It is compared in Fig. 2 with a theoretical spectrum calculated for the experimental conditions, taking into account the effective electron-beam energy spread as well as the angular dependence due to the finite geometry of the system. Agreement of the shape of the spectrum is excellent. The peak wavelength also agrees with the theoretical value within the degree to which the beam energy is known (1%). In the following experiments, the beam energy is actually calibrated by comparing the wavelength of the spectrum maximum with the theoretical value since the absolute calibration of the analyzer is less precise. The taper of the wiggler shifts the peak of the spectrum to shorter wavelengths as compared to a constant wiggler. The long-wavelength tail is due to the finite solid angle over which the radiation is collected.

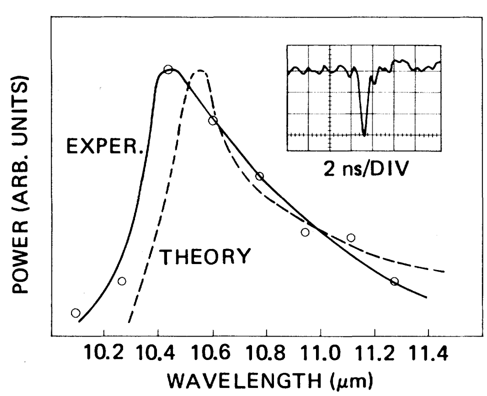

FIG. 2. Spectrum of spontaneous radiation. Circles, experimental data; dashed line, calculated spectrum. $\gamma = 48.3$, determined with energy analyzer. The inset shows an oscilloscope trace of the total spontaneous radiation.

The initial observations of the actual FEL interaction were made by detecting the change in the electron energy spectrum rather than optical gain because the former is more sensitive to the interaction. The gain will be measured in the next series of experiments. The beam-energy loss is the quantity directly calculated in the FEL theories and is, therefore, the most meaningful number to compare with the experiment. Many measurements on the beam-energy loss were performed with the corresponding efficiencies falling within the error bar of Fig. 4(a). A representative example is reproduced here.

The laser and electron beams are synchronized to pass through the wiggler interaction region simultaneously, with a jitter of less than 40 ps. An example of the corresponding energy distribution is shown in the top trace of Fig. 3. Another distribution, taken when both beams did not overlap in time, and therefore did not interact, was subtracted from this trace. The lower trace of Fig. 3 shows this difference on a scale 2.5 times more sensitive. It can be clearly seen that the high-energy side of the spectrum has lost particles (positive signal) while the lower energy side has gained particles (negative signal). A

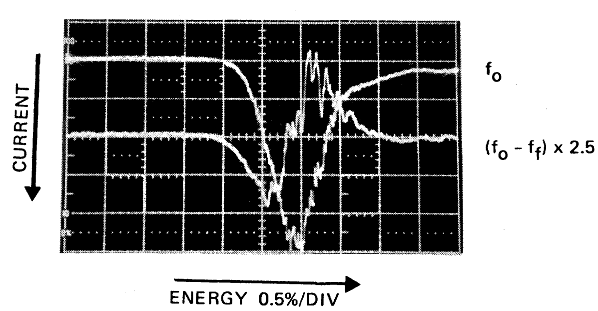

FIG. 3. Upper trace, electron-beam energy spectrum. Lower trace, difference of spectra with and without interaction.

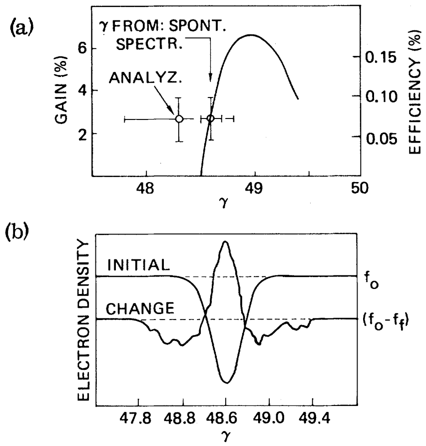

FIG. 4. (a) Theoretical gain and efficiency curve and experimental value calculated from energy loss of Fig. 3. (b) Upper trace, initial beam energy spectrum assumed for theoretical model. Lower trace, calculated difference of spectra with and without interaction.

comparison of the areas beneath the curves indicates that $12.6 \pm 4.1\%$ of the electrons were decelerated by about 0.6%. The error was determined from the temporal fluctuations of the energy spectrum. Because the wiggler was adjusted to decelerate the electrons by 0.6%, the result is consistent with the predicted bucket deceleration. The measured beam-energy loss corresponds to an efficiency of 0.07% and a gain of 2.7% for the 2.25% taper used in this experiment.

Figure 4(a) shows the theoretical gain and efficiency and Fig. 4(b) the modification of the beam distribution, calculated for the parameters of Fig. 3. These predictions were obtained with a theoretical model that includes finite beam emittance and energy spread as well as a Gaussian, diffraction-limited optical beam.[9] The gain and efficiency curve is compared with the experimental point obtained from Fig. 3 by use of both the beam energy measured with the energy analyzer and that calculated from the spontaneous spectrum. Within the experimental error, which is large for the analyzer energy measurement, the points agree with the theoretical prediction. For the electron beam energy calculated from the spontaneous spectrum, the theoretical gain and efficiency is more than one order of magnitude larger than for a constant-wiggler FEL. The calculated modification of the energy distribution [Fig. 4(b)] is somewhat different from the example of Fig. 3. Beam heating as well as energy loss are evident in the calculated case. Although some beam heating was observed in some of the measurements no consistent correlation of the heating with the beam parameters was established.

Trapping of the electrons was not unambiguously demonstrated because the deceleration was less than the FWHM of the energy spectrum. In the next set of experiments the wiggler's taper will be adjusted for an extraction greater than 1%, which will decelerate trapped electrons completely out of the untrapped distribution. The largest source of error in the data presented here is the slow and fast accelerator energy drift.

In summary, we have described an ongoing experiment designed to demonstrate efficiency with a tapered-wiggler FEL amplifier. Initial results clearly show the existence of the tapered-wiggler FEL interaction. The experiment is being improved to measure the gain and remove any possible ambiguities in the interpretation.

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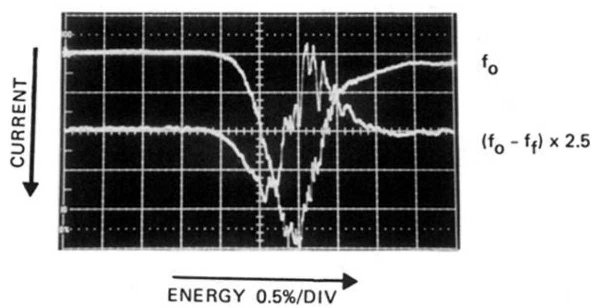

FIG. 3. Upper trace, electron-beam energy spectrum. Lower trace, difference of spectra with and without interaction.