Experimental Demonstration of an Electromagnetically Pumped Free-Electron Laser with a Cyclotron-Harmonic Idler

R. A. Kehs, Y. Carmel, V. L. Granatstein, and W. W. Destler

Laboratory for Plasma and Fusion Energy Studies, University of Maryland, College Park, Maryland 20742

(Received 4 September 1987)

A three-wave, free-electron laser was operated with a powerful 8.4-GHz electromagnetic "pump" wave replacing the usual magnetostatic wiggler. The presence of a uniform axial magnetic field B_0 produced cyclotron-harmonic "idler" waves. Peaks in the emission spectrum corresponding to cyclotron harmonics were observed covering a frequency range from 16.5 to 130 GHz. The frequency spectrum of this novel free-electron laser mechanism was tuned continuously by variation of B_0.

PACS numbers: 42.55.Tb, 52.75.Ms

In recent years there has been strong interest in free-electron lasers (FEL's) for the production of high-power, coherent, tunable electromagnetic radiation. Both two-wave FEL's[1-4] and three-wave FEL's[5-7] have been demonstrated, and have exhibited great potential for extending the available range of wavelengths and power levels of coherent sources while maintaining high operating efficiencies. Three-wave FEL's consist of an idler wave on the electron beam, a pump wave, and a radiation wave. Typically, the pump wave is created via a static, periodic magnet (wiggler). However, any field that induces a transverse electron oscillation would, in principle, function as a pump field. For example, a static periodic electric field[8] or an electromagnetic field[9] could be used.

In experiments where a solenoidal guide magnetic field is present in addition to the wiggler field, either beam space-charge waves or beam cyclotron waves act as idlers in a three-wave FEL. The case of an FEL with a space-charge wave idler was carefully studied in the experiments of Fajans *et al.*[10] The effect of electron cyclotron motion on FEL operation has been studied both theoretically[11] and in experiments.[12-14] The three-wave FEL with a magnetostatic wiggler and a fundamental cyclotron-frequency idler was studied experimentally,[13,14] and that work is closely related to the present study.

In backward-wave oscillator experiments using intense relativistic electron beams to generate high-power microwaves at a wavelength of several centimeters and peak power levels of $\simeq 100$ MW, powerful radiation was also observed at millimeter wavelengths.[15,16] In the present work, we present for the first time the spectrum of the millimeter-wave radiation which is observed in very high-power backward-wave oscillators and use the features of the observed spectrum to deduce the radiation mechanism. We found the unexpected result that the millimeter-wave spectrum is composed of an array of regularly spaced peaks. The frequencies of the peaks and their variation with the strength of the axial guide magnetic field indicate that the spectrum is due to a three-wave FEL interaction with cyclotron-harmonic beam waves acting as "idlers" and with the backward-wave oscillator radiation at a frequency of 8.4 GHz acting as the pump wave.

The experimental configuration is shown in Fig. 1 in which an annular electron beam (625 kV, 2 kA, 100 ns) is guided through a corrugated-wall, slow-wave structure.[17-19] The slow-wave structure allows the electron beam to couple kinetic energy from the beam into the propagating electromagnetic modes of the structure. The pump wave is the $n = -1$ spatial harmonic of the TM_{01} mode,[16] which propagates antiparallel to the electron beam.

An electron beam with an axial velocity $v_\parallel$ supports natural modes of oscillation, which can act as idler waves in a three-wave FEL; viz. the slow space-charge wave mode with dispersion relation

$$\omega_i = k_i v - \omega_p/\gamma_\parallel, \tag{1}$$

and the slow cyclotron-harmonic modes with dispersion relation

$$\omega_i = k_i v - l\Omega, \tag{2}$$

either of which may act as idler waves in the generation of coherent electromagnetic radiation. Here ω_i and k_i are the frequency and wave number of the idler wave, $\omega_p = (ne^2/m\epsilon_0\gamma)^{1/2}$ is the relativistic electron-beam plasma frequency, $\Omega = eB_0/\gamma m$ is the relativistic electron cy-

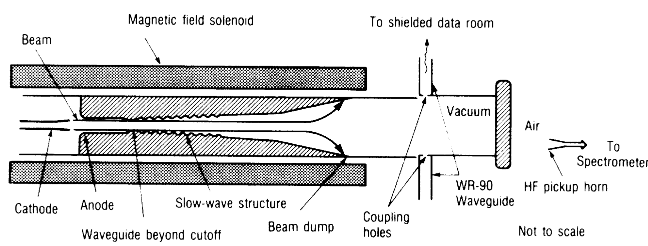

FIG. 1. Experimental configuration (not to scale).

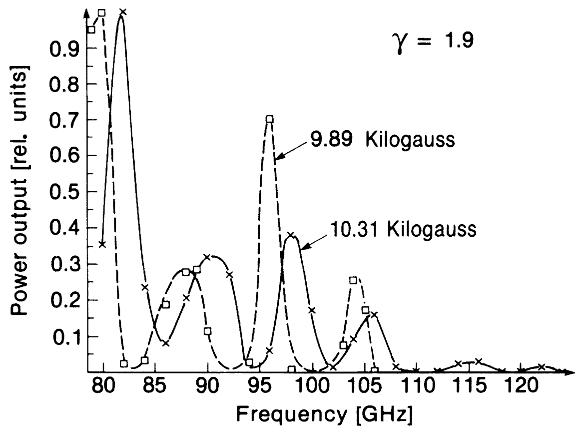

FIG. 2. The measured spectrum of the electromagnetically pumped FEL with cyclotron-harmonic idler waves for two applied magnetic fields, 9.89 and 10.31 kG.

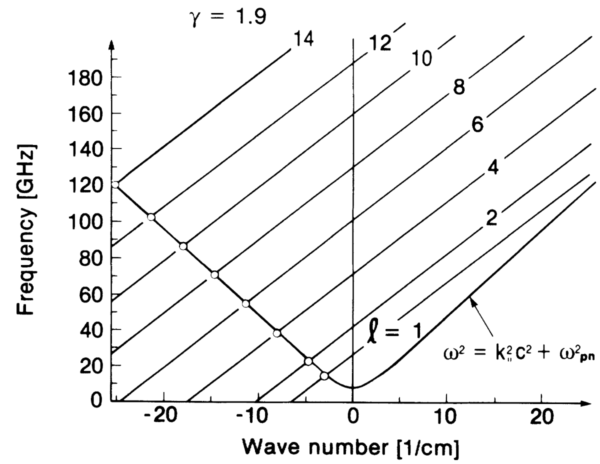

FIG. 3. Simplified dispersion relations of the waveguide mode [Eq. (6)] and the cyclotron-harmonic mode down-shifted by the electromagnetic wiggler [Eq. (5)].

clotron frequency in the guide magnetic field, and l is the cyclotron harmonic number. The relativistic energy factors γ and $\gamma_\parallel$ are defined by $\gamma=[1-(v_\parallel/c)^2-(v_\perp/c)^2]^{-1/2}$ and $\gamma_\parallel=[1-(v_\parallel/c)^2]^{-1/2}$, where $v_\perp$ is the electron velocity perpendicular to the axis.

A three-wave FEL is a parametric amplifier. Conservation of energy requires

$$\omega_w=\omega_i+\omega, \tag{3}$$

where ω_w is the pump wave frequency and ω is the frequency of the amplified FEL output wave. Conservation of momentum requires

$$\mathbf{k}_w=\mathbf{k}_i+\mathbf{k}, \tag{4}$$

where $\mathbf{k}_w$, $\mathbf{k}_i$, and $\mathbf{k}$ are the axial wave vectors of the pump wave, the idler wave, and the FEL wave, respectively. Combining Eqs. (2), (3), and (4) gives

$$\omega=kv_\parallel+\omega_w(1+v_\parallel/v_{ph})+l\Omega, \tag{5}$$

where $v_{ph}=\omega_w/|k_w|$ is the phase-velocity magnitude of the pump wave, and we have assumed pump wave propagation counter to the electron beam.

The amplified FEL wave propagates inside the drift tube, which acts like a waveguide so that its frequency and axial wave number must satisfy

$$\omega^2=k^2c^2+\omega_{pn}^2, \tag{6}$$

where ω_{pn} represents the cutoff frequency of the waveguide mode with azimuthal eigennumber p and radial eigennumber n. Radiation growth occurs near frequencies corresponding to the crossing points of the dispersion curves represented by Eqs. (5) and (6). Solving Eqs. (5) and (6) simultaneously yields the frequencies of two unstable classes of modes; viz.

$$\omega=\beta_\parallel\gamma_\parallel^2cK_{\rm eff}\left\{1\pm\beta_\parallel\left[1-\left(\frac{\omega_{pn}}{K_{\rm eff}\gamma_\parallel\beta_\parallel c}\right)^2\right]^{1/2}\right\}, \tag{7}$$

where

$$K_{\rm eff}=\frac{\omega_0}{v_0}\left(1+\frac{v_0}{v_{ph}}\right)+\frac{l\Omega}{\beta_\parallel c}, \tag{8}$$

$\beta_\parallel=v_\parallel/c$, and the plus or minus signs in Eq. (7) represent the up- or down-shifted interaction branches. Note that "down shifted" refers to a family of interaction frequencies and that they are generally higher than the 8.4-GHz pump frequency.

The expression for the radiation frequencies of a two-wave FEL with a magnetostatic wiggler of period l is the same as Eq. (7) except that $K_{\rm eff}$ is replaced with $k_w=2\pi/l$. We also note that the radiation frequencies of a cyclotron-harmonic autoresonance maser[20] (for which we coin the acronym CHARM) are also given by Eq. (7) with $\omega_0=0$, i.e., $K_{\rm eff}=l\Omega/\beta_\parallel c$.

The measured spectrum of the millimeter-wave radiation exhibits a distinct line structure, part of which is shown in Fig. 2; the frequencies of the spectral peaks are in good agreement with calculations of the down-shifted, electromagnetically pumped FEL with cyclotron-harmonic idlers corresponding to the negative sign in Eq. (7). Figure 3 is a graphical representation of the dispersion relationship given by Eqs. (5) and (6). Harmonic numbers $l=1$ and 5 through 14 were identified during the scanning of most of the spectrum between 7 and 130 GHz. Furthermore, the locations of the measured spectral peaks move with axial magnetic field, which would not be expected in the FEL with space-charge idler. Adequate microwave diagnostics were not available for the range from 18.6 to 50 GHz where harmonic numbers $l=2,3$, and 4 were predicted to appear. Figure 4 shows the excellent match between the theoretical predictions for the frequency shift and the experimental results; only the modes corresponding to odd cyclotron-harmonic

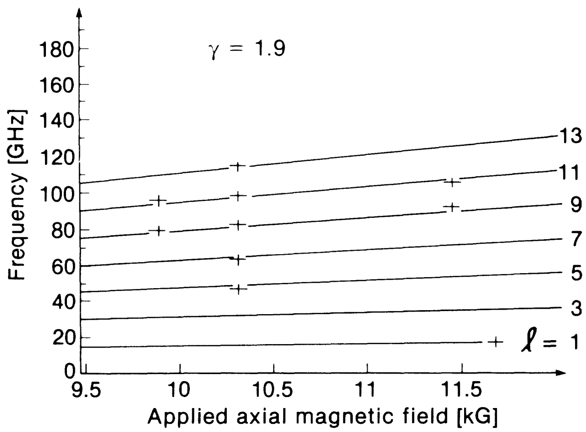

FIG. 4. Theoretical prediction (solid lines) and experimental data (plusses) for electromagnetically pumped FEL with cyclotron-harmonic idlers including waveguide effects.

numbers are shown to avoid overcrowding the figure. A similar set of data has been generated for even harmonic numbers.

Another mechanism with a somewhat similar spectrum is a counterwave cyclotron-harmonic autoresonant maser[20] (counterwave CHARM). However, the counterwave CHARM has a significantly different spectrum at low harmonic numbers. Specifically, radiation with that mechanism should be produced at 12.5 and 18.2 GHz (for an applied field of 10 kG), but in an intensive spectral search from 7 to 18.6 GHz, microwave radiation was only detected at 8.4 GHz, the frequency of the pump wave, and at 16.5 GHz, the $l=1$ harmonic of the electromagnetically pumped FEL with cyclotron-harmonic idler. Also, measurements of the electron-beam parameters indicated that $\beta_\perp < 0.05$, which is insufficient for the production of radiation via a CHARM-type interaction. Finally, when a smooth metallic liner was inserted into the drift tube to eliminate the periodic wall, no electromagnetic radiation at any frequency could be detected.

The relative linewidth of the FEL emission spectrum was measured (see Fig. 2) and found to be $\Delta\lambda/\lambda \simeq 2.5\%$. It is expected that the measured 8.4-GHz electromagnetic pump linewidth ($\simeq 0.2$ GHz) will translate into the FEL linewidth according to

$$(\Delta\lambda/\lambda)_{\mathrm{FEL}} = (\Delta\lambda/\lambda)_{\mathrm{PUMP}}\ (\lambda_{\mathrm{PUMP}}/\lambda_{\mathrm{FEL}}), \tag{9}$$

which is in good agreement with the experimental results. The resolution of the spectrometer is $\Delta\lambda/\lambda \cong 1.5\%$. The power in the emission at 16.5 GHz corresponding to $l=1$ is $\simeq 250$ kW with decreasing power level for emission lines corresponding to larger values of l.

We have demonstrated that electromagnetic pumping in the presence of a uniform axial magnetic field resulted in a three-wave FEL interaction involving cyclotron-harmonic idler waves. This mechanism produced coherent, powerful, millimeter-wave radiation with a relatively modest value of the uniform magnetic field. A continuous tunability over a very wide frequency range is a distinguishing feature of this FEL mechanism.

We would like to acknowledge helpful discussions with G. Bekefi, A. Bromborsky, B. Danley, A. Fliflet, H. Freund, B. Levush, K. Minami, B. Ruth, and J. Wurtele. We also thank D. Presgraves and W. R. Lou for assistance in operating the experiment and Professor D. Boyd for his grating spectrometer. This work was supported in part by the Harry Diamond Laboratories and the Office of Naval Research.

[1] L. R. Elias *et al.*, Phys. Rev. Lett. **36**, 710 (1976).
[2] D. A. G. Deacon *et al.*, Phys. Rev. Lett. **38**, 892 (1977).
[3] B. Girard *et al.*, Phys. Rev. Lett. **33**, 2405 (1984).
[4] T. J. Orzechowski *et al.*, Phys. Rev. Lett. **57**, 2172 (1986).
[5] D. B. McDermott *et al.*, Phys. Rev. Lett. **41**, 1368 (1978).
[6] R. K. Parker *et al.*, Phys. Rev. Lett. **48**, 238 (1982).
[7] S. H. Gold *et al.*, Phys. Rev. Lett. **52**, 1218 (1984).
[8] G. Bekefi and R. E. Shefer, J. Appl. Phys. **50**, 5158 (1979).
[9] V. L. Granatstein *et al.*, Appl. Phys. Lett. **30**, 384 (1977); V. L. Granatstein *et al.*, in *Handbook of Laser Science and Technology*, edited by M. J. Weber (CRC, Boca Raton, 1982), p. 449.
[10] J. Fajans *et al.*, Phys. Fluids **28**, 1995 (1985).
[11] W. A. McMullin *et al.*, Phys. Rev. A **25**, 1826 (1982).
[12] A. Grossman *et al.*, Phys. Fluids **26**, 337 (1983).
[13] P. Efthimion and S. P. Schlesinger, Phys. Rev. A **16**, 633 (1977).
[14] R. M. Gilgenbach *et al.*, Phys. Fluids **22**, 971 (1979).
[15] P. G. Zhukov *et al.*, in *Proceedings of the Third International Topical Conference on High Power Electron and Ion Beam Research and Technology,* edited by A. N. Skrinsky (Institute of Nuclear Physics, Novosibirsk, U.S.S.R., 1979), Vol. 1, p. 705; G. G. Denisov *et al.*, Int. J. Infrared Millimeter Waves **5**, 1389 (1984).
[16] Y. Carmel *et al.*, Phys. Rev. Lett. **51**, 566 (1983).
[17] R. A. Kehs *et al.*, IEEE Trans. Plasma Sci. **13**, 559 (1985).
[18] N. Kovalev *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **18**, 232 (1973) [JETP Lett. **18**, 138 (1973)].
[19] Y. Carmel *et al.*, Phys. Rev. Lett. **33**, 21 (1974).
[20] V. L. Bratman *et al.*, Int. J. Electron. **51**, 541 (1981).

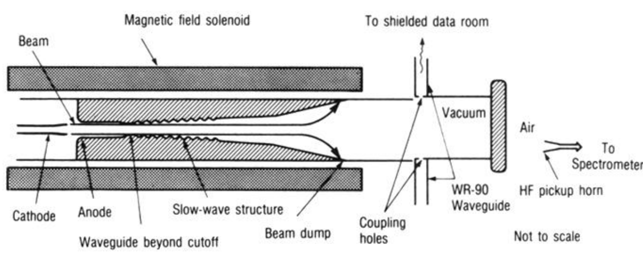

FIG. 1. Experimental configuration (not to scale).