

Microwave Radiation from a Low-Energy Rotating Electron Beam in an Azimuthally Periodic Magnetic Wiggler Field

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Abstract—The generation of microwave radiation by the interaction of a low-energy rotating electron beam (25 kV, 0.5 A, 5 μ s) with an azimuthally periodic magnetic wiggler field has been studied experimentally. Narrow-band radiation has been observed at a frequency of 10.15 GHz at power levels of about 100 W, corresponding to an electronic efficiency of about 1 percent. Results are in reasonable agreement with theoretical expectations when the electron cyclotron frequency is adjusted to account for a precession in the electron orbits caused by the wiggler field.

I. INTRODUCTION

MANY theoretical and experimental studies of free-electron lasers (FEL's) have been reported in which radiation has been produced by the interaction of linear electron beams with periodic magnetic wiggler fields [1]–[10]. Recently, a novel circular geometry free-electron laser has been explored both experimentally and theoretically in a collaborative effort by researchers at the Massachusetts Institute of Technology and the University of Maryland [11]–[16]. In this concept, an annular, rotating electron beam interacts with an azimuthally periodic wiggler field produced by samarium cobalt magnets placed radially exterior and/or interior of the beam. This new configuration is of interest because of its longer effective interaction region, its more compact geometric configuration, and the fact that it may operate with internal feedback produced by the recirculation of the electromagnetic wave. As a result, the device may be capable of operating as an oscillator without the use of external mirrors as are required in linear FEL's.

Experimentally, a rotating annular electron beam is produced by passing a hollow, cylindrical nonrotating electron beam through a sharp magnetic cusp [17]. The $v_z \times B_r$ force at the cusp transition effectively converts the axial beam velocity into rotational velocity downstream of the cusp. If the cusp is symmetric, the downstream beam performs simple axis-encircling helical orbits with

gyroradius equal to the upstream linearly streaming beam radius.

An azimuthally periodic wiggler field produced by samarium cobalt magnets is added to the uniform axial magnetic field about which the electrons rotate. In previous experiments, these magnets were placed behind smooth conducting coaxial walls interior and exterior to the beam. In this manner, beam electrons experience a wiggler field of essentially pure radial composition. In the present experiment, however, design constraints allowed the use of only one set of magnets placed exterior to the beam.

In high energy experiments, the electron beam pulse is produced by a field-emission diode driven by a high-voltage pulse line accelerator [12], [13]. In this paper, we report the first results of a lower energy, thermionic diode experiment of this type operating with electron beam parameters of 25 kV, 0.5 A, 5 μ s, 60 pps. In addition to allowing the study of device performance in this new parameter regime, this small, modulator-driven experiment allows a more careful comparison of device performance with available theory.

Section II of this paper contains a review of available theory related to the experiment, and Section III contains the result of experiments. Conclusions are drawn in Section IV.

II. THEORETICAL DISCUSSION

A. Electron Motion in the Combined Axial and Wiggler Magnetic Fields

The general configuration used for these studies is illustrated in Fig. 1. Downstream of the cusp transition, the electron orbits have axial (v_{z_2}) and azimuthal (v_{θ_2}) velocity components given in terms of the upstream axial velocity (v_{z_1}) by

$$v_{z_1}^2 = v_{z_2}^2 + r_L^2 \Omega_{\parallel}^2, \quad (1)$$

where r_L is the downstream Larmor radius, which is equal to the cathode radius for a balanced cusp, and $\Omega_{\parallel} = eB_z/\gamma m_0$ is the relativistic electron cyclotron frequency in the downstream axial magnetic field [17]. Thus, as the magnetic field is raised toward a cutoff value given by

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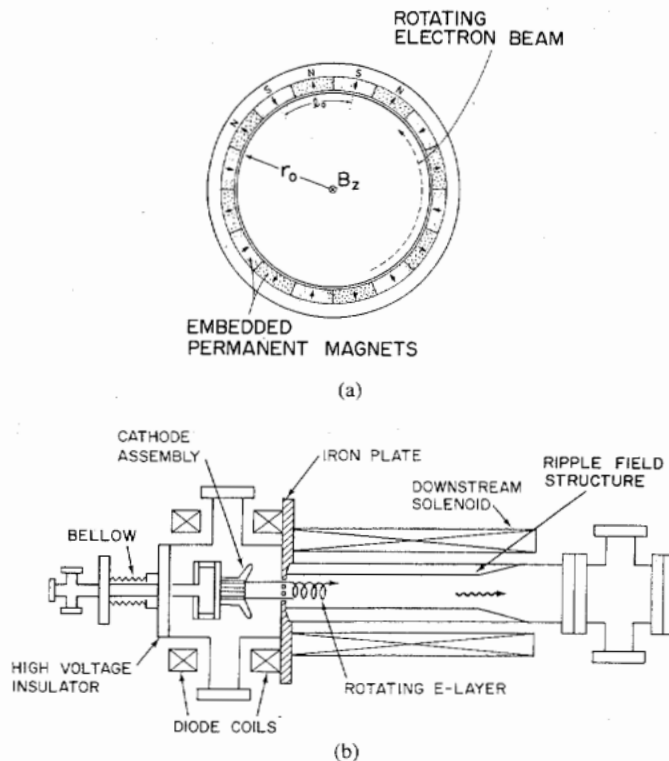


Fig. 1. General experimental configuration: (a) aximuthally periodic magnet assembly and (b) experimental configuration used to produce rotating, nonrelativistic electron beams.

$$B_{zc} = \frac{v_{z1} \gamma m_0}{e r_L}, \quad (2)$$

the axial velocity is reduced and the electron orbits become fairly tight helices. Downstream of the cusp, the electrons move under the influence of the combined axial and wiggler magnetic fields, which can be approximated subject to the condition that $\nabla \cdot \vec{B} = \nabla \times \vec{B} = 0$ in the region inside of the outer conducting boundary of radius r_0 by

$$\vec{B} = B_w \left(\frac{r}{r_0} \right)^{N-1} [\cos(N\theta) \hat{a}_r - \sin(N\theta) \hat{a}_\theta] + B_z \hat{a}_z. \quad (3)$$

Here, \hat{a}_r , \hat{a}_θ , and \hat{a}_z are the unit vectors in the radial, azimuthal, and axial directions, respectively, N is the number of spatial wiggler periods around the azimuth (ten for the experiments reported here), and B_w/r_0^{N-1} is a parameter which has been matched to measured wiggler field values. For the experiments reported here, $B_w/r_0^{N-1} = 7.153 \times 10^{14} \text{ T/m}^9$.

Because of the complicated nature of the combined axial and wiggler fields, a single particle computer simulation has been used to check the particle orbits. Projections of these orbits onto the x - y and x - z planes are shown in Figs. 2-5 for two cases carefully matched to the experiments, which include off-centered orbits due to finite cusp transition width. In the first case (Figs. 2 and 3) electrons are launched downstream with parameters corresponding

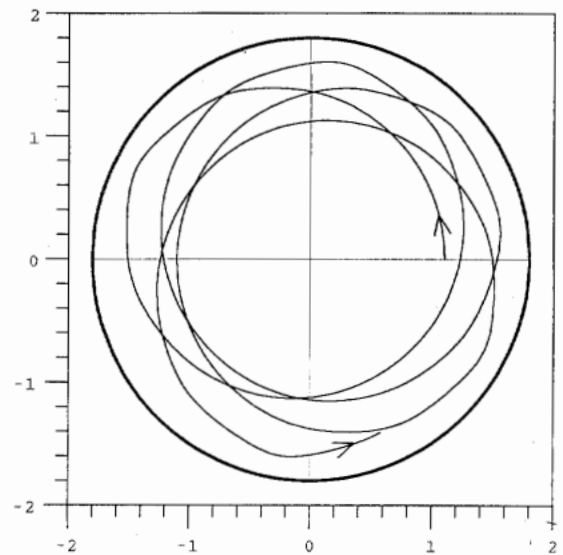


Fig. 2. Projection of downstream particle orbit onto x - y plane for electron launched with initial $\beta_\theta = 0.269$ and $\beta_z = 0.148$ into combined wiggler and axial magnetic fields (balanced cusp, $B_1/B_2 = 1$). Dimensions are in centimeters.

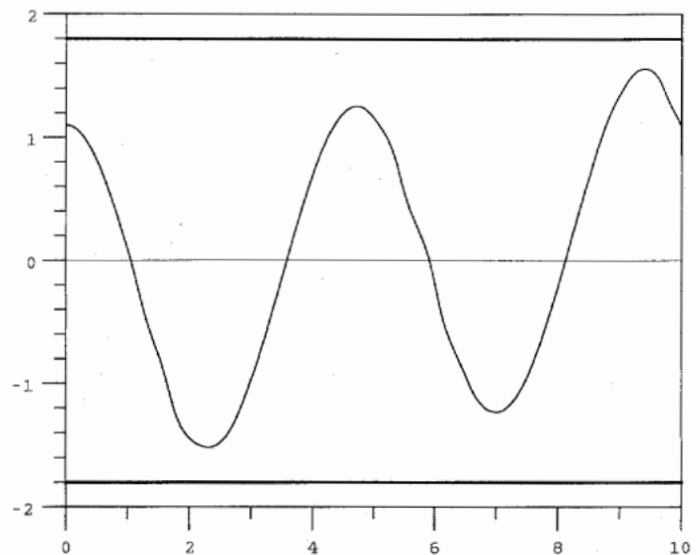


Fig. 3. Projection of downstream particle orbit onto x - z plane for electron launched with initial $\beta_\theta = 0.269$ and $\beta_z = 0.148$ into combined wiggler and axial magnetic fields (balanced cusp, $B_1/B_2 = 1$). Dimensions are in centimeters.

to a particle energy of 26 keV, cathode radius 1.4 cm, balanced cusp field $B_z = 345 \text{ G}$, and wiggler field strength as given above. In the second case (Figs. 4 and 5), electrons are launched under similar conditions but with $B_z = 448 \text{ G}$, corresponding to unbalanced cusp operation with a downstream magnetic field 1.79 times the upstream field magnitude. It was under these conditions that optimum radiation was produced experimentally.

It is interesting to note that in both cases a significant precession is evident in the electron orbit guiding center. This precession was not observed in similar studies of particle orbits in configurations employing both inner and outer magnet arrays [13], due to the more nearly transverse nature of the wiggler field in that case.

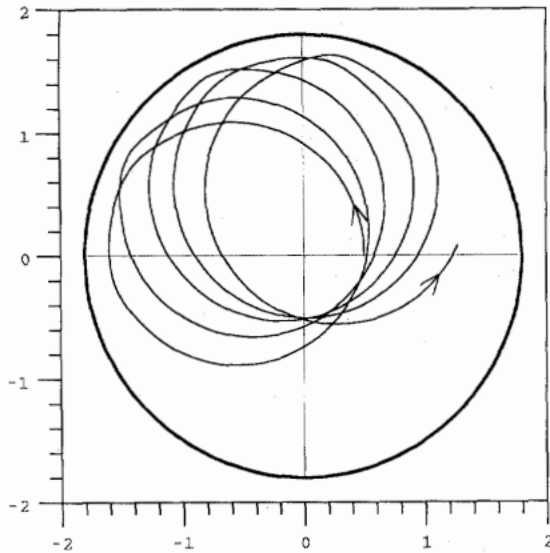


Fig. 4. Projection of downstream particle orbit onto x - y plane for electron launched with initial $\beta_\theta = 0.273$ and $\beta_z = 0.122$ into combined wiggler and axial magnetic fields (imbalanced cusp, $B_1/B_2 = 0.56$).

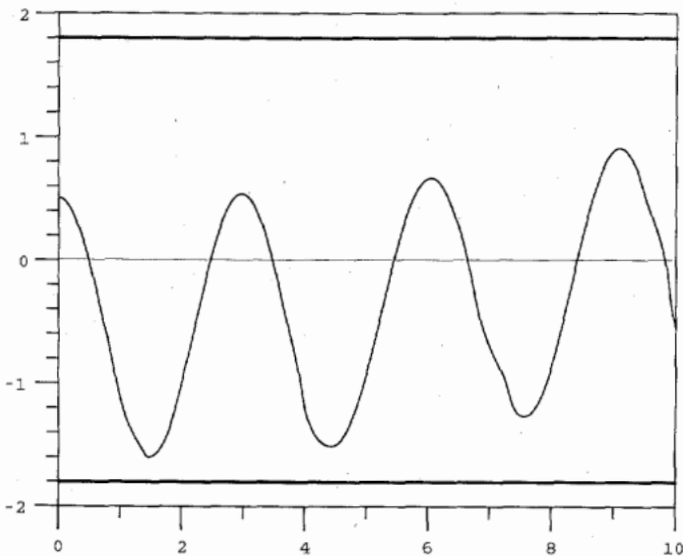


Fig. 5. Projection of downstream particle orbit onto x - z plane for electron launched with initial $\beta_\theta = 0.273$ and $\beta_z = 0.122$ into combined wiggler and axial fields (imbalanced cusp, $B_1/B_2 = 0.56$).

B. Excitation of Electromagnetic Waves by the Rotating Electron Beam

In previously reported theoretical studies of this configuration, Yin and Bekefi [15] have identified the radiative process as a coupling of a "synchronous mode" upshifted in frequency by the wiggler periodicity N :

$$\omega = k_z v_z + (\ell + N)\Omega_\parallel, \quad (4)$$

to one or more of the TM waves supported by the conducting boundary system:

$$\omega^2 = k_z^2 c^2 + \omega_c^2(\ell, n) \quad (5)$$

where ℓ is the TM wave azimuthal mode number, n is the radial mode number, and $\omega_c(\ell, n)$ is the cutoff frequency.

Interestingly, in the present study where the wiggler is not primarily transverse to the electron flow, it may be possible to excite TE modes as well. Schuetz *et al.* [18] have reported that the interaction can also occur when the synchronous mode is downshifted by the number of wiggler periods:

$$\omega = k_z v_z + (\ell - N)\Omega_\parallel. \quad (6)$$

The present experiment was originally designed to produce radiation at the 11th cyclotron harmonic, where $\ell = 1$ and $N = 10$. However, as will be seen in the next section, the experimental results are most consistent with radiation at the ninth harmonic when the effective cyclotron frequency is adjusted for the precession in the particle orbits discussed previously.

Recently, Saito and Wurtele [16] have presented a detailed comparison of circular geometry free-electron lasers and linear FEL's. In this work, it was reported that circular geometry FEL's can have higher gain and efficiency than linear configurations due to the enhancement of the beam-wave interaction provided by the negative mass instability. They also indicated, however, that such devices may be more sensitive to energy spread.

III. EXPERIMENTS

A. Apparatus

The experimental configuration used to produce a rotating electron beam is shown in Fig. 1. A magnetic cusp is formed by opposing solenoids with a soft iron plate placed in between to narrow the cusp transition width. The iron plate has an annular slot centered on axis to allow passage of the electron beam. A cylindrical, nonrotating electron beam is emitted from a thermionic cathode Pierce-type electron gun and the sharp radial magnetic field at the cusp transition produces a $v_z \times B_r$ force which results in axis-encircling Larmor orbits downstream with reduced axial velocity. The thermionic cathode has an inner radius of 1.4 cm, outer radius of 1.6 cm, and is located 4.9 cm from the anode surface which is a stainless-steel plate attached to the iron plate. The gun is pulsed for 5 μ s at a repetition rate of 60 pps with typical beam voltage 25 kV and current 0.5 A. The solenoids that produce the axial cusp field are operated dc with magnetic field amplitudes typically in the range 300–500 G.

The azimuthally periodic wiggler field is produced by samarium cobalt magnets placed behind a smooth conducting boundary exterior to the beam, as shown in Fig. 1. The radius r_o of the outer conducting boundary is 1.8 cm and the axial extent of the wiggler field is 20 cm. Plots of the measured radial and azimuthal component of the magnetic wiggler field at $r = 1.5$ cm versus wiggler period number are shown in Figs. 6 and 7. The experiment was originally designed to excite the TM_{11} mode at the 11th ($\ell + N$) harmonic of the cyclotron frequency assuming symmetric cusp operation. The reduction in the effective cyclotron frequency due to the electron guiding center precession made operation at the 11th harmonic

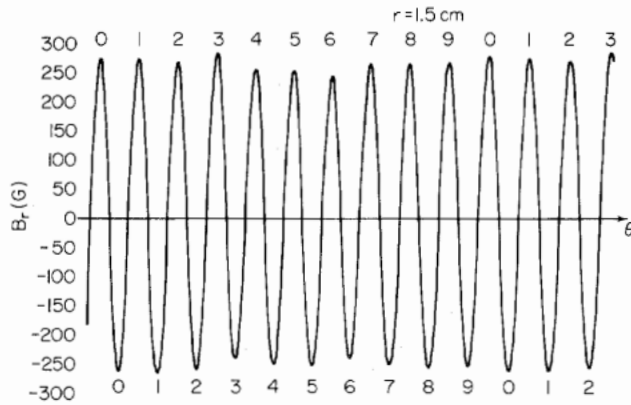


Fig. 6. Measured radial component of wiggler magnetic field versus period number.

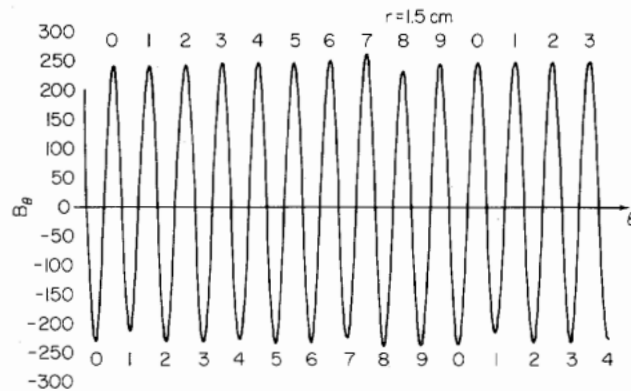


Fig. 7. Measured azimuthal component of wiggler magnetic field versus period number.

impossible, however, and radiation was finally produced at the ninth ($\ell - N$) harmonic using imbalanced cusp operation.

B. Microwave Measurements

Microwave output power is collected by an X-band standard gain horn positioned at the output window. The signal is sent through a directional coupler and rotary vane attenuator to a detector and spectrum analyzer. The receiving horn aperture encompasses the smooth-wall waveguide diameter, however, cold cavity tests have shown that less than 10 percent of the output power couples to the receiving horn. Poor conversion from the cylindrical waveguide modes to the rectangular waveguide TE_{01} mode is the main reason for the low coupling coefficient, and since cold cavity testing of this type is prone to large errors, the accuracy of the total power measurements is believed to be no better than a factor of two. The accuracy of the magnetic field measurements and the spectrum analyzer measurements of the radiation frequency are much better, typically better than 1 percent.

Displayed in Fig. 8 are oscilloscope photographs of a typical microwave detector signal, diode voltage waveform, and coarse- and fine-scale spectrum analyzer measurements of the radiated power spectrum. Instantaneous total microwave power for the case was ~ 100 W. These results were obtained using the asymmetric cusp config-

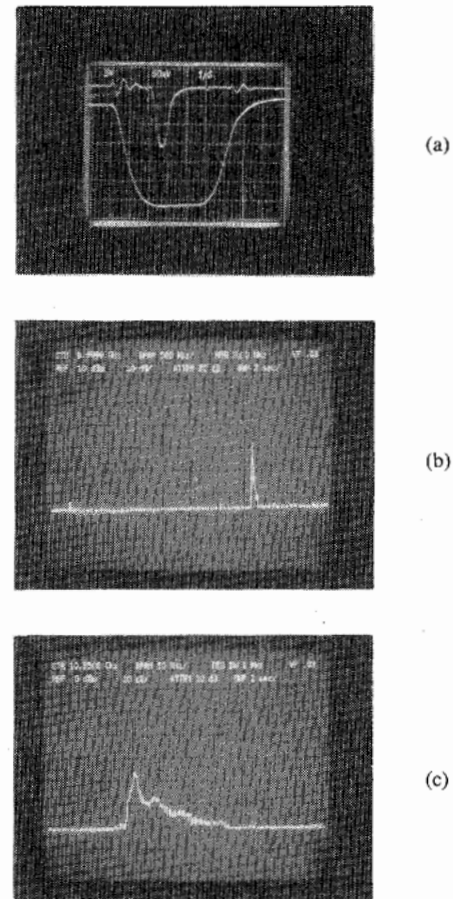


Fig. 8. (a) Microwave signal (top) and diode voltage waveform (5 kV/division) (bottom), (b) spectrum analyzer measurement of output frequency and line width (coarse scale, 9 GHz center, 0.5 GHz/div), (c) spectrum analyzer measurement of output frequency and line width (fine scale, 10.25 GHz center, 50 MHz/division).

uration described previously, as little or no radiation was observed in the symmetric cusp experiments. A high degree of sensitivity of the radiated power output to experimental parameters is evidenced by the relatively short microwave burst duration compared to the diode voltage pulse duration. The resultant microwave power spectrum is seen to be essentially single mode at 10.15 GHz, with a measured line width of about 10 MHz at the 3 dB point and about 50 MHz at the 10 dB point, with most of the line width occurring on the high-frequency side. Although the details of the power spectra are not fully understood, similar power spectra were obtained in the high-power experiments reported previously.

A comparison of the theoretically predicted output frequencies with the results of the experiment is shown in Figs. 9 and 10. Fig. 9 shows beam and waveguide dispersion curves along with the measured signal frequency for the case where the cyclotron frequency has not been corrected for the guiding center precession observed in the electron orbits. Fig. 10 shows the same case, but with the beam mode represented by

$$\omega = k_z v_z + (\ell - N)(\Omega_{||} - \omega_{pr}), \quad (7)$$

where the precession frequency ω_{pr} (78 MHz in this case)

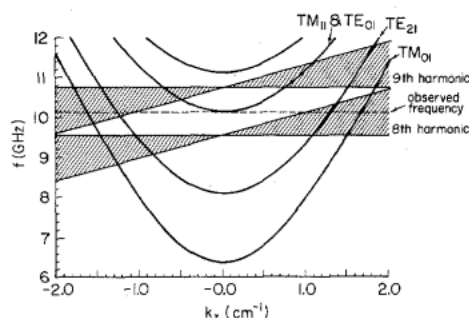


Fig. 9. Beam and waveguide dispersion curve. Beam lines are uncorrected for calculated orbit precession.

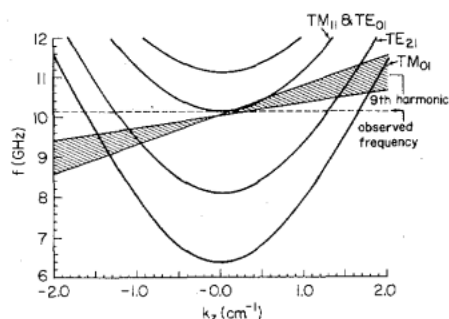


Fig. 10. Beam and waveguide dispersion curves. Beam line has been adjusted to account for calculated orbit precession.

was taken directly from the orbit calculations. In this case, agreement between the theoretically predicted frequency and the observed value is good.

IV. CONCLUSIONS

In this paper we have reported observations of microwave radiation from a low-energy rotating electron beam in an azimuthally periodic wiggler field. The observed radiation frequency is consistent with theoretical expectations when the precession in the electron orbits caused by the wiggler field is taken into account. Total radiated power at approximately the ninth cyclotron harmonic (10.15 GHz) has been measured to be about 100 W, corresponding to an electronic efficiency of about 1 percent.

These results are not optimum, however, since the device was designed to be operated at the 11th cyclotron harmonic employing a symmetric magnetic cusp. The unexpected precession in the electron orbits forced operation at the ninth harmonic using an asymmetric cusp, and the resultant electron beam density in the interaction region was undoubtedly reduced over that achievable using symmetric cusp operation. The overall sensitivity of the device to experimental parameters may also be a result of asymmetric cusp operation, since particle orbit off-centering is quite large in this case and orbit calculations for electrons launched at different radii indicate that many electrons may have simply hit the conducting boundary. With this information in hand, it should be possible to design a symmetric cusp system to operate more efficiently. Specifically, higher beam energy may have to be used to enable operation in a coaxial geometry.

We plan to continue studies of this novel FEL configuration to determine the true limits on its performance. Use of smaller wiggler magnets should easily allow operation at higher frequencies, and higher current operation may well improve device efficiency and power.

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R. Chojnacki, photograph and biography not available at the time of publication.

W. W. Destler (M'84), photograph and biography not available at the time of publication.