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Coherent radiation from an intense relativistic electron beam rotating in a background plasma

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Radiation at $\lambda \sim 1$ cm and megawatt power level is observed when a rotating, relativistic electron beam interacts with a background plasma. The emission spectrum is peaked at the 20th cyclotron harmonic, and the parametric dependence of the radiation is consistent with a model of interaction between single-particle cyclotron radiation and a beam-plasma streaming instability.

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The mechanism of coherent curvature radiation has been invoked to explain coherent radio emission from pulsars.[1] It is also a probable mechanism for coherent radiation which has been observed in the controlled thermonuclear research of the Astron program.[2] A number of theoretical analyses of this process have been published.[3,4] The most general treatment, that of Buschauer and Benford,[4] motivated the present experimental study. Briefly, the process involves single-particle cyclotron radiation from accelerated electrons which is made coherent by spatial bunching of the electrons due to a streaming instability arising from the interaction between the electron beam and a background plasma.[5] In the study of this mechanism described below, we find that a hollow e-beam rotating with speed $v = 0.95c$ and radius of curvature $\rho = 3$ cm interacts strongly with a background plasma emitting megawatt level cyclotron harmonic radiation peaked at a wavelength $\lambda \sim 1$ cm corresponding to a harmonic number ~ 20.

The experimental arrangement is shown in Fig. 1. An annular electron beam (typically $V = 1.2$ MV, $I = 30$ kA, radius $r_0 = 3$ cm, and thickness $t = 5$ mm) was injected through an anode foil into a chamber prefilled with plasma from a Marshall gun. The streaming electron beam passed through a magnetic cusp in which axial magnetic field B_z reversed from a value of $-B_0$ to $+B_0$. This converted a large fraction of electron streaming velocity, v_z, into rotational velocity, v_θ. After passing through the cusp

$$v_\theta = eB_0 r_0/m\gamma, \tag{1}$$

where $\gamma = (1 - v_z^2/c^2 - v_\theta^2/c^2)^{-1/2}$, and for $V = 1.2$ MV, $\gamma = 3.3$.

The rotating electron then emitted *single-particle* cyclotron harmonic radiation whose spectrum peaked at a characteristic frequency[6] $\omega^*/2\pi = 0.45\,\gamma^3 c/2\pi\rho \lesssim 0.45\,\gamma^3 c/2\pi r_0 = 26$ GHz, where the radius of curvature of the electron orbits $\rho = \gamma v_\theta (1 + v_z^2/v_\theta^2)\Omega^{-1}$ and the cyclotron frequency $\Omega = eB_z/m$.

The first test for the existence of *coherent* radiation was to fire the plasma gun through a puff valve and then fire the electron-beam pulse into the drift tube at some specific elapsed time, t_d, after the plasma gun had been fired. As t_d was increased, the background plasma frequency, ω_p, decayed to lower values. The value of ω_p was continuously monitored with a 2-mm interferometer. Coherent curvature radiation was searched for using a K_a band antenna and receiver. The K_a band waveguide used in the receiver line had a cutoff frequency of 21 GHz and single mode operation up to 42 GHz. Radiation was also monitored in other microwave bands covering 8–26 GHz and 110–170 GHz; in all cases the radiation flux was at levels far below the maximum K_a band level.

K_a band radiation is plotted versus t_d in Fig. 2. For short t_d, $\omega_p \gg \omega^*$ and no K_a band signal was observed. Then, there was a sharp onset of signal when $\omega_p/2\pi \approx 50$ GHz, a peak in signal when $\omega_p/2\pi \approx 30$ GHz, and, finally, persistent radiation for lower ω_p. When various baffles were placed in front of the plasma gun so as to change the initial value of ω_p, the onset and peak of the radiation occurred at values of t_d different from those in Fig. 2; however, the value of $\omega_p/2\pi$ where onset and peak radiation occurred did not change perceptibly from 50 and 30 GHz, respectively.

This behavior is basically in agreement with that expected for coherent curvature radiation. When an electron beam spirals in a background plasma, a streaming instability can occur which will bunch the beam electrons with spatial period $2\pi c/\omega_H$, where ω_H is the upper hybrid frequency (i.e., $\omega_H^2 = \omega_p^2 + \Omega^2$, and $\omega_H \approx \omega_p$ for the cases of interest in this paper). When $\omega_H \approx \omega^*$, the bunching period is optimized for cyclotron radiation from electrons in adjacent bunches to add in

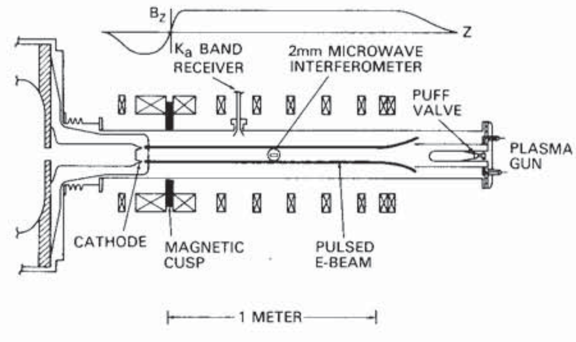

FIG. 1. Experimental apparatus.

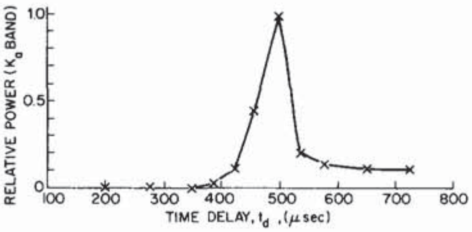

FIG. 2. Radiated power versus plasma-beam delay time. Latter delay times correspond to lower background plasma densities.

phase. This coherence effect can lead to a large increase in radiated power.

A second experiment consisted of keeping t_d fixed near the value required for peak radiation, but changing B_0, the magnetic field step through the cusp. This varies the value of v_θ and tests if the observed coherent radiation at $\omega \approx \omega_p$ is indeed related to cyclotron radiation from the beam electrons. When B_0 is increased, the electrons travel through the cusp with increasing transverse velocity as given by Eq. (1) until B_0 approaches a critical value, B_{cr}, at which point all the initial energy has been ideally converted to rotation. It is easily shown that

$$B_{cr} = (mc\gamma/er_0)(1-\gamma^{-2})^{1/2}. \qquad (2)$$

We have measured the ratio v_θ/v_z as a function of B_0 by a damage pattern technique described elsewhere.[7] We find that v_θ increases with B_0, and when $B_0 = B_{cr}$, the experimental velocity component ratio $v_\theta/v_z = 2.5$. Current which can be injected through the cusp has also been monitored in separate measurements by inserting a steel rod across the drift tube downstream from the cusp, and detecting x rays emitted when the e-beam struck the rod. Using this technique, injected current was found to fall off strongly for $B_0 > B_{cr}$.

Observed K_a band radiation is plotted versus B_0 in Fig. 3. The radiation rose initially as B_0 and v_θ increases, and then fell sharply for $B_0 > B_{cr}$ when electron current through the cusp was "cut off". Two curves are plotted in Fig. 3, one for $\gamma = 3.3$ and the second for $\gamma = 2.9$. It is seen that the value of B_0 where the radiation peaks shifted to smaller B_0 as γ was decreased. This behavior is consistent with Eq. (2) and other features of the proposed model. It should also be noted that when the cusp is deactivated and B_0 kept constant from the cathode into the drift tube, the K_a band emission disappears.

Although the electron-beam current pulse had a duration of ~50 nsec, the pulse width of the K_a band radiation was only a few nanoseconds, presumably because optimum matching of the beam and background plasma parameters occurred only for this short time. The shortness of the K_a band pulse facilitates determination of the frequency spectrum of the radiation. The signal from the experimental chamber first passed through 10 m of waveguide and then was split in a directional coupler. One part of the signal was sent directly from the coupler to detector No. 1, while a second part was sent through an additional 35 m of waveguide prior to exciting detector No. 2. The waveguide was dispersive so that a pulse of radiation which was composed of several frequencies appeared as a series of pulses separated in time after passing through a length of waveguide.

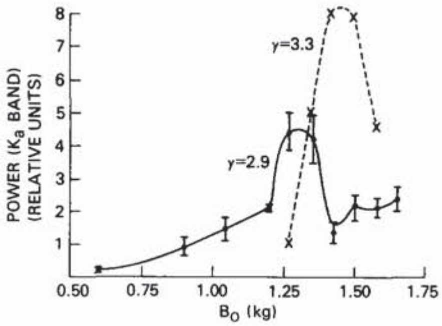

FIG. 3. Radiated power versus cusp magnetic field. Error bars indicate data spread from several shots taken at same nominal parameters.

A typical negative-going signal obtained by summing the outputs of the two microwave detectors is shown in Fig. 4. By measuring the time delay between each pulse from detector No. 1 and the corresponding pulse from detector No. 2 the frequency of each pulse can be determined; confirmation is obtained by measuring the frequency-sensitive waveguide attenuation. For the signals in Fig. 4, the three most powerful pulses occurred at frequencies of 28.0, 29.7, and 31.4 GHz and the corresponding radiated power coupled to the K_a band antenna at each of these frequencies was calculated to be respectively 400, 160, and 140 W.

Relativistic electrons moving along a spiral trajectory with pitch angle θ emit harmonics spaced with an interval $\Delta\omega = \Omega/(\gamma \sin^2\theta)$. In Fig. 4, $\Omega/2\pi\gamma = 1.3$ GHz and $\theta \approx 67°$ so that $\Delta\omega/2\pi \approx 1.5$ GHz in approximate agreement with the observed separation. Thus, it appears that we have observed radiation from the beam electrons and not radiation connected with excitation of electrostatic waves in the background plasma[5,8] which would have spacing between harmonics of $\Delta\omega/2\pi = \Omega/2\pi \approx 4.2$ GHz.

Total power radiated by the beam electrons was estimated by dividing power coupled to the K_a band antenna by the fraction of the drift tube wall subtended by that antenna; total K_a power was ~1 MW. Single-particle cyclotron radiation gives a power[9] $P_{sp} \sim e^2\Omega^2 v_\theta^2 \gamma^2/6\pi\epsilon_0 c^3$, which when multiplied by the number of beam electrons in the drift tube, N, yields $NP_{sp} \sim 5$ W for the parameters of our experiment. Buschauer and

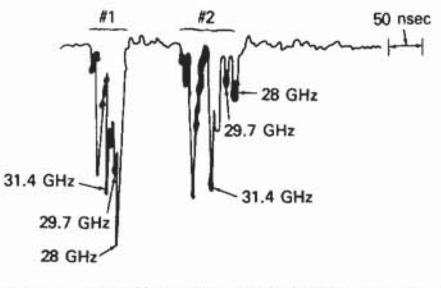

FIG. 4. Oscillogram of frequency spectrum measurement obtained by passing K_a band signal through dispersive lines.

Benford[4] give a coherence enhancement factor, $\epsilon=\pi p A_t \tilde{n}/2\gamma^3$ where A_t is the area of the beam bunches transverse to the beam particle velocity and $\tilde{n}$ is the rms fluctuation in beam density n due to the streaming instability. Estimating[4] that $A_t \approx 0.1$ cm^2, the coherent power would be $\epsilon N P_{sp} \approx 10^9$ W for $\tilde{n}/n = 1\%$. Thus, single-particle power has been vastly exceeded in our experiment without reaching the theoretical maximum for coherent curvature radiation. Additional evidence for a coherent process is given by the data of Fig. 3 where the maximum rate of power increase with B field is seen to be well over an order of magnitude more rapid than the dependence $P_{sp} \propto \Omega^2 v_\theta^2 \gamma^2 \propto B_0^4$.

Finally, it should be noted that maximum radiation in Fig. 4 occurred at ~20th cyclotron harmonic. In contrast, one may cite results of an expermanental[10] and analytical[11] study of coherent radiation from a relativistic rotating electron beam in *vacuum*. In that case, radiation was found to be maximum at the fourth cyclotron harmonic when $\gamma=5$. Similarly, in the observations of Fessenden and Stallard[2] where the Astron e-beam rotated in a tenuous background plasma with $\Omega \gtrsim \omega_p$ the radiation peaked at ~γth harmonic of the beam cyclotron frequency. The present process, in which the rotating e-beam interacted with a background plasma having $\omega_p \gg \Omega$, produced maximum radiation at a much higher harmonic number ~γ^3. Thus, the present process recommends itself for further study as a powerful radiation source not only at millimeter but also at submillimeter wavelengths.

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[1] V. L. Ginzburg and V. V. Zheleznyakov, Ann. Rev. Astron. Astrophys. **13**, 511 (1975).

[2] T. J. Fessenden and B. W. Stallard, Lawrence Radiation Laboratory, Controlled Thermonuclear Research Annual Report UCRL-50002-70, 1970, p. 3-27.

[3] W. J. Cocke and A. G. Pacholczyk, Astrophys. J. **195**, 279 (1974); A. Saggion, Astron. Astrophys. **44**, 285 (1975); P. C. W. Fung, Can. J. Phys. **46**, 1073 (1968).

[4] R. Buschauer and G. Benford, Mon. Not. R. Astron. Soc. **176**, 335 (1976).

[5] C. D. Striffler and T. Kammash, Plasma Phys. **15**, 729 (1973).

[6] G. Bekefi, *Radiation Processes in Plasmas* (Wiley, New York, 1966), p. 193.

[7] C. W. Roberson, G. Saenz, and D. Tzach, Rev. Sci. Instrum. **48**, 31 (1977).

[8] S. Gruber and G. Bekefi, Phys. Fluids **11**, 123 (1968); B. R. Kusse and A. Bers, Phys. Fluids **13**, 2372 (1970).

[9] G. Bekefi, Ref. 6, p. 180.

[10] V. L. Granatstein, R. K. Parker, and P. Sprangle, Sandia Laboratories Document SAND 76-5122, 1975, Vol. II, p. 401 (unpublished).

[11] P. Sprangle, J. Appl. Phys. **47**, 2935 (1976).

Surface electromagnetic wave launching at the edge of a metal film

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Propagating ir surface electromagnetic waves have been launched on and off the edges of a metallic film evaporated on the base of an NaCl prism. The coupler does not make use of an air gap or a grating.

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A technique has been developed which does not require an air gap or a grating to couple laser radiation to surface electromagnetic waves (SEW's) on a metal surface in the infrared. In this note, we test the coupler efficiency and show that the loss introduced by thin dielectric coatings on metal surfaces can be readily measured with this technique.

SEW's have been known since the time of Zenneck[1] and Sommerfeld[2] to constitute a class of inhomogeneous wave solutions to Maxwell's equations at a metal-air interface. These SEW's are TM electromagnetic waves trapped on a metal surface with an amplitude which decays exponentially with distance from the surface both in the air and in the metal.

SEW's cannot be excited directly by plane waves incident on a metal since the parallel component of their propagation vector is always larger than that of the propagation vector associated with the incident plane wave.[3] Otto,[4] in 1968, was the first to realize that the phenomenon of total internal reflection could be used to match the parallel component of the propagation vector to that of the SEW. In 1973, Schoenwald *et al.*[5] reported the propagation of SEW's along a copper/air interface over several cm for a wavelength of 10.6 μ. More recently, other workers[6-8] have used this technique to measure the absorption coefficient of dielectric films and adsorbed molecules on metal surfaces. The prism coupling scheme used in all of these studies relies on tunneling of the evanescent wave from the prism surface across an air gap to the metal surface. The metal surface must be close to, but not in contact with, the