Microwave Emission Produced by the Interaction of an Intense Relativistic Electron Beam with a Spatially Modulated Magnetic Field

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Intense microwave emission was detected when a pulsed relativistic electron beam traversed a spatially modulated magnetic field. The microwave intensity was $\gtrsim 70$ dB above the noise level. The wavelength of the electromagnetic radiation was equal to the characteristic length of the rippled magnetic field. At a critical averaged magnetic field, the radiation appeared to be almost monochromatic ($\Delta\lambda/\lambda \lesssim 0.5\%$); below the critical field, a broad spectrum appeared ($\Delta\lambda/\lambda \gtrsim 10\%$).

Various effects place upper limits on the voltages and currents of electron beams used in conventional microwave tubes.[1] These, in turn, limit the amount of microwave power that can be generated, especially at frequencies $\gtrsim 10$ GHz. Several nonconventional generators have been suggested to produce intense microwave radiation,[2] but these devices generally have suffered from all or some of the limitations of conventional generators.

One suggestion to increase the power level of microwave generators (or amplifiers)[3,4] was to utilize the interaction between a magnetically undulated periodic electron beam and the TE_{01} mode in an unloaded circular waveguide. The beam and the electromagnetic wave can be coupled without slowing the phase velocity of the wave to the velocity of the electron beam. This device (named the "Ubitron") uses a large circular waveguide as well as a large-diameter annular electron beam and can work at high current and power levels. Recent developments[5-7] in intense relativistic electron-beam generators, with peak powers $\gtrsim 10^{10}$ W, make such devices attractive for the production of high-power microwaves.[8] This work describes preliminary results of the characteristics of the high-power rf radiation emitted from an intense relativistic electron beam propagating in a Ubitron-like device. In our laboratory a pulsed electron beam, having a current ≈ 20 kA, voltage ≈ 720 kV, and duration ≈ 50 nsec, has been used as an electron beam source for a Ubitron-type device. Typical voltage and current traces are shown in Fig. 1, top and middle, respectively. A foilless diode[9] was used to produce an annular beam [Fig. 2(a)]. The microwave generator consisted of two parts:

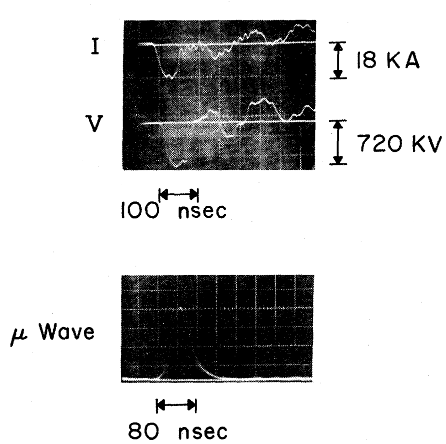


FIG. 1. (Top) Current and (middle) voltage traces of the electron beam accelerator. (Bottom) Typical microwave trace.

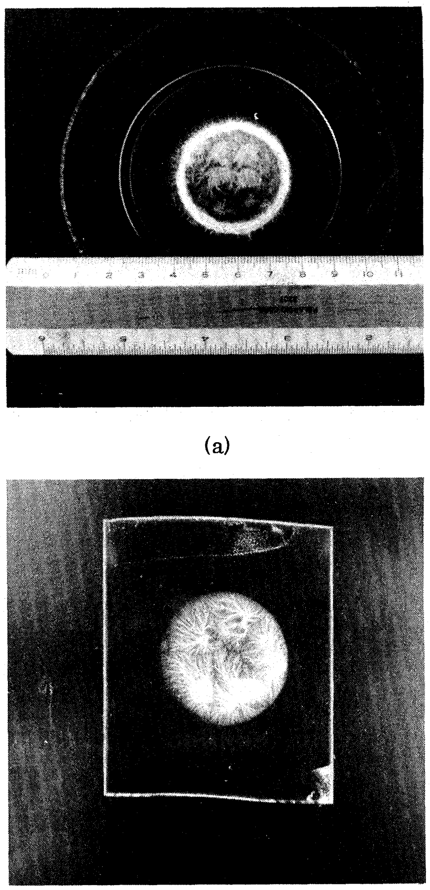
(1) A modulated magnetic field region, which was produced by alternately inserting aluminum and iron disks inside a solenoid. The magnetic field intensity at a distance r from the center had the shape

$$B(r,z) = B^*[1 + h(r)\sin(2\pi z/L)],$$

where the pitch was $L \approx 3.8$ cm. At $r = 2$ cm and for $B^* = 3$ kG, $h(r) \approx 0.05$.

(2) A homogeneous magnetic field region, $B = B^*$, which followed downstream from the rippled field.

The experimental arrangement is shown in Fig. 3. The annular electron beam with a 1.7-cm radius was propagated inside a circular waveguide embedded in the magnetic field configuration. The size of the waveguide was chosen such that the cutoff frequency for the TE_{01} mode was ≈ 7.5 GHz. The experiment was designed to use a nonadiabatic process to introduce perpendicular motion into the electron beam instead of using an external microwave source.[3,4] It is well known that electrons can have their motion changed nonadiabatically, i.e., have parallel velocities changed to perpendicular velocities (or *vice versa*), by traversing a rippled magnetic field which fulfills



(a)

(b)

FIG. 2. (a) Damage pattern on a Lucite plate (located 1 m downstream) caused by the annular electron beam. The electron beam propagated in a homogeneous magnetic field. (b) Damage pattern on a Lucite plate caused by the electron beam after it transversed the interaction region. The magnetic field B^* was equal to B_{cr}.

the relation[10]

$$B_{av} \equiv B^* \approx (2\pi/eL)\gamma m_0 c^2,$$

where $\gamma = (1-\beta^2)^{-1/2}$, $\beta = v/c$, and L is the periodicity of the magnetic field.

This nonadiabatic process has a resonance feature; the width of the resonance depends on the amplitude of the ripple and the number of periods.[11] The rf field needed for the Ubitron mechanism[3,4] was produced when the electron beam with transverse velocity gained in the rippled-field region drifted in the homogeneous magnetic field region and emitted radiation.[12,13] By such a construction the Ubitron was modified to become a microwave generator.

The microwave intensity was measured by two methods: first, by using a 40-dB directional coupler and calibrated microwave absorbers; and second, by using the attenuation characteristics of a long section of waveguide.[1] In both methods the attenuated signal was measured with a crystal detector.

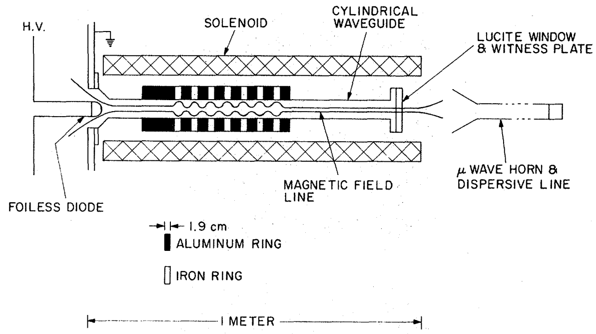


FIG. 3. Experimental schematic.

The wavelengths (and the spectral distribution) were deduced from the dispersive characteristics of the long waveguide section.[1,14] The width of the spectral distribution was also found in some cases by using interferometric techniques.

The electron beam was analyzed qualitatively by observing the damage pattern produced on a Lucite plate at the end of the homogeneous magnetic field region. We have observed microwave emission from the device under three sets of conditions: (1) when the beam was propagated only in a homogeneous magnetic field; (2) when the beam was propagated only in a rippled magnetic-field region; (3) when the beam was allowed to propagate in the complete device. The base pressure in the drift tube was $\lesssim 0.05$ mTorr. The magnetic field B^* was varied from 3 kG up to 10 kG.

In each of the three conditions, the total microwave power measured in the X band was found not to be influenced by the magnetic field intensity. The ratios of the microwave power emitted under each of the three conditions were

$$I_1 : I_2 : I_3 = 1 : \lesssim 10^4 : \gtrsim 10^7.$$

The duration of the microwave emission was approximately equal to the duration of the current pulse. A typical microwave trace is shown in Fig. 1, bottom trace. Under the second and third sets of conditions, we have found that there existed a critical value of magnetic field, B_{cr}, which was equal to B_{av} in Eq. (2). When $B < B_{cr}$, the spectrum was broad ($\Delta\lambda/\lambda \gtrsim 10\%$); when $B \approx B_{cr}$, the spectrum was narrow ($\Delta\lambda/\lambda \lesssim 0.5\%$); and when $B > B_{cr}$, one or two narrow lines appeared in the spectrum, each with $\Delta\lambda/\lambda \lesssim 0.5\%$. The wavelength

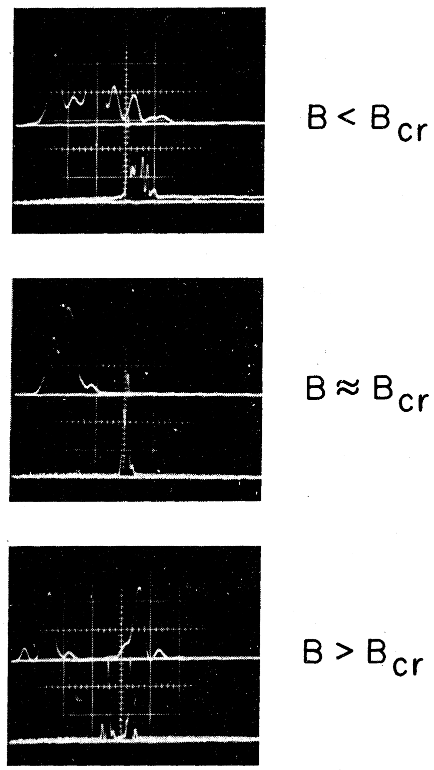


FIG. 4. Dispersed microwave traces obtained under the following conditions: (top) $B < B_{cr}$, (middle) $B \approx B_{cr}$, and (bottom) $B > B_{cr}$. The microwave pulses were detected after propagation in a ~140-m-long X-band waveguide. In each condition, the time scale for the top traces is 50 nsec/division, and for the bottom traces, 200 nsec/division. In addition, time zero for the bottom traces in each condition was the time the current had started.

of the rf radiation was $\lambda \approx 3.8$ cm, approximately equal to L. The variation of λ with magnetic field, except for that which was described before, was insignificant.

Typical microwave traces for these three ranges of magnetic field ($B^* < B_{cr}$, $B^* \approx B_{cr}$, and $B^* > B_{cr}$) are shown in Fig. 4. The microwave pulses were detected after propagation in a 140-m-long waveguide, which acted as a dispersive line. An accurate measurement of the width of the spectrum, Δf, was obtained by using microwave interferometric techniques. When $B^* \simeq B_{cr}$, Δf was found to be ≈ 50 MHz. The damage pattern on the Lucite plate did not show any detectable change in the shape of the electron beam after passing through only the rippled magnetic field. However, when the homogeneous magnetic field region was added, strong bunching occurred as can be seen on the Lucite plate [Fig. 2(b)].

Comparing the original Ubitron results with the new ones we have found that although (i) the two devices require relativistic electrons for their operation, and (ii) the frequencies of the rf radiation emitted in both mostly depend on the pitch of the magnetic field, these devices differ in other respects. The new one is a generator which emits radiation with a spectral distribution that can be controlled by the magnetic field. The Ubitron is an amplifier. It emitts rf radiation with a very wide spectral distribution that does not depend on the magnetic field intensity. These differences suggest that some additional or different mechanism must be responsible for the new results. Theoretical and experimental efforts are in progress to understand this mechanism and will be reported later.

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Pressure Dependence of Electron Drift Velocity in Hydrogen at 77.8°K

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Our measurements show at $E/P < 0.03$ V/Torr cm a decrease of the drift velocity in hydrogen with increasing pressure (up to 50 000 Torr), which cannot be explained by an electron trapping mechanism. It is shown that this effect is in agreement with Legler's theory which takes into account multiple scattering. For $E/P > 0.03$ V/Torr cm, the observed decrease of the drift velocity can be explained by an electron trapping mechanism.

Grünberg[1] and Huber[2] observed a pressure dependence of the electron drift velocity in the gases H_2, N_2, ethane, and propane at room temperature. They found a decreasing drift velocity with increasing pressure at a given E/P [in the following P is given by $P = N/(3.30\times10^{16}\ \mathrm{cm}^{-3}\ \mathrm{Torr}^{-1})$, with N the density]. The decrease of the drift velocity at high pressures could be explained by the hypothesis that the electrons are captured by molecules for a short time τ. Ritchie and Turner[3] showed that electrons drifting a distance d need a time

$$t_d = (1+\tau\nu)d/v_-(0), \tag{1}$$

where ν denotes the frequency of collisions which produce a trapped electron and $v_-(0)$ the drift velocity without electron capture. Grünberg and Huber showed that $\tau\nu$ is proportional to P in the gases mentioned above. That means $\tau\nu = \tau\nu_1 P$, where $\tau\nu_1$ is pressure independent. From this it follows that

$$v_-(P) = v_-(0)(1+\tau\nu_1 P)^{-1}. \tag{2}$$

Frommhold[4] tried to explain the electron capture in H_2 and N_2 as a rotational resonance.

In recent experiments Crompton and Robertson[5] described the pressure dependence of electron drift velocity in normal hydrogen and parahydrogen at 77°K and gas densities up to 10^{20} cm^{-3} (about 3000 Torr; see also Robertson[6]) and found that the drift velocity decreases up to approximately 1.5% in the range $0.018 < E/P < 0.15$ V/Torr cm. They showed that their results of the pressure dependence are consistent with Eq. (2) and with Frommhold's hypothesis that the electron capture is associated with the rotational excitation of the hydrogen molecules.

We have measured the drift velocity in hydrogen at 77.8°K at high pressures up to 50 000 Torr ($N = 1.65\times10^{21}$ cm^{-3}). A time-of-flight method has been used similar to that described in Ref. 1. The E/P range is 0.001–0.25 V/Torr cm. The possible error is 2%. The results at low pressure (2000 Torr) agree to within 2% with those of Lowke.[7] The agreement is within the combined error limits.

Figure 1 shows the quotient $q = v_-(P)/v_-(2000$ Torr) taken from our measurements: q decreases with decreasing E/P, passing through a minimum between 0.1–0.5 V/Torr cm, and then increases to a maximum. The value of E/P correlated with the maximum is different for different pressures. Then q falls monotonically with decreasing E/P to a constant value: The electrons are in thermal equilibrium with the gas (to be seen in curve 1 of Fig. 1).

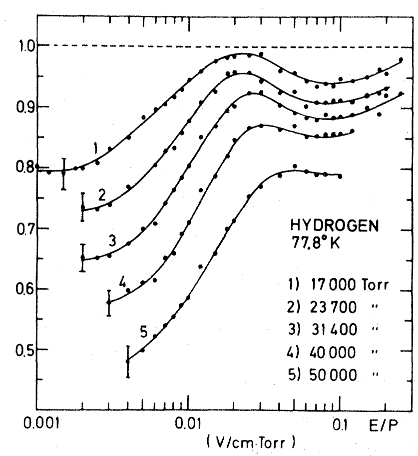


FIG. 1. The quotient q of the drift velocity at high pressures and the drift velocity at low pressure (here 2000 Torr) as a function of E/P.

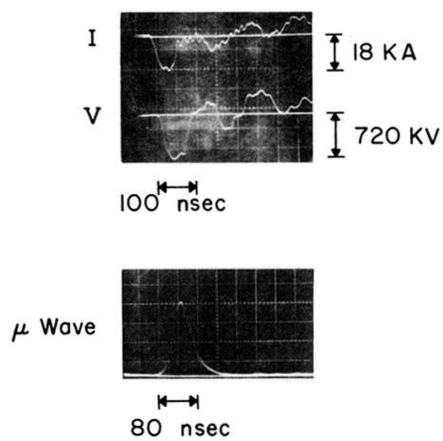
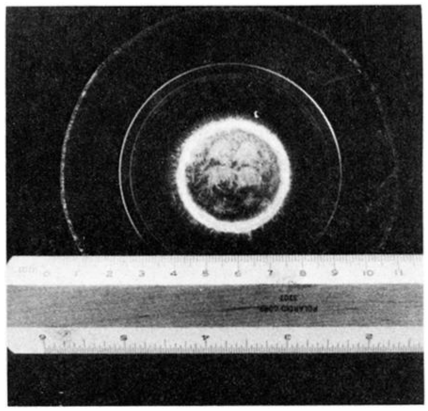
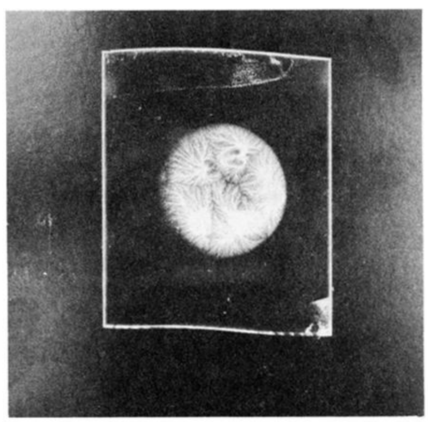


FIG. 1. (Top) Current and (middle) voltage traces of the electron beam accelerator. (Bottom) Typical microwave trace.



(a)



(b)

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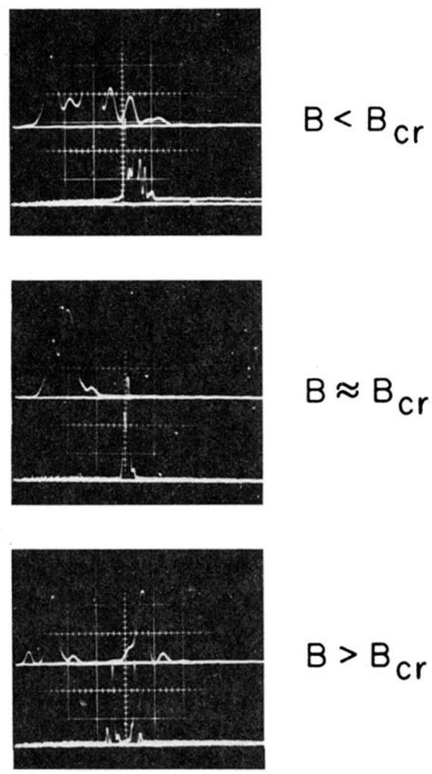

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