Giant Microwave Bursts Emitted from a Field-Emission, Relativistic-Electron-Beam Magnetron*

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(Received 10 May 1976)

A magnetron operating at a wavelength of 10 cm has been constructed with six resonant cavities cut in a cylindrical anode block. A graphite cylinder acting as a field-emission cathode delivers ~12 kA in an accelerating radial potential of ~360 kV. The magnetic field directed along the diode axis is ~8 kG. Linearly polarized microwaves of 30 nsec duration at powers of ~1.7 GW are achieved. The conversion efficiency of electron energy into microwave is ~35%.

Advances in high-voltage pulse technology permit the generation of intense relativistic beams of electrons ranging in power from gigawatts to terawatts. Efficient conversion of this energy into electromagnetic radiation is a task pursued at several laboratories. In these studies one excites on the beam one of several known collective modes of oscillation and promotes wave growth at the expense of the beam's kinetic or potential energies. The techniques used to date fall into the following three categories. In the first, axial bunching[1-3] is induced on the relativistic beam. In the second, the electrons are made to bunch transversely[4-7] to a guiding axial magnetic field. And in the third,[8,9] one uses modes of oscillation which are typical of "crossed-beam" devices[10-12] of which the magnetron is the best known example. Here the electron beam moves under the simultaneous action of a dc electric field and an orthogonal dc magnetic field. The well-known[11] efficiency of crossed-beam devices operating with convectional thermionic cathodes of relatively low current densities suggests that one apply them in the regime of high currents and high voltages characteristic of field-emission diodes. The magnetron described in this Letter yielded[13] a power of ~ 1.7 GW; the efficiency of converting beam energy to microwave energy was close to 35%.

A schematic of the cylindrical vacuum diode is illustrated in Fig. 1. The anode block has an inner radius of 2.1 cm and within it are six vane-type resonators[10] designed to oscillate at a frequency of 3.0 GHz. Each resonator is 7.2 cm long; one of the resonators is provided with a slot through which the radiant energy is coupled into a microwave horn having a rectangular aperture 17 cm wide and 23 cm high. The coaxial cathode cylinder is made from graphite and is 4.8 cm in radius. It is connected via a steel shank to the inner conductor of the water-filled coaxial capacitor of our 4-Ω Nereus high-voltage facility. The anode is connected to the grounded wall of the capacitor. The entire system, including the transmitting horn, is pumped to pressures less than 10^{-4} Torr. The axial magnetic field B_z acting on the diode is generated by two solenoids mounted in an approximate Helmholtz-pair configuration.

The diode current is measured with a Rogowski coil wound around the steel shank that connects to the cathode. The diode voltage is obtained from the signal delivered by a calibrated copper sulphate voltage-divider network. There is an unwanted inductive contribution on this voltage which is subtracted out by a technique described elsewhere.[8,9]

Time histories of the voltage and the current are shown in Fig. 2 for the case of an axial magnetic field equal to 7.5 kG. At this field the diode is magnetically insulated, an azimuthally rotating space-charge field is established and microwave emission is expected. The bottom of Fig. 2

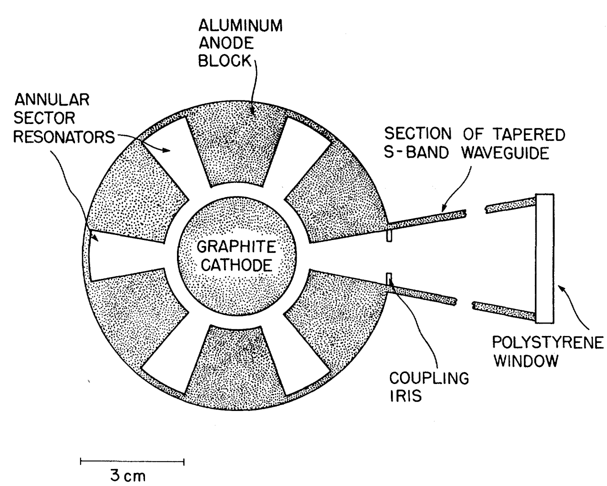

FIG. 1. Schematic of the cylindrical diode. The scale gives the correct diode dimensions only. The size of the transmitting horn is given in the text.

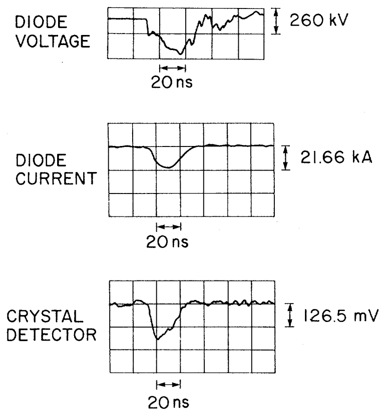

FIG. 2. Oscilloscope traces of the diode voltage (corrected for inductive effects), of the diode current, and of the voltage output from the microwave crystal detector. $B_z = 7500$ G.

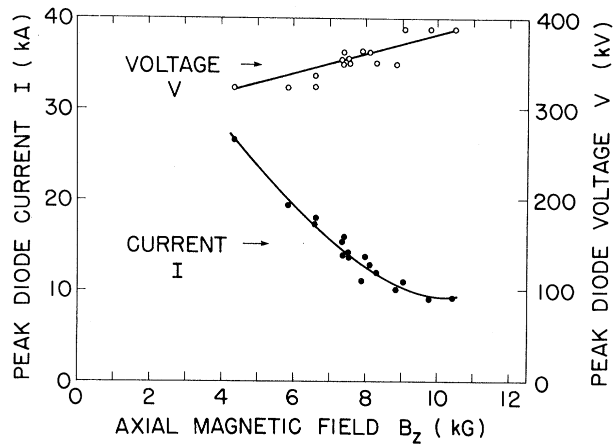

FIG. 3. Peak diode voltage and current as a function of magnetic field, as measured in the cutoff regime $B_z \gtrsim B^*$.

shows the microwave signal output from the crystal detector. To bring the emitted power (1–2 GW) to reasonably low levels measurable by the crystal detector, we employed the following arrangement. A receiving antenna (a section of open S-band wave guide) was placed facing the transmitter and separated 4.0 m from it. Precision attenuators further reduced the radiation to levels which were typically in the milliwatt range. This power was allowed to impinge on a previously calibrated broadband crystal detector. Knowledge of the antenna gains and of their separation allows one to compute[14] the ratio P_t/P_x, where P_t is the power transmitted by the horn and P_x the power measured by the crystal. As a check on this procedure, we injected a known 10-cm wavelength signal into the horn transmitter from a conventional cw klystron and, using the same receiving antenna placed at the identical distance of 4 m, we measured P_x at the crystal detector. In this way a determination of the ratio P_t/P_x was obtained which did not require knowledge of the antenna gains.

An independent method, based on the microwave breakdown of gases, was also used in deducing the emitted power. A quartz tube was filled with dry, spectroscopically pure air[15] to a pressure of 10 Torr, and inserted, together with a camera, in a light-tight box. The contraption was placed in the microwave beam and the distance from the horn varied until electrical breakdown of the gas just did not occur. This happened at a distance of 5 m from the transmitter, at which point air-breakdown measurements and theory[16] require that the peak electric field be ~2.2 kV/cm. Knowledge of the antenna gain gives an emitted power ~1.7 GW, a result which is in good agreement with the earlier determination. We mention that at the power levels of these measurements (1–2 GW) atmospheric breakdown in front of the horn is about to become a worrisome problem. At our maximum power of 1.7 GW the electric field amplitude is ~57 kV/cm (at its peak, in time and space) whereas pulsed-microwave air breakdown occurs[16] at a peak field of ~57 kV/cm (40 kV/cm rms).

In Fig. 3 are shown the currents and voltages plotted as a function of the externally applied magnetic field B_z. When B_z is zero, I is typically 35 kA and $V \simeq 260$ kV giving a diode impedance equal to 7.4 Ω. As B_z increases from zero, a critical magnetic field $B_z \equiv B^*$ is reached at which point the diode is said to be magnetically insulated,[8,9] and ideally, no current should flow across the diode. For our voltages, geometry, and gap spacing ($d = 5.2$ mm), $B^* = 4800$ G. That substantial current does flow in the forbidden regime, $B_z \geq B^*$, represents one of the classical properties of all magnetrons.[8,9,11] It signifies that "nonconservative" oscillatory processes must, in fact, be occurring. Thus, strong onset of microwave emission is expected to occur at this critical field. As B_z is increased beyond B^*, the diode current keeps falling, and the diode voltage increases slightly, showing that the diode impedance becomes more and more mismatched relative to the 4-Ω nominal impedance of the Nereus generator.

In the cutoff regime ($B_z > B^*$), an azimuthally rotating cloud is established characterized by a

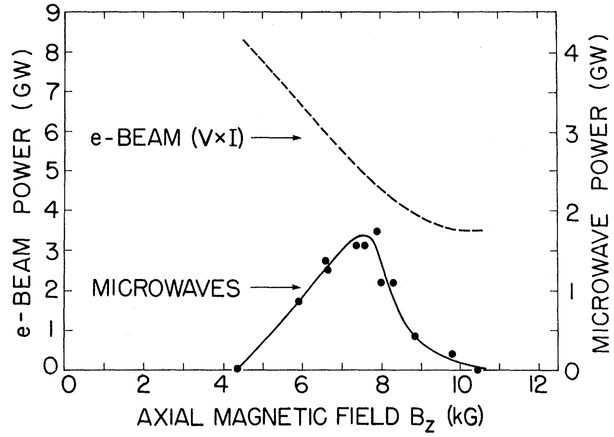

FIG. 4. Microwave-power output and electron-beam power as a function of magnetic field.

radially dependent drift $\vec{v}_d(r) = \vec{E}(r) \times \vec{B}/B^2$. The microwave cavities in the anode block act as a slow-wave structure: They permit the establishment of a wave whose velocity v_p approximately equals the drift velocity $v_d(r)$ of a "resonant" electron layer. Under these conditions efficient transfer of energy from the beam to the wave can occur. For a fixed diode geometry and for a fixed diode voltage V, the magnetron can oscillate only over a limited regime of magnetic fields. The minimum field is $B_{\rm min} = B^* \simeq 4800$ G. The maximum field $B_{\rm max}$ is determined by the drift velocity v_d of the fastest (outermost) electron layer. Using the theory developed by Ott and Lovelace[17] we find that for our situation $B_{\rm max} \simeq 1.75B^* = 8400$ G. The lower trace of Fig. 4 shows that significant microwave emission is indeed limited to a rather narrow range of magnetic fields, in good accord with theory.[17] The emission reaches a value of ~1.7 GW. The upper curve of Fig. 4, shown dashed, represents the power in the electron beam as it is derived from the results of Fig. 3. The peak conversion efficiency equals nearly 35%.

The frequency spectrum of the microwave burst has been measured (approximately) by a technique suggested by L. D. Smullin. The discharge tube described earlier was placed in a steady magnetic field $\vec{B}_0$ which varies axially in a known (linear) manner. With $\vec{B}_0$ perpendicular to the tube axis and perpendicular to the rf electric field, electron-cyclotron breakdown occurred locally within the discharge chamber. From a knowledge of $|B_0|$ at that point, the frequency of the radiation was determined from the relation $\omega = eB_0/m$. The measured value of 3 GHz agreed with an indirect determination made on a "cold" magnetron. Here, a low-level microwave signal of variable frequency was injected into the diode structure. A strong absorption resonance at the design frequency of 3.0 GHz was noted. Its band width equaled 80 MHz.

In conclusion, we have described the operation of an efficient, relativistic-electron-beam magnetron employing a field-emission cathode capable of supplying currents with densities (prior to cutoff) as high as ~1 kA/cm^2. We wish to point out that crossed-beam, field-emission systems may well be amenable to long-pulse operation, typically of the order of 1 μsec. This comes about because of the magnetic field oriented parallel to the electrode surfaces. The strong field inhibits[7,8] motion of cathode and anode plasmas which, if left to themselves, eventually lead to diode closure, that is, to the electrical shorting of the system. Most devices described in Refs. 1–7 do not have this built-in feature, and long-pulse operation may not be possible.

*This work was supported in part by the U. S. Energy Research and Development Administration and in part by the National Science Foundation.

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[16]L. Gould, "Handbook on Breakdown of Air in Waveguide Systems," Microwave Associates Report, April 1956 (unpublished); P. Felsenthal and J. M. Proud, Rome Air Development Center Report No. RADO-TR-65-142, 1965 (unpublished); A. D. McDonald, *Microwave Breakdown in Gases* (Wiley, New York, 1966).
[17]E. Ott and R. V. Lovelace, Appl. Phys. Lett. 27, 378 (1975). We note that these calculations are for a planar magnetron and therefore are applicable only approximately to our cylindrical device.

COMMENTS

Relativistic Particle Dynamics for an N-Body Interacting System

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Claims in a recent Comment by Liou to find new forms for the three-body interactions to order $1/c^2$ in an N-body relativistic interacting system are shown to arise from a misunderstanding. The proposed forms are encompassed by the solution to this problem obtained previously by the present authors. Several other clarifications are also made.

In a recent Comment in this journal[1] the discovery of "new particular solutions" to order $1/c^2$ for the three-body interactions in an N-body relativistic system is claimed; "new" has reference relative to the results previously reported in earlier publications by the present authors.[2,3] Regretfully, we must dispute this claim and in this Comment attempt to clarify the proper relation between the two sets of results. It appears to us that a misunderstanding is the principal reason for the disputed claim, this misunderstanding arising perhaps from the way in which the term "particular solution" is used in Ref. 1.

References 1, 2, and 3 are concerned with the solution of commutation relations which, in this particular context, is analogous to the problem of solving a system of linear inhomogeneous partial differential equations. It is well known that (a) the general solution of such a system is the sum of *any particular solution* and the general solution of the associated set of homogeneous equations (the complementary function); (b) the difference between two particular solutions is a specific complementary function; (c) conversely, the sum of any particular solution and a specific complementary function is another particular solution. Hence if one knows *a* particular solution and the complementary function there is no more to be determined beyond the satisfaction of boundary conditions.

If we examine the question of determining one quantity of interest, $V^{(2)}$ in the terminology of Ref. 1, we find that it must satisfy[4] Eqs. (I.6a) and (I.6b) where in the latter the first two terms on the right-hand side are dropped because of the assumption that $V^{(0)}$ and $\vec{W}^{(2)}$ are zero.[5] A set of solutions of these equations are presented in Eq. (I.10). Each member of the set is a particular solution.[5] The difference between any two is a solution of (I.6a) and (I.6b) with the right-hand side of the latter now zero. The general solution of the last set of these equations is any rotationally invariant function of internal variables only; this is indicated obliquely in the text following Eq. (I.10).

If one examines Ref. 3 one finds in its Eq. (III.31) one of the members of the set given in Eq. (I.10), and indeed this is remarked in Ref. 1.