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Strong Submillimeter Radiation from Intense Relativistic Electron Beams

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Abstract—**Radiation from an intense relativistic electron beam at submillimeter wavelengths has been measured with bandpass and high-pass filters. Radiated power ~100 kW has been measured in the passband 390–540 μm. The generation of this radiation depends on giving the electrons a large energy component transverse to the magnetic field. Coherent wave generation mechanisms which may account for the observed radiation are discussed.**

I. INTRODUCTION

DURING the early 1960's rapid advances in high-voltage and pulsed-power technologies led to the development of high-current relativistic electron accelerators [1]–[4]. These accelerators are now capable of generating beam power levels $> 10^{13}$ W for pulse times of 10–100 ns. The unique capabilities of these systems has stimulated intense interest in such diverse areas as material response [5], plasma heating [6],[7], high-energy short-pulse lasers [8], collective ion acceleration [9], and the generation of high-power microwave and submillimeter wave pulses. The present paper is concerned with this latter topic.

A. *Intense Relativistic Electron Beam Technology*

These electron accelerators typically incorporate four major components: an energy storage circuit, a pulse forming network, a low-inductance switch, and a cold-cathode diode. The accelerator employed in the present microwave studies is pictured in Fig. 1. Initially, energy is stored in a Marx generator, a circuit in which the capacitors are charged in parallel but discharged in series. The Marx generator is switched to pulse charge a pulse forming network which in this case takes the form of a coaxial water Blumlein [a folded transmission line with deionized water as the dielectric medium ($\epsilon = 80$)]. The Blumlein is connected in series with a tapered coaxial transformer which increases the voltage at the diode load.

An overvolted water switch terminates the inner coaxial conductor within the Blumlein. When the Blumlein is charged to the desired voltage, the switch closes and a square voltage pulse of 60-ns duration traverses the transformer and is finally applied to the cold-cathode diode [10],[11] which terminates the line. The diode then responds by accelerating an intense electron beam to relativistic energies. This beam propagates along magnetic field lines in an evacuated drift tube where the beam-wave interactions of interest take place.

B. *Microwave Emission from Intense Beams*

Powerful microwave emission from this type of beam was first reported by Nation [12] who loaded the drift tube with a periodic structure. Several research groups [13]–[15] have followed up on this work with periodically loaded drift tubes and a 10-percent efficiency for converting beam energy into microwave energy has recently been reported [15].

Other experimenters have not loaded the drift tube

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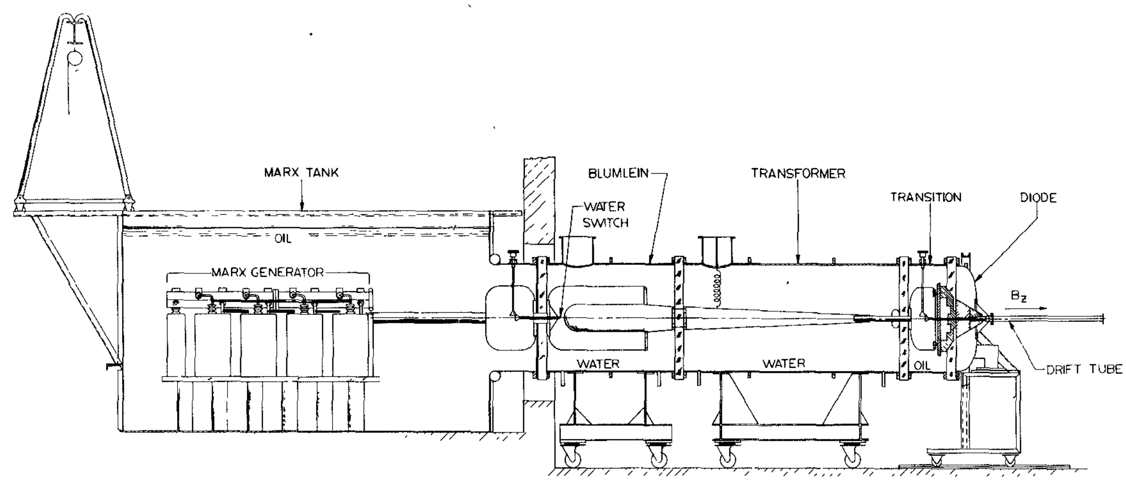

Fig. 1. Accelerator for producing a pulsed intense relativistic electron beam.

with slow wave structures but instead have relied on processes involving beam cyclotron instabilities. These instabilities require large electron energies transverse to the applied axial magnetic field (B_z), and various arrangements have been used to produce this transverse energy, viz., a periodic ripple in B_z [16]–[18], a rising B_z at the cathode [19], passage of the electron beam through a thick scattering foil [20], and having the beam encounter a very sharp nonadiabatic decrease in B_z [21].

The coherent cyclotron radiation produced in these experiments is driven only by the transverse energy of the beam which is a fraction of the total beam energy, and so efficiency of converting total beam energy to microwave energy is inherently lower than in the slow wave experiments. However, relativistic electrons can emit strongly at the harmonics of the electron cyclotron frequency as well as at the fundamental so that a coherent radiator may have an extensive frequency spectrum [22].

The results of Friedman and Herndon [16] gave the first experimental indication of the extensive nature of the radiation spectrum from an intense electron beam with large transverse energy. Their measurements of simultaneous emission in various wavebands extending from 7 to 90 GHz are tabulated in Table I. The experimental conditions for Table I were $B_z = 5.5$ kG, diode voltage $V_D = 625$ kV, and diode current $I_D = 15$ kA. These beam parameters are a modest example of the beam powers available from existing accelerators, and radiated power levels as large as 1 GW in X band have now been measured [18] using a more powerful beam ($V_D = 3.3$ MV, $I_D = 80$ kA).

II. EXPERIMENTAL STUDY OF RADIATION AT SUBMILLIMETER WAVELENGTHS

The first attempt to extend the microwave measurements into the submillimeter regime was made by Friedman and Herndon [23] using their 625-kV accelerator. We were unable to reproduce their result of 1 kW of transmitted radiation through a high-pass filter in the form of a metal mesh with a 25-μm period and a 1-cm^2 area, and believe that there may have been leakage of

TABLE I

Frequency band (gigahertz)	Radiated power (megawatts)
X band (7–13)	$\gtrsim 10$
K_u band (14–22)	$\gtrsim 20$
K_a band (22–40)	$\gtrsim 8$
W band (60–90)	$\gtrsim 2$

radiation around the mesh holder in the original experiment. On the other hand with a larger accelerator voltage ~ 2 MV, we were able to measure significant levels of transmitted power through coarser filters with mesh periods in the range of hundreds of microns. Furthermore, by using bandpass filters in addition to high-pass mesh filters, some information on the spectral distribution of the submillimeter radiation has been obtained.

A. Apparatus

The experimental arrangement which was used to search for the submillimeter radiation is shown in Fig. 2. A thin annular electron beam (OD = 3.6 cm, thickness = 2 mm) was guided down an evacuated drift tube by an externally applied magnetic field. The magnetic field was rippled by a periodic structure of iron and aluminum rings inserted inside the solenoid (ripple period $l_r = 3.8$ cm), and this rippling enhanced the electron energy transverse to the axis. The conical antenna and the microwave absorber minimized reflection of the powerful radiation at centimeter and millimeter wavelengths.

The submillimeter radiation was measured with a pyroelectric detector having a sensitivity of 2×10^{-4} V/W

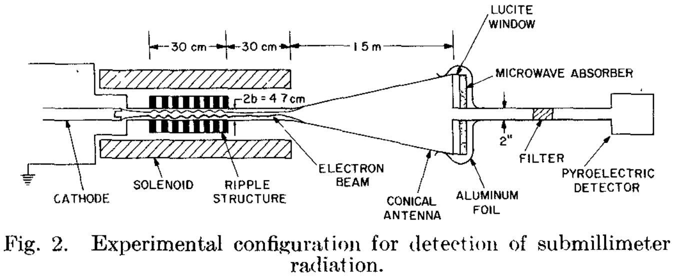

Fig. 2. Experimental configuration for detection of submillimeter radiation.

TABLE II

Bandpass filters (micrometers)	High-pass filters (micrometers)
390–540	
200–300	287
50–90	50

and a risetime of 5 ns. The filters placed in front of the pyroelectric detector were of two types. First, three bandpass filters were used which were similar to those reported on by Varma and Moller [24]; these filters have a sharply defined passband. Secondly, two high-pass filters were used which consisted simply of metal meshes. The half-power points for all these filters are listed in Table II.

Care was exercised to minimize any leakage of radiation when mounting these filters in the metal pipe leading to the pyroelectric detector. A filter holder was designed to make tight knife edge contacts both with the filter body and with the pipe. A noise level was established by recording the pyroelectric signal with a solid piece of metal mounted in this filter holder.

With these filters in place, one at a time, the axial magnetic field B_z and the diode voltage were scanned and the signal on the pyroelectric detector was monitored. Magnetic field was varied over the range 4–16 kG. Diode voltage ranged from 0.7 to 2.6 MV. Diode current changed roughly in step with the voltage with diode impedance being 60 Ω.

B. Experimental Results

A detectable signal was observed through the 390–540-μm bandpass filter for $V_D > 1.5$ MV. This signal increased with V_D, and at $V_D = 2.6$ MV the power transmitted through the filter with its 1/2-in diameter was 220 W. This implies power levels of ~4 kW in the 2-in-diameter pipe leading to the pyroelectric detector, and ~100-kW total radiated in-band power in the 12-in-diameter conical antenna. The time resolved signal on the pyroelectric detector is shown in Fig. 3 where it may be compared with the diode voltage and current pulse shapes.

It was only near the maximum value of $V_D = 2.6$ that some signal could also be seen through the 200–300-μm bandpass filter and the 287-μm high-pass filter. No significant signal level was observed through the two smallest wavelength filters. Also, no signal was observed for any combination of filter B_z and V_D when the ripple structure was removed.

The most extensive data were obtained with the 390–540-μm filter and are presented in Fig. 4. Here detected power is plotted as a function of axial magnetic field B_z, with diode voltage V_D as a parameter. Note that the value of B_z where peak emission occurs rises with the diode voltage.

Finally, in a separate experiment, the longer wavelength microwave radiation was measured using previously established techniques [16]. The measurement was made

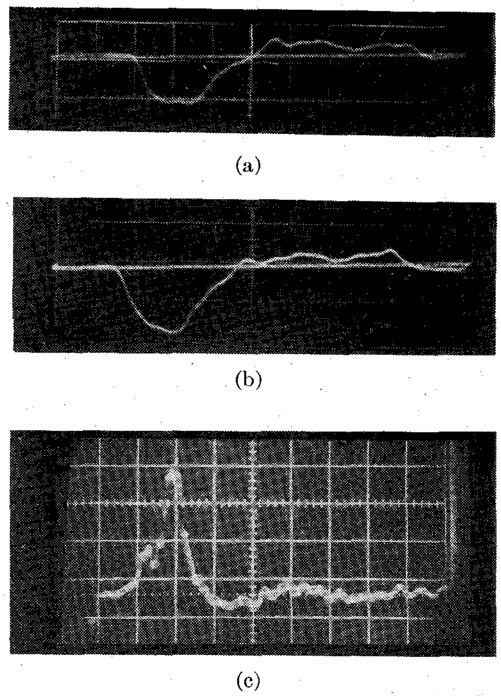

Fig. 3. Time resolved signal pulses. (a) Diode voltage. (Peak voltage = 2.6 MV; 40 ns/division.) (b) Diode current. (Peak current = 43 kA; 40 ns/division.) (c) Radiation passing through 390–540-μm filter as recorded on pyroelectric detector. (Power averaged over pulse time = 220 W; 50 ns/division.)

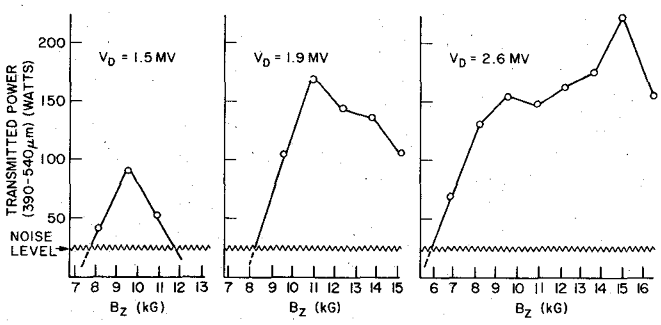

Fig. 4. Submillimeter power versus B_z (bandpass 390–540 μm; filter aperture diameter = 0.5 in; each experimental point is an average over several shots of the accelerator.)

for the same experimental conditions that produced the strong submillimeter radiation, viz., $V_D = 2.6$ MV and $l_r = 3.8$ cm. In Fig. 5, the radiated power in the various wavebands extending from 4 to 40 GHz are plotted versus B_z. This specific knowledge of the longer wavelength emission should be useful in attempting to understand the source of the submillimeter signal.

III. DISCUSSION

A. Coherent versus Incoherent Radiation

The preceding measurements implied that with a 2.6-MV accelerating voltage absolute power in the 390–540-μm band was on the order of 10^5 W. One may estimate the expected level of incoherent radiation by taking the product of the single-electron cyclotron radiation power in

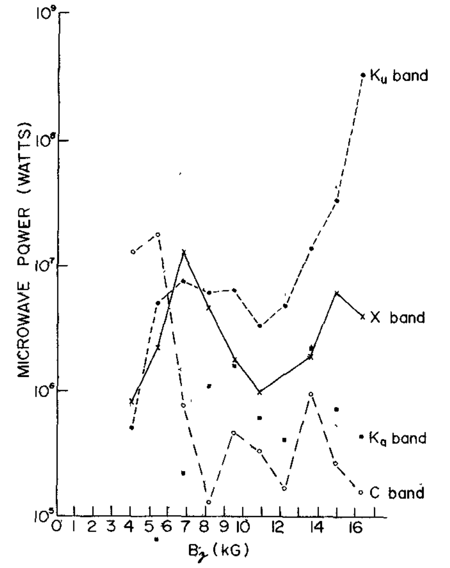

Fig. 5. Microwave power versus B_z. (C band covers 4–7 GHz: Other bands are designated in Table I. Note that as B_z increases, first the C-band emission peaks, then the X-band emission, and then the K_u-band emission.)

this waveband and the number of electrons in the beam; the result of such a calculation is an incoherent power level of ~ 800 W. Hence, the present submillimeter measurements apparently cannot be explained by a single particle incoherent process, and one must invoke collective mechanisms.

B. Dependence on Energy Transverse to B_z

An outstanding feature of the data in Fig. 4 is that the value of B_z where peak emission occurs rises with diode voltage. This rise takes place in such a way that at the peak of each curve the relativistic electron cyclotron frequency ω_{ce} remains constant, viz., at each of the three peaks in Fig. 5.

$$\omega_{ce} = eB_z/\gamma m_0 \approx 2\pi \times 9 \text{ GHz} \tag{1}$$

where γm_0 is the relativistic electron mass. As V_D rises, the increase in B_z at peak emission is compensated for by the rise in the relativistic factor γ.

At $\omega_{ce}/2\pi \approx 9$ GHz, there is a resonant interaction between the cyclotron motion of the electrons and the magnetic field ripple, i.e.,

$$\omega_{ce}/2\pi \approx V_z/l_r \tag{2}$$

where V_z is the axial component of electron velocity. Such a resonant interaction results in a conversion of streaming electron energy $W_{\|}$ into energy transverse to the magnetic field $W_\perp$ [27]. Previous measurements [19] have shown that this conversion is so strong that $\langle V_\perp^2 \rangle \approx \langle V_{\|}^2 \rangle$. The existence of the submillimeter radiation is evidently tied to the existence of a large $W_\perp$.

C. Some Possible Models for Coherent Radiation

Although the existence of a large $W_\perp$ has been established, the details of the electron distribution function remain a mystery. Two extreme possibilities are shown in Fig. 6. In Fig. 6(a), the transverse electron motion is well ordered. All electrons have virtually the same value of transverse momentum $P_\perp$ and the width of the distribution (thermal spread) is small. In Fig. 6(b), the transverse energy is completely thermalized. The particular mechanism which can give rise to the submillimeter emission will depend on whether Fig. 6(a) or (b) is closer to the true situation.

1) *Coherent Radiation at the Cyclotron Harmonics:* If Fig. 6(a) is close to the truth, then instabilities can arise which are driven by the free energy due to population inversion ($\partial f/\partial p_\perp > 0$). In the beam frame, such instabilities excite waves at harmonics of the cyclotron frequency, viz., $\omega = n\omega_{ce}$. In the laboratory frame, the frequency will be determined by the intersection of the cyclotron harmonic beam modes with waveguide modes of the metal drift tube. The process is illustrated in Fig. 7.

Growth rates and saturation power levels have been calculated for both the interaction involving the fundamental cyclotron beam mode [28] and for the first few harmonics [29], and have been found to be large. A good part of the radiation at the longer microwave wavelengths has been attributed to this process [13].

However, there is some question as to whether this coherent cyclotron harmonic radiation could produce emission at submillimeter wavelengths with required harmonic number of $n \gtrsim 30$. Bekefi *et al.* [22] have pointed out that the largest harmonic number for which wave growth is possible will be limited by thermal Doppler broadening of the radiation as given by

$$n < (\Delta\epsilon/\epsilon)^{-1} \tag{3}$$

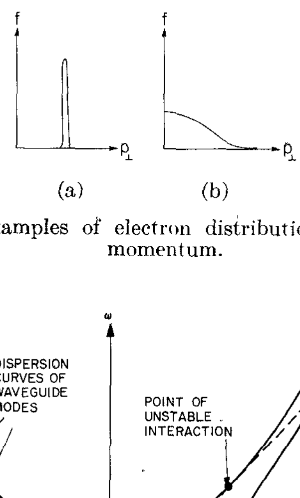

Fig. 6. Two examples of electron distribution in perpendicular momentum.

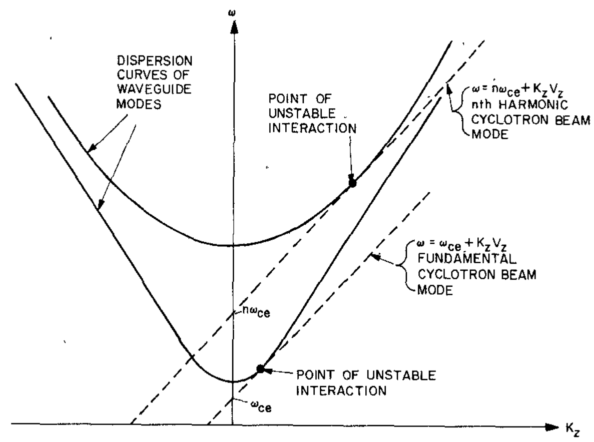

Fig. 7. Dispersion curves showing points of unstable interaction between cyclotron beam modes and waveguide modes.

where $\Delta\epsilon/\epsilon$ is the fractional spread in the distribution of electron energies. Even if the distribution function in the present experiment is relatively sharply peaked as Fig. 6(a), it is doubtful whether the peaking could be so sharp as to make $\Delta\epsilon/\epsilon$ as large as 30.

2) *Temperature Anisotropy:* If the situation in Fig. 6(b) holds, then there is no population inversion and coherent cyclotron harmonic radiation will not be excited. However, a different class of instabilities can arise which are driven by the free energy in the temperature anisotropy ($T_\perp > T_{||}$). Such instabilities excite waves which propagate parallel to the magnetic field. The question of whether this mechanism can account for the submillimeter radiation is currently under investigation [30].

3) *Stimulated Parametric Scattering:* Still another mechanism which could lead to submillimeter radiation has been suggested [23]. Microwaves generated by either of the two processes just described could interact with a second group of beam electrons to produce both a plasma oscillation in the electron beam and a scattered electromagnetic wave [31]. The scattered wave could have its frequency enhanced over the incident frequency due to Doppler shifting by a factor of several times $(1 - V_{||}^2/c^2)^{-1}$. If this second group of electrons participating in the stimulated scattering has not had an appreciable fraction of its energy converted to $W_\perp$, then $V_{||}/c$ for this group could approach unity and the enhancement factor could be large.

For example, it may be seen from Fig. 5 that strong microwave emission occurs in K_u band ($f \approx 20$ GHz). Upconversion to the submillimeter regime would require $(1 - V_{||}/c^2)^{-1} \gtrsim 10$; this requirement is attainable in the present experiment. An analysis of scattering cross sections is in progress [32].

IV. CONCLUSIONS AND RECOMMENDATIONS

Submillimeter radiation from intense relativistic electron beams has been observed under conditions where the electrons are given large energy transverse to an applied magnetic field; the power level of the radiation ($\sim 10^5$ W) implies that a coherent mechanism is involved. Several possible mechanisms have been suggested and work is in progress to calculate growth rates and saturation power levels [29],[30],[32]. Further experimental work is planned both at the Naval Research Laboratory and elsewhere [33] to obtain data that will better distinguish between the possible mechanisms and that will more precisely define both the spectrum and the total radiated power in the submillimeter regime.

Finally, it should be stressed that the present result should not be taken to represent the ultimate submillimeter power levels which might be produced with an intense relativistic electron beam. An analysis of power limiting factors, such as RF breakdown at the generator walls, predicts that these factors will not be important at submillimeter wavelengths until power levels of ~ 10 MW are reached. Further studies should include using a much larger value of B_z to obtain a lower cyclotron harmonic number in the submillimeter regime, and improving the conversion of $W_{||}$ into $W_\perp$.

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Josephson Junctions as Heterodyne Detectors

Y. TAUR, J. H. CLAASSEN, AND P. L. RICHARDS

Abstract—**Heterodyne detection with a point-contact Josephson junction has been investigated both experimentally and theoretically. The measured performance of the device at 36 GHz is in good agreement with the theory. By operating vanadium point contacts at 1.4 K, we have achieved a single-sideband (SSB) mixer noise temperature of 54 K with a conversion gain of 1.35 and a signal bandwidth on the order of 1 GHz. From our results we can extrapolate a potentially impressive performance for these devices at submillimeter wavelengths.**

I. INTRODUCTION

JOSEPHSON junctions have long been considered promising as sensitive detectors of microwave and far-infrared radiation [1]. The principle of detection with Josephson junctions relies on the fact that the relation between the current and voltage for an ideal Josephson element [2] is highly nonlinear:

$$I(t) = I_c \sin\left[\frac{2e}{\hbar}\int_0^t V(t')\,dt'\right]. \tag{1}$$

An element satisfying this equation can be thought of as a lossless nonlinear inductor, which is generally useful for high-frequency device applications.

We have studied both experimentally and theoretically the use of point-contact Josephson junctions as heterodyne detectors with an externally applied local oscillator (LO). In this mode of operation a small signal is mixed with a relatively large LO signal in the junction to produce an output at a difference frequency much lower than the signal frequency. The experiments were performed with superconducting point contacts since they have a higher impedance and can be efficiently coupled to conventional waveguide modes more easily than other types of Josephson structures.

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II. THEORY AND SIMULATOR CALCULATIONS

It has been demonstrated that most of the properties of a point-contact Josephson junction can be understood in terms of the resistively shunted junction (RSJ) model [3], [4]. The model assumes that a real junction is equivalent to an ideal Josephson element defined by (1) in parallel with a constant resistor R. Although the product RI_c varies over a considerable range among different junctions, it has an upper limit given by the energy gap of the superconducting material from which the junction is made [5]. This product gives an intrinsic frequency $\omega_c = (2e/\hbar)RI_c$, which scales the important features of the RF response of the junction.

When a sufficiently large amplitude LO is applied to a Josephson junction, the zero-voltage current of the junction is suppressed and current steps appear on the static I–V curve of the junction at $V_{dc} = n\hbar\omega_{LO}/2e$, as shown in Fig. 1(a). The variation of the step heights with LO amplitude depends on the normalized frequency $\Omega = \omega_{LO}/\omega_c$. Fig. 1(b) and (c) shows the nature of such variations for the zeroth and first steps in the case $\Omega = 0.16$. If a small signal whose frequency ω_s is close to ω_{LO} is superimposed on the LO, the result is, in effect, an amplitude modulation of the LO at the intermediate frequency (IF) $|\omega_{IF}| = |\omega_s - \omega_{LO}| \ll \omega_{LO}$. We can therefore predict the IF output from a series of static I–V curves for various LO levels in the vicinity of that chosen to drive the junc-