EXPERIMENTAL STUDY OF THE MICROWAVE RADIATION FROM A RELATIVISTIC ELECTRON BEAM IN A STRONG MAGNETIC FIELD

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The results are given of an experimental study of the microwave radiation from a powerful relativistic electron beam in a longitudinal magnetic field. The design and the characteristics of the bandpass microwave filters used in the analysis of the radiation spectra are described. Radiation spectra have been obtained for different values of magnetic field. It is shown that the observed radiation is in fact cyclotron radiation from the beam. The reasons for the high radiation intensity are discussed.

It has been reported [1-3] that powerful microwave radiation is produced when a beam passes through a vacuum in a magnetic field. In this paper we study the spectrum of this radiation. The experiments were carried out on the "Inar" apparatus.

A 1-MeV electron beam with a current of 10 kA and a diameter of 2.5 cm was injected into the drift chamber along a strong magnetic field H = 3-12 kOe. The length of the chamber was 230 cm, the diameter 11 cm, and the residual pressure 10^{-6} mm Hg. The diode current reached 10 kA but as a result of electrostatic suppression in the space charge the current in the drift chamber did not exceed 3 kA (in our geometry this value corresponds to the critical current). In contrast to [1, 2], the beam was injected into a glass chamber placed in a homogeneous magnetic field rather than into a specially shaped waveguide.

The microwave radiation spectra were analyzed by means of bandpass filters. Figure 1 is a diagram of the experimental apparatus, of one microwave channel, and of the recording unit. The radiation received by the horn antenna (A) is fed to the filter input along an extended waveguide through the directional coupler (DC) which acts as a stepwise attenuator. The filter consists of two cutoff waveguides (CW-1 and CW-2), two matched loads (ML), and a double T-junction (DT). The first cutoff waveguide passes frequencies above $f_1 = c/2a_1$, where a_1 is the width of the wider wall of the waveguide. The part of the spectrum which is passed through this waveguide goes to the double T-piece. Here the signal is divided, half of the power being absorbed by ML-1 and the other half being fed to CW-2 in which the width of the wider wall a_2 is smaller than a_1. Frequencies $f > f_2 = c/a_2$ are absorbed by ML-2 and the frequencies $f_1 < f < f_2$ reflected from CW-2 pass to the fourth arm of the double T-piece and are fed through the calibrated attenuator (AT) to the detector (D). The dimensions of the cutoff waveguides were chosen so that the half-power bandwidth of the filter was ~2-4 GHz. The frequency characteristics of one of the filters is shown in Fig. 2. The attenuation inside the passband is 10 dB and there is a 30-dB suppression of frequencies outside the band. Four such filters were used in the experiment, with the following frequency ranges: 8-12, 14.5-17.5; 21-23, and 32.5-34.5 GHz.

The envelope of the microwave signal is fed to the mixer (Mx), which also receives the signal from the other channel after it has first passed through the delay line (DL) ($\tau \sim 100$ nsec). After the mixer, the signals are amplified and fed to the input of an oscilloscope. In this way it was possible to observe on the screen of the DÉSO-1 double-beam oscilloscope the radiation received in four microwave channels simultaneously.

After each series of experiments the attenuations in all the channels were measured and the sensitivities of the detectors and recording circuits were calibrated. The filters, the delay lines, the mixers, the amplifiers, and the oscilloscope were placed in a second room at a sufficient distance from the beam appa-

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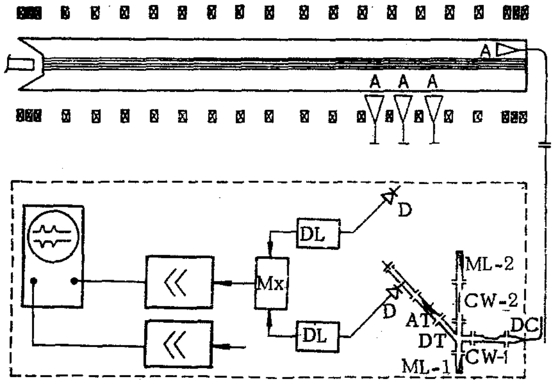

Fig. 1

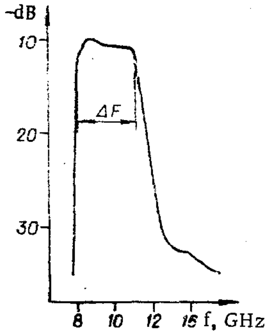

Fig. 2

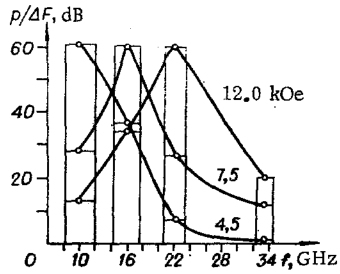

Fig. 3

ratus to eliminate electromagnetic noise and the effect of x-ray radiation on the semiconductor microwave detectors.

Strong radiation was recorded over the entire frequency range of 8-35 GHz. It can be seen from Fig. 3, that for a fixed value of the magnetic field the radiation spectrum has a clearly defined maximum. As the magnetic field is increased this maximum shifts towards higher frequencies, and there is a linear relationship between the frequency f_{max} and the value of the field (within the limits of experimental error).

The cyclotron frequency of a relativistic electron in a laboratory system is

$$f_{He} = (1/2\pi)(eH/mc)(1/\gamma)[1/(1 - (v_{\parallel}/c)\cos\theta)],$$

where $\gamma = (1 - v^2/c^2)^{-1/2}$ is the relativistic factor, v is the total velocity, $v_{\parallel}$ is the component of this velocity along the magnetic field, and θ is the angle between the direction of motion and the radiation direction. In the experiments the radiation was recorded perpendicular to the beam and along its direction so that $\cos\theta = 0$ and 1. Knowing the value of the magnetic field, $f_{max}(\theta = \pi/2)$ and $f_{max}(\theta = 0)$, we can find γ and $v_{\parallel}$. When $H = 5.5$ kOe, $f_{max}(\theta = \pi/2) = 12$ GHz and $f_{max}(\theta = 0) = 33.5$, and this gives $\gamma = 1.4$ and $v_{\parallel} = 0.7c$. These values of γ and $v_{\parallel}$ are in good agreement with those found by other methods and quoted in [3]. We can therefore conclude that the maximum in the radiation spectrum corresponds to the fundamental of the cyclotron frequency.

It is to be noted that the intensity of the radiation received at $\theta = 0°$ is about an order of magnitude smaller than for $\theta = 90°$. The power received in the direction perpendicular to the beam was estimated with due allowance for the polar diagram of the horn antenna. The results show that at the frequency f_{max} the radiation in the given direction from unit volume of the beam per unit solid angle is $\sim 10^2$ W, while the total intensity of the radiation from individual electrons in 1 cm^2 volume is $\sim 10^{-7}$ W according to the Schott equation [4]. In our experiments the beam was propagating practically in free space (large vacuum chamber, homogeneous magnetic field) and so the powerful radiation cannot be explained by the presence of a high-Q resonator in the system. Thus, the beam itself must be the cause of this very intensive radiation.

If the beam contains density irregularities with a linear size smaller than the electron gyro radius r_{He}, it is possible to get coherent radiation with an intensity which is some $r^3_{He} n_b (\Delta n_b/n_b)^2$ times greater than the level of the incoherent radiation.

Small-scale density irregularities could be caused either by the way the beam is produced (microexplosive cathode emission) or by beam instability (if a supercritical beam is injected, for example). However, the wide scatter in velocities $\Delta v_{\perp} \sim v$ in the beam would mean that density irregularities would be smeared out after a few cyclotron revolutions. It thus appears that the irregularities must be self-sustaining, i.e., there must be an irregularity which produces a modulation in the density.

In order to study effects caused by the injection of a supercritical current we carried out measurements with $I < I_{cr}$. Since the critical current in a vacuum [5] depends only weakly on the beam radius, it is always possible to get a current below the critical value by reducing the total current. The current was limited in radius by means of a graphite diaphragm. When this was done the frequency f_{max} ($\theta = \pi/2$) decreases by a factor of 1.5; this corresponds to an increase in γ to a value of 2. The radiation intensity remained almost constant. Thus, the high radiation intensity is not related to a supercritical current. It seems that in a magnetic field there may be an instability in the beam itself which develops at the cyclotron frequencies as a result of the anisotropy of the distribution function in the beam system. However, this suggestion requires further study.

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