Excitation of an Electron-Cyclotron Wave by a Modulated Helical Electron Beam

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The interaction between a helical electron beam with modulated transverse velocities and plasma is investigated. It is shown that the beam excites an electron cyclotron wave at the modulation frequency and that the intensity of this wave is greater by a factor of 1000 as compared with the case of an unmodulated beam. It is also shown that the main source of oscillation energy is the energy of the electron beam.

THERE has recently been considerable activity in researches concerned with the microwave heating of plasma. A particularly interesting area is the investigation of the interaction of microwave fields with plasma in the region of the electron gyroresonance. The point is that, in this frequency range, it is possible to excite electron-cyclotron waves of large amplitude, whose damping leads to the heating of plasma electrons.[1] Moreover, if two electron-cyclotron waves are excited in the plasma, the nonlinear interaction between them results in a substantial proportion of their energy being transferred to ion oscillations whose damping leads to the heating of plasma ions.

The main problem, therefore, in realizing this method of heating in practice is the excitation of forced electron-cyclotron waves of large amplitude.

In this paper we report an experimental study of the excitation of electron-cyclotron waves in a system consisting of an electron beam and plasma. The waves were excited by an electron beam with modulated transverse velocities. The choice of this method of modulation was dictated by the fact that perturbations of the macroscopic particle velocity in the cyclotron wave are directed across the external magnetic field. Therefore, these waves are most conveniently excited by an electron beam with a considerable transverse velocity component modulated at the frequency of the cyclotron plasma oscillations.

The experimental study of the excitation of electron-cyclotron waves by a modulated electron beam was carried out with the apparatus shown schematically in Fig. 1. The discharge chamber was a tube, 1 m long with a diameter of 6 cm, which was placed along the axis of a solenoid producing a quasistatic magnetic field whose magnitude could reach up to 4 kOe at the center of the system. Figure 1b shows the magnetic field distribution along the axis of the system. The particular feature of the magnetic field configuration was that an iron screen was used in the region of the electron beam entrance into the discharge chamber to produce a magnetic field gradient, dH/dz, which was chosen so that the condition for the adiabatic motion of the beam particles was definitely not satisfied,[2] i.e.,

$$(L/H)\,|dH/dz| \gtrsim 1, \qquad (1)$$

where L is the displacement of a particle during one period of the cyclotron rotation. The electron beam was thus given a substantial transverse velocity component.

The beam of electrons with energies 10–20 keV and current up to 6 A was shaped by the three-electrode gun described in[3]. Most of the experiments were performed at a current of 3 A. The pulse length was 200 μsec.

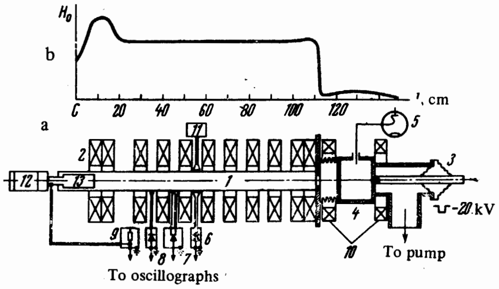


FIG. 1. Schematic illustration of the apparatus. a) 1–Discharge chamber, 2–solenoid, 3–electron gun, 4–cavity, 5–magnetron, 6–detector of probing microwave signal, 7–phase detector, 8–resonance wavemeter, 9–beam current load, 10–focusing field coils, 11–3-centimeter generator, 12–pulsed leak, 13–Faraday cylinder. b) Magnetic field distribution along the axis of the system.

A cylindrical cavity operated in the TE_{11} mode was used to modulate the electron beam. For this type of oscillation the electric vector is perpendicular to the cavity axis. The cavity was supplied by a magnetron generator at a frequency f = 3.75 GHz. The high-frequency power at the generator output was of the order of 100 W and the pulse length was 500 μsec.

The ultimate vacuum in the discharge chamber was of the order of 2×10^{-6} mm Hg and the experiments were performed with a pulsed gas leak at a pressure of the order of 10^{-4} mm Hg.

During the experiments on the interaction of the modulated electron beam and plasma, the main attention was paid to the study of microwave radiation which was detected by an external antenna which recorded the magnetic component of the electromagnetic wave near the wall. The frequency spectrum of this radiation was investigated with a resonance wavemeter in the range 2.4–7.5 GHz and is shown in Fig. 2, from which it is clear that oscillations were produced in the plasma at the modulation frequency of the electron beam. The radiation pulse appears at the time of formation of the beam-plasma discharge and takes the form of individual peaks with a repetition frequency of the order of 20–50 kHz. The power radiated at the modulation frequency is higher by three orders of magnitude as compared with the microwave power in the absence of electron-beam modulation.

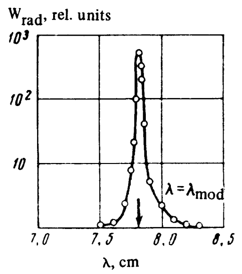


FIG. 2

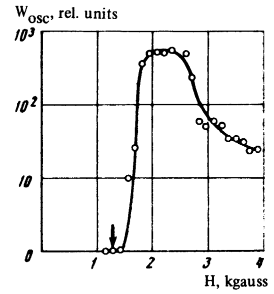


FIG. 3

FIG. 2. Frequency spectrum of radiation from the plasma.

FIG. 3. Intensity of oscillations in plasma as a function of the external magnetic field. The arrow shows the external magnetic field at which the electron gyrofrequency is equal to the electron beam modulation frequency.

Studies of the dependence of the amplitude of these microwave frequency oscillations on the magnitude of the external magnetic field H enabled us to establish that the oscillations appeared only in the magnetic-field region where $\omega_{mod} < \omega_{He}$. For $\omega_{mod} > \omega_{He}$ the amplitude of the microwave oscillations at the modulation frequency was zero (Fig. 3).

It is well known that near the electron-cyclotron frequency there is the possibility of a slow electromagnetic wave for which the dispersion relation for longitudinal propagation without taking damping into account is given by

$$\frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_0^2}{\omega(\omega - \omega_{He})}, \tag{2}$$

where k is the wave vector, ω is the oscillation frequency, ω_0 is the plasma frequency, ω_{He} is the electron gyrofrequency, and c is the velocity of light.

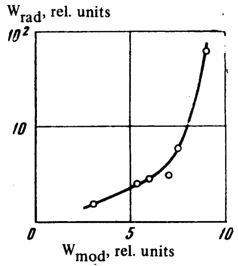
This type of oscillation is often referred to as the electron-cyclotron wave. Its particular feature is that it can propagate only for magnetic fields for which the electron gyrofrequency is greater than the wave frequency. When the wave frequency is close to the gyrofrequency the wave experiences strong cyclotron damping over a length given by[5]

$$\delta = 2\left(\frac{\sqrt{2}}{\pi}\frac{c^2 v_{Te}}{\omega\omega_0^2}\right)^{1/3}, \tag{3}$$

where v_{Te} is the thermal electron velocity, and the wave energy is then transferred to the plasma electrons.

The propagation parameters of the electromagnetic wave, such as the phase velocity, polarization, direction of rotation of the electric vector in the wave, and the type of oscillation, were investigated in a magnetic field H_0 corresponding to the maximum oscillation amplitude. A simple phase indicator was used for this purpose. Signals from two probes lying near the chamber wall were fed through an attenuator and ferrite isolators into a tee-junction. The resultant signal was then fed into a frequency filter (resonant wavemeter) and displayed on a CRO screen. A line of variable length was included in the circuit of one of the probes and was used to compensate the phase shift between the signals which was produced when one of the probes was displaced.

FIG. 4. Radiation intensity as a function of the electron beam modulation intensity.



To determine the longitudinal wave number k_z and the type of oscillation, we determined the phase of the wave both along the direction of the magnetic field H_0 and as a function of the angle φ around the plasma chamber. The polarization of the wave was determined from the relation between the components $\tilde{H}_\varphi$ and $\tilde{H}_r$ of the microwave field.

The wave propagation parameters obtained from these measurements are as follows: $k_z = 1.2$, the type of oscillation corresponds to the mode with m = 1, the wave polarization corresponds to the electron-cyclotron wave polarization for which the rotation of the electric vector of the wave is the same as the direction of rotation of a negative charge in the magnetic field.

The above measurements show that the electron-cyclotron waves are, in fact, excited under our experimental conditions.

In subsequent measurements, we determined the amplification of the beam-plasma system, which we defined as the ratio of the intensity of the high-frequency oscillations in the plasma to the intensity of the modulating signal with other discharge parameters held constant. Figure 4 shows the oscillation intensity as a function of the modulation intensity. It is clear that when the modulation intensity is increased by a factor of 10 the oscillation intensity increases by roughly two orders of magnitude.

Our results thus lead to the following conclusions: a) when the helical electron beam with transverse velocity modulation is injected into plasma, this results in efficient excitation of electron-cyclotron waves at the modulation frequency; b) a substantial fraction of the energy carried by the electron-cyclotron oscillations is drawn from the electron-beam energy. This can be used to obtain a large oscillation amplitude at low modulation intensity.

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