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EXCITATION OF ELECTROMAGNETIC WAVES OF THE WHISTLER MODES DURING INTERACTION OF AN ELECTRON BEAM

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Results are presented of an experimental investigation of the oscillation spectrum produced by an electron beam in a plasma confined by a magnetic field. It is shown that under conditions when the plasma electron frequency ω_{0e} is greater than the electron cyclotron frequency ω_{He}, electromagnetic waves of the whistler mode type are most intensively excited, their frequencies being lower than the electron cyclotron frequency ω_{He} or its harmonics. A correlation between the intensity of these waves and that of the hard x-radiation produced by the electrons accelerated in the plasma is observed.

1. INTRODUCTION

IT was observed experimentally[1,2] that when an electron beam interacts with a plasma contained by a magnetic field, a group of heated electrons is produced, with an average energy much larger than the energy of the beam electrons. There is no doubt that this phenomenon is connected with excitation of oscillations in the plasma by the beam. Various models of the heating were proposed in a number of papers[3-5], by considering the interaction of the electrons with various types of slow waves whose phase velocity is smaller than the velocity of light. Such waves are electrostatic plasma oscillations and electromagnetic circularly-polarized waves, frequently also called electron cyclotron waves or whistler modes.

Electrostatic oscillations excited by an electron beam in the plasma were experimentally investigated in[2,5,6], and the authors connected the observed electron heating with just these oscillations. It is shown in the present paper, however, that electromagnetic waves of the whistler type are also excited in the plasma. The main difference between this experiment and the cited experiment[2,5,6] is that the longitudinal plasma dimension in our case was 5–10 times larger and the oscillations were registered (with probes) at a considerable distance from the entrance of the beam into the plasma. Under these conditions, it was observed that waves of the whistler type have a much higher intensity than electrostatic plasma oscillations. At the same time, the presence of plasma oscillations (apparently localized near the entrance of the beam in the plasma) was indirectly manifest, since it turned out that the appearance of heated electrons was observed only when the plasma frequency ω_{0e} coincided with harmonics of the cyclotron frequency ω_{He}.

A correlation was observed experimentally between the intensity of the whistler modes and the appearance of heated electrons, on the basis of which it can be assumed that in this case the electron heating is the consequence of excitation of this type of wave by the beam. If we succeed in proving that the electrons are heated by electromagnetic waves, then this will apparently explain also the mechanism of the experimentally observed heating of electrons under conditions when the energy is introduced into the plasma directly in the form of electromagnetic waves ("high-frequency heating"). For a final clarification of the heating mechanism, additional investigations are needed.

The observed excitation of electromagnetic waves by a beam of electrons may be of interest also from the point of view of explaining the mechanism of generation of electromagnetic radiation in cosmic plasma, for when the geometrical-optics conditions are satisfied these electromagnetic waves may emerge from the plasma and propagate in free space.

2. DESCRIPTION OF EXPERIMENTAL SETUP AND OF THE MEASURING APPARATUS

A schematic diagram of the experimental setup and of the employed apparatus is shown in Fig. 1. The distribution of the magnetic field over the length of the apparatus is also shown to scale in this figure.

The stainless steel vacuum chamber is 550 cm long and 30 cm in diameter. The end parts of the chamber, where the coaxial plasma injector and the electron gun are located, are separated from the central part of the chamber by diaphragms with apertures of 7 cm diameter. The evacuation by means of diffusion pumps is carried out only from the ends of the chamber. In the central part are installed azotite and four titanium

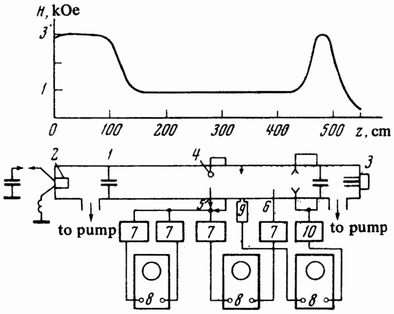

FIG. 1. Diagram of experimental setup: 1–vacuum chamber, 2–electron gun, 3–plasma injector, 4–magnetic probe, 5–main electric probe, 6–auxiliary electric probe, 7–receivers, 8–oscilloscopes, 9–photomultiplier with crystal, 10–interferometer. On the top is shown, to scale, the distribution of the magnetic field intensity.

evaporators, with the aid of which a residual gas pressure smaller than 1×10^{-8} mm Hg and a rate of hydrogen evacuation up to 5×10^3–10^4 liters per second can be obtained. The vacuum conditions prevented the entry of additional cold plasma into the interaction volume upon injection of the electron beam.

The magnetic field was produced by a system of coils fed in such a way that the intensities of the mirror field and the main field could be adjusted independently. The maximum field in the mirrors was 3 kOe. The diaphragms were located at the maxima of the magnetic field. The coaxial plasma injector made it possible to fill the central part of the trap with plasma having a density up to 10^{12} cm^{-3}, which was contained between the mirrors for ≈2 msec. The electron beam was injected after the trap was filled with plasma, and usually with a delay of 0.5–1.5 msec after the operation of the injector.

The electron gun consisted of a flat cathode (lanthanum hexaboride) of 4 cm diameter, made incandescent by thermal radiation from a tantalum heater, and a tungsten grid mounted at a distance ~1 cm from the cathode. With such a construction of the electrodes, the electrons in the beam should have in the main a longitudinal velocity component relative to the magnetic field. A high voltage (10 kV) was applied to the electron gun from a capacitor bank of capacitance such that during the time of beam injection the gun voltage remained practically constant. The beam was interrupted by short circuiting the bank with a powerful thyratron. The beam current in the high vacuum was determined both from the signal picked off a resistor connected in the circuit of the capacitor bank and of the gun, and from the recharging of a capacitor connected to the electrode of the coaxial injector. The heating of the cathode was chosen such that at a voltage of 10 kV the beam current was approximately 10 A. Under the working conditions, in the presence of a plasma in the central part of the setup, the average current determined from the signal picked off the resistance in the gun circuit was the same as in the high vacuum, but current fluctuations (“grass”) were observed.

We registered the following parameters: the electron beam current, the x-radiation from a target located near the plasma boundary, the plasma density averaged over the cross section, and the oscillations in the frequency range 400–7300 MHz.

The x-rays were registered with a collimated photomultiplier and a crystal covered with an absorber (5 mm of aluminum) to remove the x-rays with energy lower than 30–35 keV. The intensity of the x-rays from the target was high, and therefore we registered the integral radiation flux. The plasma density averaged over the cross section was measured with a radio interferometer operating at an 8 mm wavelength and having an accuracy not worse than 10° and a time resolution of 60 μsec.

The plasma oscillations were registered with the aid of three high-frequency probes. Two probes (electric and magnetic, which henceforth will be called the main probes) were located near the central section of the chamber. The receiving part of the electric probe had a coaxial construction consisting of a central tungsten conductor of 0.25 mm diameter, an unshielded part 2 mm long, and an external shield of 2.5 mm diameter, with separation by means of alundum insulators. The magnetic probe was a screened loop measuring 3 × 6 mm. These probes could be moved radially from the azotite to the center of the vacuum chamber. The third (auxiliary) probe had exactly the same construction as the electric probe, but could not be moved radially. Both electric probes were so oriented that they measured the radial component of the electric field oscillations. The magnetic probe could be rotated, in order to register the components of the high frequency field $\tilde{H}_z$ and $\tilde{H}_\varphi$.

The signals from the probes were fed through coaxial cables to superheterodyne receivers. Four receivers were used, covering continuously the frequency band from 400 to 7300 MHz. The receivers had at their inputs adjustable resonators, which attenuated the signal in the mirror-frequency band, intermediate frequency amplifiers with bandwidths 4–5 MHz, and high-speed automatic gain control, which expanded the dynamic range of the receivers by approximately 10–15 dB. Before the start of the measurements we determined the absolute sensitivity (with the aid of a standard noise generator) and the relative sensitivity of the receivers, and the sensitivity as a function of the frequency of the entire circuit, including the main probes and the cables. In the data reduction, corrections were introduced in accordance with the calibration measurements.

During the measurement of the oscillation spectrum, we varied the setting of the receiver connected to the main probe, while the receiver connected to the auxiliary probe was tuned all the time to 2350 MHz, and was used to monitor the reproducibility of the results from pulse to pulse. For the same purpose, we registered the x-rays and the plasma density in each pulse. From among the large number of oscillograms, we selected for processing those on which the control parameters coincided.

3. EXPERIMENTAL RESULTS AND A DISCUSSION

We are interested in oscillations excited in the plasma under conditions when hot electrons were observed. It was observed that the intensity of the x-rays produced by these electrons depend nonmonotonically on the plasma density, and the maximum intensity is apparently observed at the instant when the electron plasma frequency ω_{0e} is the close to the harmonics of the cyclotron frequency ω_{He}. Thus, the intensity of the x-radiation depends both on the plasma density and on the intensity of the main magnetic field. The dependence on the density can be clearly seen on the oscillograms presented in this paper. The dependence of the intensity of the x-rays on the magnetic field intensity is shown in Fig. 2. In calculating the plasma frequency, we took into account the fact that the plasma density at the center of the setup, where an electron beam of ~6 cm diameter passes, is approximately 1.5–2 times larger than the average density measured by the interferometer (the plasma diameter is 14 cm).

Many of the oscillograms were processed in such a way that the oscillation intensity was determined at the

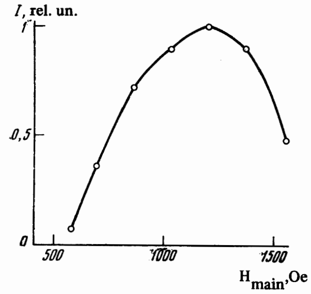

FIG. 2. Dependence of the x-ray intensity on the intensity of the main magnetic field. Average plasma density (2.5 – 3.5) X 10^{11} cm^{-3}.

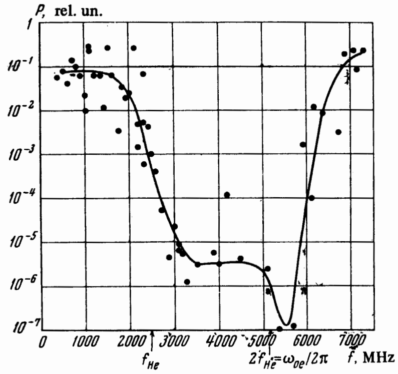

FIG. 3. Oscillation spectrum of state under the condition $\omega_{Oe} \approx 2\omega_{He}$.

instant of time corresponding to the maximum x-ray intensity, under conditions when $\omega_{0e} \approx 2\omega_{He}$. This yielded the oscillation spectrum shown in Fig. 3. A characteristic feature of this spectrum is the strong decrease of the oscillation intensity at frequencies larger than f_{He}, the low level of the oscillations in the frequency region $f \leq 2f_{He}$, and the presence of intense oscillations in the region of the third harmonic of the cyclotron frequency. At the chosen magnetic field intensity, and owing to the limited frequency band covered by the receivers, it was impossible to plot the spectrum near frequencies corresponding to the third harmonic of f_{He}. Measurements were therefore made, which showed that the amplitude of the oscillations at two frequencies ($f_2 = 3f_1$) vary synchronously when the magnetic field is varied, i.e., the oscillations at frequencies close to 7100 MHz are more likely the third harmonics of the oscillations close in frequency to 2450 MHz. A sharp decrease of the intensity of the oscillations when the cyclotron frequency changes in both directions of the reception frequency was observed in the entire range of the employed magnetic field, from 500 to 1500 Oe.

To determine the nature of the observed oscillations, simultaneously calibrated probes were used to measure the electric and magnetic components of the oscillations. The results of these measurements are shown in Fig. 4 in the form of the dependence of the power registered by receivers tuned to the same frequency on the intensity of the main magnetic field. From the calibration measurements made at the employed frequency, the signal received by the magnetic probe should exceed by approximately two times the signal from the electric probe in the case when the oscillations are of an electromagnetic nature. It is seen from Fig. 4 that for magnetic fields such that the cyclotron frequency is larger than the frequency to which the receivers are tuned, the signal from the magnetic probe actually is double the signal from the electric probe. For weaker magnetic fields, the signal from the two probes becomes equal, and sometimes the electric-probe signal exceeds the magnetic-probe signal by several times.

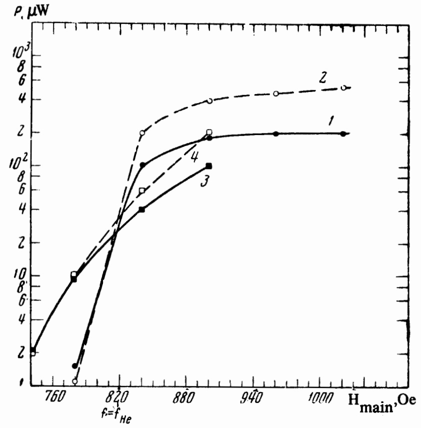

FIG. 4. Power from the electric and magnetic probes vs. intensity of the main magnetic field. Curves 1 and 2–signals from electric and magnetic probes moved to a radius of 4 cm; curves 3 and 4–the same signals but a radius 9 cm. Frequency f = 2300 MHz.

It is necessary to emphasize the importance of calibrating the probes and choosing the frequency at which the measurements are made. To verify the correctness of this procedure, measurements similar to those described above were made at 2700 MHz, at which calibration has shown the ratio of the signals from the electric and magnetic probes to be 3×10^{-4}. Measurements of the plasma signals at this frequency have shown that the signal from the electric probe was only 6×10^{-3} of the signal from the magnetic probe. The discrepancy between these figures may be the consequence of inaccuracy in the tuning of the receivers during the time of calibration and measurement. Frequency regions in which the sensitivity of the probes differ so strongly (by about 10^4 times) are quite narrow and therefore a slight inaccuracy in the receiver tuning can have a strong effect.

Figure 5 shows plots similar to those of Fig. 4, but obtained at different initial energies of the main electrons. We see that a sharp decrease of the oscillation intensity occurs independently of the beam-electron energy, for the same value of the intensity of the main magnetic fields, whereas the maximum of the oscillation intensity depends strongly on the beam energy. We note that in this experiment, a change in the electron energy (intensity) produced also a change in the beam current in accordance with the $^3\!/_2$ law.

Measurements of the intensity of oscillations in frequency $\omega < \omega_{He}$ at different distances from the center of the plasma have shown a weak radial dependence of the oscillation intensity in the region occupied by the plasma. Within the limits of the beam (approximately 3 cm in radius), the intensity does not change, and decreases by a factor of only 4–6 at a radius of

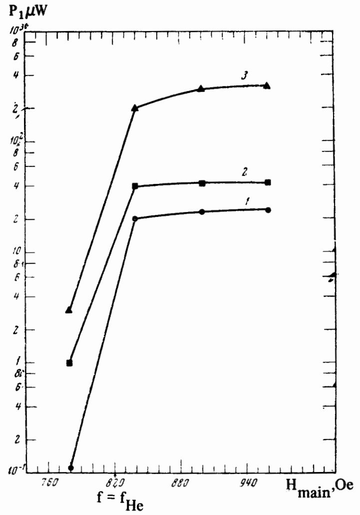

FIG. 5. Power entering the receiver from the magnetic probe against the intensity of the main magnetic field at different values of the beam electron energy. Curve 1—energy 3 kV, curve 2—6 kV, curve 3—13 kV.

10 cm, but at a 12 cm radius the intensity decreases approximately by one order of magnitude relative to the intensity at the 10 cm radius. Following a change of the orientation of the magnetic probe relative to the main magnetic field, it was observed that the oscillation component $\tilde{H}_\varphi$ is approximately 2–3 times larger than the component $\tilde{H}_z$.

Comparison of the aggregate of the experimental data with the theory of waves in a plasma enables us to conclude that the observed oscillations are waves with circular polarization (waves of the whistler type). Indeed, the refractive index N of these waves, at $\omega_{0e}^2/\omega_{He}^2 \gg 1$, is written in the form[7] (for a wave having a resonance at the frequency $\omega_{He}\cos\theta$)

$$\frac{k^2c^2}{\omega^2} \equiv N^2 = 1 + \frac{\omega_{0e}^2}{\omega(\omega_{He}\cos\theta - \omega)} \tag{1}$$

where k is the wave number, c is the velocity of light, ω the frequency of the wave, and θ is the angle between the wave vector and the direction of the external magnetic field. From expression (1) we see that the frequency of these waves is always smaller than $\omega_{He}\cos\theta$. Experiment yields an approximate value ω_{He} for the upper limiting frequency of the intense oscillations, i.e., the waves propagate mainly along the magnetic field ($\theta = 0$). According to the theory, these waves are electromagnetic; experiments have revealed the presence of a magnetic component polarized in a suitable manner and close in magnitude to the electric component of the wave. The frequency range of the oscillations, as expected, does not depend on the electron energy or on the beam current. The waves are concentrated mainly inside the plasma, more likely because the refractive index of the plasma is $N^2 \gg 1$, and the waves incident on the plasma-vacuum boundary at small angle experience total internal reflection. The presence of harmonics with frequencies $m\omega_{He}$ does not follow from the linear theory, and apparently is the consequence of nonlinear effects taking place upon excitation of the waves. The absence of a second harmonic can be explained by the fact that no electromagnetic waves with frequencies in the range $\omega_{He} < \omega < \omega_{0e}$ can propagate in the plasma. Propagation of the third and higher harmonics is not forbidden in the case $\omega_{0e} = 2\omega_{He}$ ($3\omega_{He} > \omega_{0e}$).

From the observed correlation between the intensity of the x-rays and the intensity oscillations at different frequencies of the spectrum, it is possible to establish the frequencies of the oscillations whose excitation correlates with the appearance of the fast electrons. First, it is easy to check whether the hot electrons cause the excitation of the oscillations with the spectrum shown in Fig. 3. To this end, a thin conductor (2.5 mm diameter) was inserted into the plasma up to the center; all the fast electrons were absorbed by this conductor, as was manifest the strong decrease of the intensity of the x-radiation from the target. Figure 6 shows oscillograms illustrating this experiment. We see that elimination of the fast electrons has practically no effect on the oscillation intensity, i.e., the latter are excited by the beam electrons that pass through, and not by the fast electrons that are captured in the magnetic trap. Comparison of the oscillograms of the oscillations of different frequencies allows us to conclude that only the intensity of the oscillations at frequencies lower than f_{He}, but not very far from it (in the case of the spectrum of Fig. 3, approximately from 2600 to 2000 MHz), correlates with the x-ray intensity, i.e., apparently it is precisely the oscillations of these frequencies which are responsible for the electron heating, regardless of whether the heating condition $\omega_{0e} \approx 2\omega_{He}$ or $\omega_{0e} \approx 3\omega_{He}$ is realized.

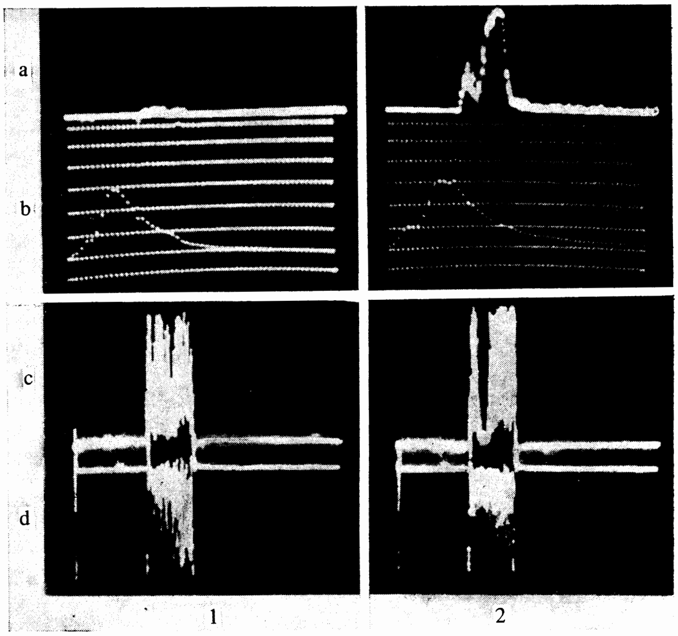

FIG. 6. Oscillograms of x radiation (a), plasma density (b), oscillations at frequencies 2350 MHz (c) and 1800 MHz (d), obtained with a conductor introduced inside the plasma (1) and without such a conductor (2). The intensity of the main magnetic field is 930 Oe. The distance between the points of the density oscillogram corresponds to a time interval of 60 μsec.

Inasmuch as the main electric probe was calibrated, we were able to estimate the intensity of the alternating electric field in the plasma under conditions under which the oscillation spectrum was obtained. The estimate yielded a value of 100–150 V/cm for the intensity of the electric field of the oscillations in the frequency band 2000–2600 MHz.

In conclusion, we advance certain considerations with respect to the mechanism of excitation of waves of the whistler type by a beam of electrons having initially only a longitudinal velocity component. It is known from the theory that waves of this type, which propagate almost along the magnetic field, are excited with the largest increment by electrons having a velocity component transverse to the external magnetic field (see, for example,[3]), i.e., the primary beam electrons cannot take part in the effective buildup of these waves. There should therefore exist mechanisms that lead to the rotation of the electron-velocity vector. In our case, such a mechanism is apparently the scattering of the beam by the plasma oscillations excited by the beam near the entrance into the plasma. The excitation of such oscillations was investigated experimentally[9]. It was shown there that the greatest intensity is reached by the plasma oscillations when the plasma frequency ω_{0e} is close to harmonics of the cyclotron frequency, and the oscillations themselves are localized near the plasma boundary. It is most likely therefore that the most intense excitation of whistler-type waves and the appearance of x-radiation was observed by us under the condition $\omega_{0e} \approx m\omega_{He}$. The elementary mechanism for the excitation of these waves may be the normal Doppler effect. From the condition of the resonance of the electron and the wave ($m = +1$)

$$\omega - \mathbf{kv} - \omega_{He} = 0, \tag{2}$$

and from expression (1), assuming that ω is close to ω_{He}, we can find the frequency ω_{res} of the wave that is in resonance with an electron moving with velocity v_z (v_z is smaller than the initial beam-electron velocity v_0) along a force line of the magnetic field

$$\omega_{res} = \omega_{He}\left[1 - \left(\frac{v_z}{c}\frac{\omega_{0e}}{\omega_{He}}\right)^{2/3}\right]. \tag{3}$$

It follows from (3) that ω_{res} is much smaller than ω_{He} is v_z is sufficiently large. Thus, if $v_z = v_0/2 = 3 \times 10^9$ cm/sec, then $f_{res} \equiv \omega_{res}/2\pi$ for such an electron is lower by more than 900 MHz than the cyclotron frequency, in agreement with experiment.

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