INVESTIGATION OF THE MECHANISM OF HEATING OF THE PLASMA ELECTRON COMPONENT UNDER TWO-STREAM INSTABILITY CONDITIONS IN A MIRROR TRAP

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The effect of magnetic field inhomogeneity on plasma heating by an electron beam in a magnetic mirror machine type is investigated experimentally. The possibility is demonstrated of efficient linear absorption of energy of oscillations, excited by the beam in the plasma, in an inhomogeneous magnetic field. The data obtained confirm the mechanism if stochastic cyclotron heating of the plasma electron component in a mirror trap. The heating efficiency is maximal when the spectrum of oscillations excited by the beam in the plasma lies in the cyclotron-frequency range of the mirror machine.

THE investigation of the heating of a plasma under conditions of beam instability in magnetic mirror traps has been the subject of an ample number of experimental papers[1-7]. An analysis of these papers shows that under certain conditions it is possible to heat the plasma electrons and ions to relatively high temperatures. The heating results from the interaction of the charged particles with the fields of the electromagnetic oscillations that are excited by the electron beam in the plasma, in which case the beam can lose a significant portion of its directional energy. The heating of the plasma electron component has been studied quite thoroughly, but to this day there is still no unified point of view concerning the mechanism of that heating.

Among the various concepts about the mechanism of heating of the plasma electron component under conditions of beam instability there are two models which receive close scrutiny. The first of these models[4,8] is based on the idea that a Langmuir spectrum of oscillations with frequencies significantly in excess of the cyclotron frequencies is excited in the plasma. The plasma electrons can have no effective interaction with these oscillations, since the wave phase velocities are significantly higher than the thermal velocity of the plasma electrons. In this regard it is then, in the terms of this model, necessary to postulate at the outset the presence in the plasma of a group of high-energy electrons, the source of which can only be the beam itself. Electrons thus "knocked out" of the beam and caught in the mirror trap can acquire energy on interaction with the fields of the Langmuir oscillations.

In the second model it is assumed that the experimentally observed heating of the plasma results from stochastic cyclotron interaction of the particles with the fields of the oscillations that are excited by the beam in the inhomogeneous magnetic field of the mirror machine[3,5,6]. The cyclotron-absorption mechanism is the most effective means of transmitting oscillation energy to the plasma particles. Unlike the Cerenkov absorption mechanism, in this case it is not required that the particle velocity coincide with the phase velocity of the wave, and thus it is no longer necessary to postulate the initial existence of high-energy particles in the plasma. In this model the essential condition is that the spectrum of excited oscillations lie in the region $\omega_{c\,min} < \omega < \omega_{c\,max}$, where $\omega_{c\,min}$ and $\omega_{c\,max}$ are the cyclotron frequencies corresponding to the minimum and maximum fields of the mirror machine.

The following experimental facts may be adduced in support of the stochastic cyclotron heating model: 1) Under conditions of effective heating of the electron component, the plasma density is such that the plasma frequency is close to the cyclotron frequency ($\omega_p \sim \omega_c$). 2) A distinct correlation is observed between the excitation of the spectrum in the cyclotron-frequency range and the x-radiation from the plasma[5]. 3) Absorption of the energy of the electromagnetic oscillations is observed in the region of the cyclotron frequencies and their harmonics[3].

The most complete information about the heating mechanism under two-stream instability conditions can be obtained from studies of the spectra of the oscillations and their absorption in magnetic mirror traps. It should be noted that in practice not a single paper has devoted sufficient attention to these questions.

EXPERIMENTAL APPARATUS

A detailed investigation of the oscillation spectra and their absorption in inhomogeneous magnetic fields was carried out with the apparatus shown schematically in Fig. 1. The electron beam from an electron gun was injected into an interaction chamber consisting of a glass tube 6 cm in diameter and 60 cm in length and was incident on the collector. The interaction chamber was situated in a magnetic field produced by a system of coils that could be interconnected in various ways to produce the magnetic field configurations necessary for the investigation. The intensity of the homogeneous magnetic field with all the coils connected in series was 5 kOe. The coils were fed with direct current.

The electron gun was an ordinary incandescent-cathode diode placed in a magnetic field. The gun was capable of functioning both continuous and pulsed operation (pulse length 10–100 μsec) of the gun were possible, so that electron beams could be produced with

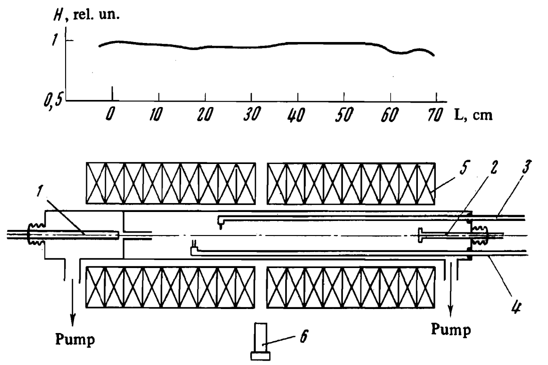

FIG. 1. Schematic diagram of the apparatus: 1—electron gun, 2—collector, 3—movable coaxial microwave probe, 4—movable double probe, 5—magnetic field coils, 6—photomultiplier with NaI(Tl) crystal. The distribution of the homogeneous magnetic field along the axis is shown above.

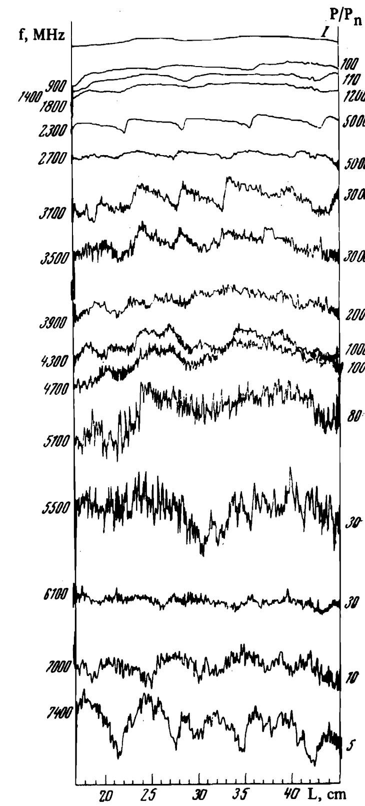

FIG. 2. The distribution of oscillation intensity along the axis of the system in homogeneous magnetic field (f is the frequency of the received oscillations, P/P_n is the ratio of the power of the received oscillations to the noise power; the frequency in MHz is on the left). Curve 1 is the ion saturation current. H = 2200 Oe, the beam current is I_b = 70 the beam energy is U_b = 1 keV, the pressure in p = 3 × 10^{-5} mm Hg, $n_{min}/n_{max} = 10^{-1}$.

currents 10—200 μA at energies of up to 5 keV. The oscillations excited by the beam were picked up with movable coaxial probes which could be displaced both radially and along the entire interaction area. Moving the probes could lead to significant changes in the plasma parameters and beam parameters, especially under heating conditions. The perturbing effect of the probes was therefore monitored continouously during the course of the experiments, and all measurements were performed under conditions where the perturbation of the plasma parameters by the probes was not significant.

The signals from the coaxial probes were fed to measuring receiver with approximate sensitivity 10^{-11} V and an operating range of 300 to 7500 MHz. The measurement circuit was calibrated with standard noise generators. The signals from the receivers were fed to an x-y recorder. The horizontal scan of the recorder was linearly dependent on the position of the probe in space. The wavelength of the oscillations was measured by the reference-signal method. As a reference we used the signal from one of the coaxial probes. The density and temperature of the plasma were measured with a double probe. The x-rays were recorded by means of a photomultiplier with a NaI(Tl) crystal. The plasma was produced by the beam itself as a result of ionization of the working gas (hydrogen, helium, air) at approximate pressures 10^{-4}—10^{-5} mm Hg. The temperature of the plasma ions was determined from the Doppler line broadening of the ionized helium.

RESULTS OF THE EXPERIMENTS

When the beam of charged particles interacts with a plasma located in an magnetic field, the most effective excitation of natural weakly-damped oscillations in the plasma occurs in the spectral region determined by the expression

$$\omega^2_{1,2} = {}^1/_2(\omega_p^2 + \omega_c^2) \pm {}^1/_2[(\omega_p^2 + \omega_c^2)^2 - 4\omega_p^2\omega_c^2 \cos^2 \alpha]^{1/2}$$

where $\cos \alpha = k_z/k$, and k_z is the component of the wave vector along the magnetic field. The electron beam in our experiments traveled in the beginning of its path in the plasma for 10—15 in a relatively homogeneous magnetic field. Since the increments of the two-stream instability are large enough, the instability develops mainly in the homogeneous field region.

The initial stages of the development of oscillations has been investigated in detail in a number of papers[9]. We have investigated the behavior of electromagnetic oscillations induced by the beam during their propagation along an inhomogeneous magnetic field in the region where the plasma density varied little. In the initial section, at the place where the beam enters the system, the variation in the plasma density could be significant. The density distribution at that point (1 to 10 cm from the point of entry of the beam) was essentially dependent on the conditions of the experiment. It was established that the distribution of the intensity of the oscillations, especially for the upper hybrid frequencies, was determined in this same section to a considerable degree by the density distribution.

We investigated experimentally the propagation of the waves and their damping in a homogeneous magnetic field and in a field of mirror geometry with various mirror ratios. Figure 2 shows the distribution of the oscillation intensity along the system for a homogeneous field. The variation of the oscillation intensity in space was studied at a distance of from 12 to 40 cm from the entry of the electron beam in the system. In the case of a homogeneous field, no signficant variation was observed in the intensity of the oscillations

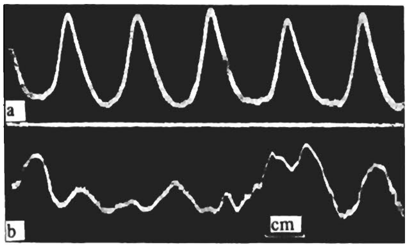

FIG. 3. Oscillograms of the ion saturation current from the probe under conditions of regular and irregular oscillations. The sweep time is $\tau = 10\ \mu$sec/cm for oscillogram a and $\tau = 50\ \mu$sec for oscillogram b.

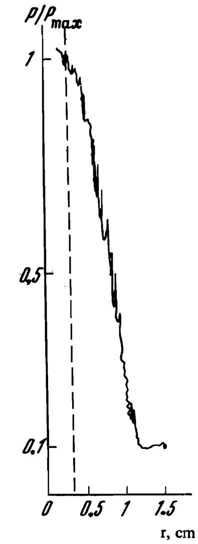

FIG. 4. Radial distribution of the oscillation intensity at f = 4000 MHz.

and in the width of the recorded spectrum along the system. The weak variation of the oscillation intensity along the system is evidence of the relatively small role played by nonlinear absorption in this region. Estimates show that such nonlinear processes as induced scattering of waves by ions and electrons are small under the conditions of this experiment[10]. As a rule, in a homogenous magnetic field the electron temperature is relatively low ($T_e \sim 5$—10 eV) and exceeds greatly the ion temperature ($T_i < 1$ eV). The most important nonlinear effect that ought to show up in the experiment is the decay of a Langmuir wave into a Langmuir wave and a low-frequency wave[11]. Indeed, apart from the high-frequency oscillations, intensive low-frequency oscillations are observed in the region from 10 keV to 1 MeV. The spectrum of the low-frequency oscillations usually consists of many frequency lines, the amplitude of which varies randomly in time. Under certain conditions, the low-frequency spectrum can consist of one or two distinctly pronounced lines.

Figure 3 shows oscillograms of the ion saturation current from the probe in the regular and in the irregular oscillation regimes. Analogous oscillations are observed with pulsed injection of the electron beam. The amplitude of the oscillations of the ion current to the probe can exceed the dc component of the ion current by more than one order of magnitude, which corresponds to similar oscillations of the plasma density at a constant electron temperature. For the spectra shown in Fig. 2, the temperature of the electron component is $T_e \approx 10$ eV, the minimum density is $n_{min} \sim 3 \times 10^{10}\ cm^{-3}$, and $n_{max} \sim 3 \times 10^{11}\ cm^{-3}$. The density varies little along the system (see the saturation ion current curve in Fig. 2). The experimentally observed oscillation spectrum is quite broad (f = 400—7400 MHz for Fig. 2). For a density that is stationary in time the spectrum of the oscillations excited in the plasma by the beam must be considerably narrower and must consist of two separate regions with intensity maxima near the frequencies $\omega_{1,2}$.

It was impossible to produce in the experiment density conditions stationary in time and, as pointed out above, the low-frequency density fluctuations were rather large. The observed broad frequency spectrum is due to a considerable degree to these oscillations of the plasma. The intensity of the oscillations is maximal in the frequency region $\omega \sim \omega_2$ and can exceed by more than two orders of magnitude the intensity of the oscillations in the region of the upper hybrid frequency ω_1. The intensity of the observed oscillations depends to a large degree on the character of the low-frequency density oscillations. Since the increments of the oscillations excited by the beam are strongly dependent on the plasma density, the average power transmitted by the beam to the oscillations is lower than under the optimum conditions in the presence of density fluctuations.

The intensity of the oscillations picked up by the probe falls off sharply when the probe is displaced in a radial direction away from the beam boundary (Fig. 4). Such an intensity distribution corresponds to the excitation of slow waves in the plasma. The experiment reveals weak periodic variations of the oscillation intensity along the system. At the maximally excited frequencies, these variations amount to a fraction of one per cent and increase with diminishing oscillation intensity. The studies have shown that this weak spatial periodicity is due to the excitation of the electromagnetic oscillations in the resonator formed by the 10 cm diam metal tube to which the solenoid coils are fastened and by other parts of the apparatus. Moving the metallic probe along the resonator changes the spatial distribution of the fields in the resonator.

In an inhomogeneous magnetic field, the spatial distribution of the oscillation intensity must differ noticeably from the homogeneous field case. When waves are propagated in an inhomogeneous medium[11,12], it is possible to achieve conditions such that the energy of the waves is effectively absorbed by the plasma particles. The increase in the efficiency of wave absorption in the plasma may be due either to strong deceleration of the waves and the ensuing increase in the Landau damping, or to cyclotron absorption in the cyclotron-resonance region of the inhomogeneous magnetic field. Unlike the methods of heating the plasma by means of externally applied high-frequency fields, where there is a non-transparency region between the plasma boundary and the region of transformation of the electromagnetic wave into a plasma wave, in the case of the interaction of an electron beam with a plasma a slow wave is excited in the volume of the plasma and can be easily transformed in an inhomogeneous magnetic field into the effective absorption region. In this sense the method of beam heating may in many cases

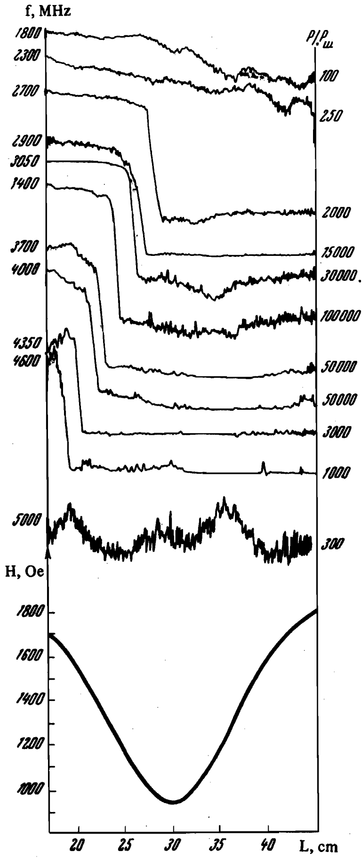

FIG. 5

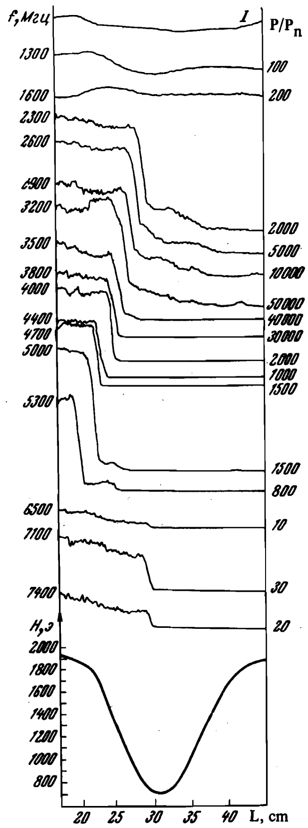

FIG. 6

FIG. 5. Distribution of oscillation intensity along the system in a mirror trap with mirror ratio R = 2. The beam current is I_b = 56 MHz, the beam energy is U_b = 1.5 keV, the pressure is p = 5 × 10^{-5} mm Hg, n_{min} = 3 × 10^{10} cm^{-3}, and n_{max} = 2 × 10^{11} cm^{-3}.

FIG. 6. Distribution of the oscillation intensity along the system in a trap with mirror ratio R = 2.8. The bean current I_b = 60 mA, the beam energy U_b = 1.5 keV, the pressure p = 7 × 10^{-5} mm Hg, n_{min} = 3 × 10^{10} cm^{-3}, and n_{max} = 3 × 10^{11} cm^{-3}. Curve I is the ion saturation current.

prove to be preferable to heating by external high-frequency fields.

Figures 5 and 6 show plots of the spatial distribution of the oscillation intensity for various profiles of the inhomogeneous magnetic field of the mirror machine at various values of the beam and plasma parameters. The most characteristic feature of the plots is the strong absorption of wave energy in the region of the cyclotron frequency and its harmonics. This absorption is especially pronounced in the region of the fundamental resonance. After passing through this region the intensity of the oscillations drops by several orders of magnitude. In the excitation region, the frequencies of these waves lie below the cyclotron frequency and should be regarded as modes with $\omega \sim \omega_2$. When propagated along a diminishing magnetic field, the waves are slowed down and are effectively absorbed in the cyclotron resonance region. As an example, Fig. 7 shows the damping of the oscillations at the cyclotron frequency. After passing through the cyclotron resonance region the intensity of the oscillations falls off by three orders of magnitude. The rise

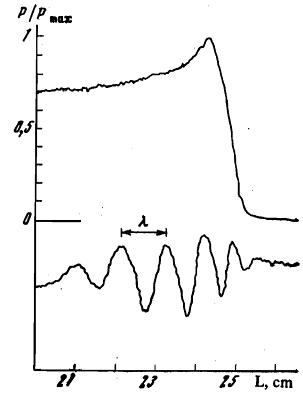

FIG. 7. Distribution of the oscillation intensity along the system and variation of the wavelenth at f = 2000 MHz. The beam energy U_b = 1.3 keV.

in the oscillation intensity on the plot ahead of the absorption region is apparently due to the slowing of the wave and the accumulation of oscillation energy in that region. The lower curve in Fig. 7 shows the change in the oscillation wavelength on approaching the cyclotron-resonance region. In the excitation region, the phase velocity of the wave is close to the beam velocity, which corresponds to the Cerenkov mechanism of oscillation excitation. The experimentally observed decrease in the wavelength was by a factor of two or three.

As observed above, the oscillation intensity is much lower in the region of the upper hybrid frequencies than in the region of frequency ω_2. Their intensity is a maximum at the point of entry of the beam into the plasma, where the magnetic field is homogeneous. Such an intensity distribution corresponds to the excitation of backward waves in the system. Absorption of the energy of these waves by the plasma particles should not lead to the capture of the particles in the trap. When these waves are propagated along a diminishing magnetic field at a constant transverse wave number $k_\perp$, their phase velocity along the magnetic field must increase. This effect is apparently the reason for the relative increase in the intensity of the electromagnetic radiation at these frequencies. The distribution of the oscillation intensity in space for the highest-frequency portion of the observed spectrum corresponds to the excitation of forward waves in the plasma. When these waves propagated along the diminishing magnetic field we observed absorption at the second and third harmonics of the cyclotron frequency. Absorption at the third harmonic of the cyclotron is seen in Fig. 6 at frequencies above 6500 MHz.

The width of the cyclotron-absorption region came to several hundred MHz and varied with the conditions of the experiment. As one would expect, an increase in the plasma electron temperature was accompanied by an increase in the width of the resonance region. When oscillations were excited as a consequence of the anomalous Doppler effect, the starting point of the region of oscillation energy absorption at a given frequency was shifted, as a result of the decreased wavelength, into the region of the stronger magnetic fields.

The obtained experimental data show that the most effective absorption of oscillation energy by the plasma electrons takes place in the regions of the cyclotron resonance. We studied experimentally the effectiveness of heating of the electron component of the plasma as a

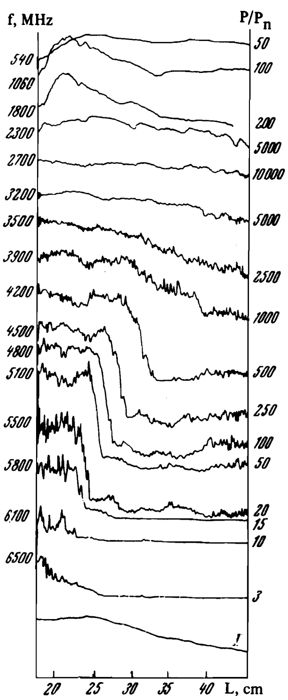

FIG. 8

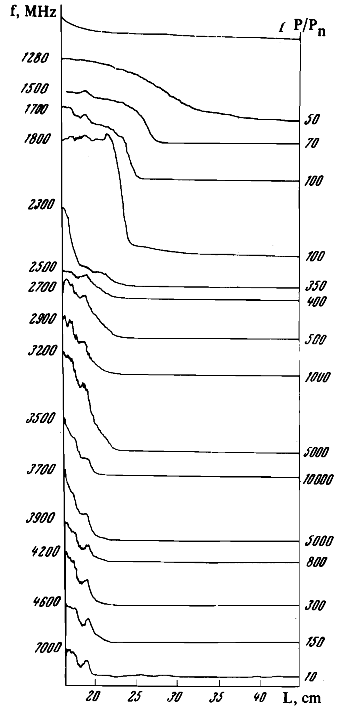

FIG. 9

FIG. 8. Distribution of the oscillation intensity in a mirror trap with mirror ratio R = 2. The magnetic field in the center of the mirror machine is H_{min} = 1450 Oe, the beam current I_b = 1.6 keV, the pressure p = 4 X 10^{-5} mm Hg. Curve I is the ion saturation current.

FIG. 9. Distribution of oscillation intensity in a mirror trap with mirror ratio R = 2. The magnetic field in the center of the mirror machine is H_{min} = 1.4 keV are the pressure p = 5 X 10^{-4} cm Hg. Curve I is the ion saturation current.

function of the spectrum of the high-frequency oscillations excited by the beam. Figures 5, 8, and 9 show the distribution of the oscillation intensity along the system for various experimental conditions. The magnetic field distribution in Figs. 8 and 9 is the same as in Fig. 5. It is seen from these figures that effective transfer of the high-frequency oscillation energy to the plasma electrons occurs in the region of the diminishing field of the first mirror at the time when the second mirror serves to capture the particles in the trap. Particles that have acquired enough energy in the resonance absorption section to be reflected from the second mirror are captured in the trap and pass through the resonance absorption region many times as a result of the untrapped oscillations between the mirrors, continuously acquiring energy.

The experiments show that each line of the excited spectrum appears in the form of bursts of monochromatic oscillations of duration $\sim 10^{-7}$ sec. In this sense the excited spectrum can be regarded as random in time. The cause of the phase randomization may be both the random character of the initial perturbations and the observed low-frequency density fluctuations. Since the plasma electrons enter the resonance absorption region at arbitrary oscillation phases, the electron heating has stochastic character. The optimum conditions for the heating of the plasma electrons are those when the intensity maximum of the beam-excited frequency spectrum lies in the resonance absorption region in the inhomogeneous magnetic field of the mirror machine (Figs. 5 and 6). In this case we observe intense x-rays with energies much in excess of the beam energy. Thus, under the conditions of Fig. 5) at a beam current 60 mA and beam energy 1.5 keV the average energy of the "hot" plasma electrons is of the order of 20 keV.

The temperature of the high-energy component of the plasma was determined from the x-ray energy distribution. The method of plotting and processing of the x-ray spectra is described in detail, e.g., in[3,5]. Probe measurements of the electron temperature relative to the cold component of the plasma give values $T_e \sim$ 20 to 30 eV. Away from the optimum conditions, i.e., when the spectrum of the maximumally excited frequencies shifts above or below the cyclotron frequencies of the mirror machine, the heating efficiency falls off sharply. The frequency spectra and the change in the distribution of the oscillation intensity over the spectrum with changing the magnetic field intensity are illustrated in Figs. 8 and 9. Under the conditions of Fig. 8 the frequencies with the maximum intensity (2300—3500 MHz) lie below the minimum cyclotron frequency of the mirror machine. Although frequencies corresponding to resonance absorption in the inhomogeneous magnetic field of the mirror machine exist in the excited oscillation spectrum, their intensity is relatively weak. In this case there is no x-ray emission.

Analogously, the heating efficiency falls off when the frequency spectrum is shifted above the cyclotron frequencies of the mirror machine (Fig. 9). The oscillation damping at the upper hybrid frequencies shown in the figure is apparently due to the transformation of these waves into strongly damped (plasma) waves on account of the density inhomogeneity in the initial stage of this regime.

It follows from the experimental material presented above that the heating efficiency must increase with increasing mirror ratio, for in this case there is broadening of the region of resonance absorption of the oscillation energy. Figure 6 shows the distribution of the oscillation intensity along the system for a mirror machine with a mirror ratio R = 2.8. In this case the resonance band to a width of the order of 3000 MHz. Increasing the mirror ratio increases the heating efficiency and increases the hardness of the x-rays from the plasma. (see also[14]).

We also studied experimentally the effectiveness of heating the plasma electrons as a function of the magnetic field intensity. Upon increasing the magnetic field intensity, both the density and the energy of the high-energy particles increase when the optimum conditions are fulfilled (when the spectrum of the excited frequencies lies in the cyclotron-frequency region of the mirror machine). In the case where a plasma is produced by the beam as a result of development of a beam-plasma discharge, it is necessary to adjust correspondingly the gas pressure and the beam current.

Earlier experiments[1-6] on the particle-energy distribution have shown that plasma electrons that are heated to a high temperature have a Maxwellian distribution and amount to up to 10% of the plasma density.

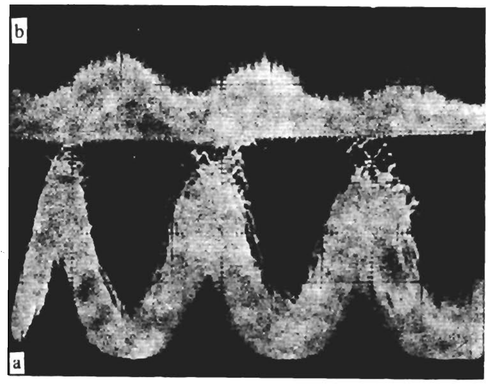

FIG. 10. Oscillations of the ion saturation current (a) and the intensities of the x-ray emission from the plasma (b); sweep time t = 10 μsec/cm.

The relatively small fraction of high-energy particles may, in light of the experimentally observed facts, be due to low-frequency relaxations of the density and the ensuing drift in time away from the optimum conditions of heating. Indeed, when strong low-frequency oscillations are excited in the system one observes strongly marked fluctuations in the microwave and x-ray emission from the plasma (Fig. 10; see also[5]).

Thus, it follows from the obtained experimental data that the mechanism of plasma-electron heating under conditions of two-stream instability in open magnetic traps is the stochastic cyclotron resonance in the inhomogeneous magnetic field of the mirror machine. The heating efficiency is maximal when the spectrum of the oscillations excited in the plasma by the beam lies in the cyclotron-frequency region of the mirror machine. Increasing the width of the absorption band leads to an increase of the heating efficiency. The electromagnetic waves excited in the plasma by the beam are practically all absorbed in the region of the cyclotron resonance in the inhomogeneous magnetic field.

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