COMBINED HEATING OF A PLASMA BY AN ELECTRON BEAM AND AN INTENSE ION-CYCLOTRON WAVE

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Results are presented of an experimental investigation of the interaction between an electron beam and plasma in which large amplitude ion-cyclotron oscillations are excited by external high frequency currents. It is shown that electromagnetic radiation in the microwave range arises, with a power ~ 20 dB greater than that of the microwave radiation from the usual beam-plasma interaction at the same plasma density. The microwave radiation frequency is the same as the electron plasma frequency. The amplitude of the radiation depends in a resonant manner on the strength of the external magnetic field and its maximum coincides with that of the ion cyclotron wave amplitude. The polarization of the microwave radiation observed corresponds to that of the extraordinary wave ($\mathbf{E} \perp \mathbf{H}_0$). The microwave radiation is amplitude-modulated at a frequency of the ion cyclotron wave. When the frequency of the microwave radiation is the same as the harmonics of the electron cyclotron frequency, the amplitude of the microwave radiation sharply drops and the gaskinetic pressure of the plasma increases by 50–70%.

As is well known[1-5], intense high-frequency fields with frequencies close to the ion-cyclotron frequency can be successfully used for effective heating of plasma ions. A shortcoming of such a method of heating of the plasma is that the electron temperature remains in this case quite low, and this leads to appreciable energy losses. It seems to us that combined plasma-heating methods, which ensure simultaneous heating of both the ions and the electrons, are more promising. To produce combined heating it is necessary to ensure simultaneous excitation of intense electron and ion oscillations that are effectively absorbed by the plasma. If the ion-cyclotron waves (ICW) are excited by an external generator, then the electron oscillations can be excited with charged-particle beams or with microwave generators.

Let us discuss the possibilities of combined heating of a plasma using ion-cyclotron high-frequency ion heating and an electron beam.

Fast electron beams excite as a rule relatively long-wave Langmuir waves, which, in view of the weak damping, do not heat the plasma rapidly. The electrons are heated more effectively by transverse slow electron-cyclotron waves (ECW), the energy of which is effectively absorbed by the electrons. ECW can be excited in a beam-plasma system in the presence of large-amplitude ICW as a result of nonlinear transformation of the Langmuir waves into ICW. It is necessary for this purpose, naturally, that some combined frequency $\omega_{\pm n} = \omega_{pe} \pm n\Omega_{Hi}$ (n are integers, ω_{pe} is the electron plasma frequency, and Ω_{Hi} is the ion-cyclotron frequency) be close to one of the harmonics $n\omega_{He}$ of the electron-cyclotron frequency. Since, as a rule, $\Omega_{Hi} \ll \omega_{pe}$, this means that the condition $\omega_{pe} \approx n\omega_{He}$ must be satisfied. If ω_{pe} is not close to ω_{He}, the Langmuir waves can be transformed into transverse waves that are absorbed weakly by the plasma and can be radiated out of the system. The beam-plasma system can then be used as a microwave generator. In addition, the outgoing microwave radiation, which carries certain information concerning the processes occurring in the plasma, can be used for plasma diagnostics.

The experimental investigations of beam-plasma interaction in the presence of an intense ICW, to the results of which we now proceed, confirm the validity of the arguments advanced above.

The experiments were performed with the "Sneg" setup which was described in detail earlier[6]. Unlike in[6], an ICW wave was excited resonantly in the plasma in this case rather than a fast magnetosonic wave. The ICW was excited in a hydrogen plasma at a frequency f = 10.4 MHz. The HF generator (pulsed power up to 300 kW) could excite in the plasma an ICW with amplitude $\tilde{H}_z \approx 100$ Oe. When an ICW of such amplitude is damped in a plasma of density $n \sim (1-5) \times 10^{13}$ cm^{-3}, the ion temperature reaches 300–500 eV at an electron temperature $T_e \approx 20$ eV. An electron beam with current up to 6 A and energy up to 40 keV was injected into the hot-ion plasma produced in this manner in the presence of ion-cyclotron oscillations. The injection duration could be smoothly varied in the range 10–100 μsec.

The microwave radiation produced in the experiment was received by an outside horn antenna and fed through a 3-cm waveguide line into the diagnostic chamber. We determined the microwave frequency band, the

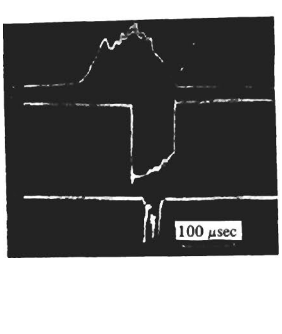

FIG. 1. Oscillograms of the envelope of H_z (a), of the beam current (b), and of the microwave radiation (c).

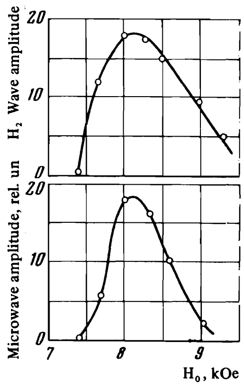

FIG. 2. Dependence of the amplitude of the microwave radiation and of H_z (in relative units) on the magnetic field.

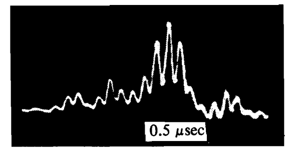

FIG. 3

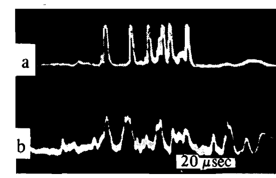

FIG. 4

FIG. 3. Oscillograms of detected microwave-radiation signal.
FIG. 4. Oscillograms of detected microwave-radiation signal (a) and of the plasma-density oscillations (b).

polarization, the radiation amplitude, and the frequencies at which the outgoing microwave radiation is amplitude-modulated. In addition, a diamagnetic probe was used to estimate the gas kinetic pressure of the plasma ($nkT_{e\perp} + nkT_{i\perp}$).

As expected, when the electron beam was injected in a plasma in which a large-amplitude ICW was excited, appreciable microwave radiation was observed (Fig. 1), with a frequency close to ω_{pe}. The measurement of the polarization has shown that the microwave radiation is polarized in a plane where $\mathbf{E} \perp \mathbf{H}$ and consequently corresponds to the extraordinary electromagnetic waves. The power of this microwave was approximately 20 dB larger than the power of the microwave radiation in ordinary plasma-beam interaction for the same plasma density in the absence of the ICW. The microwave radiation is apparently a result of nonlinear transformation of the Langmuir waves generated by the beam into transverse waves. The amplitude of the microwave radiation increases with increasing power of the electron beam and with increasing ICW amplitude. When the intensity of the external magnetic field is varied and the beam power is kept constant, the change of the amplitude of the microwave radiation has a resonant character (Fig. 2). Such a dependence of the microwave-radiation amplitude on the magnetic field confirms the assumption that the microwave radiation is the result of nonlinear transformation of the beam-excited Langmuir oscillations into ICW. In fact, in this case, the relation $a_\perp \sim a_e^l a_{Hi}$ should be satisfied ($a_\perp$, a_e^l, and a_{Hi} are the amplitudes of the transverse, Langmuir, and ion-cyclotron waves), i.e., at constant a_e, $a_\perp$ should have the same dependence on the magnetic field as the ICW amplitude, which, as seen from Fig. 2, has a resonant character. The maximum of the microwave-radiation amplitude coincides with the maximum of the ICW amplitude.

The investigations have shown that the microwave radiation is amplitude-modulated at a number of low characteristic plasma frequencies. The depth of modulation is close to 100%. The employed measuring apparatus made it possible to determine two characteristic modulation frequencies. As seen from Fig. 3, which shows an oscillogram of the microwave signal detected with an S1-11 oscilloscope (bandwidth up to 250 MHz), the microwave radiation is amplitude modulated at the frequency of the ion-cyclotron wave (f = 10.4 MHz). In addition, it was observed that the microwave radiation experiences appreciable modulation also at lower frequencies (~ 100—200 kHz) (Fig. 4a).

The low-frequency amplitude modulation of the microwave radiation, as shown in[7], points to the presence in the plasma of intense low-frequency oscillations that perturb the plasma density. Since the increment of the beam-excited Langmuir oscillations is quite sensitive to plasma-density oscillations, the microwave radiation was modulated at the frequencies at which the plasma density oscillates. A probing microwave signal of 4 mm wavelength has revealed the plasma-density oscillations (Fig. 4b), whose frequency coincides with the amplitude-modulation frequency of the microwave radiation (Fig. 4a).

By varying the initial pressure in the discharge tube, which is equivalent to varying (within certain limits) the plasma density, we found a region of initial hydrogen pressures in which the microwave radiation is greatly suppressed or is completely nonexistent when an electron beam and an ICW are simultaneously present in the plasma. In this case, an appreciable increase of the gaskinetic pressure of the plasma is observed. Figure 5 shows two superimposed diamagnetic-signal oscillograms, one of which (a) shows the variation of the gaskinetic pressure of the plasma under the influence of the ICW only, and the other (b) under the influence of simultaneous action of the ICW and the electron beam. The arrows denote the duration of the electron-beam injection.

The dependence of the gaskinetic plasma pressure increment $\Delta(nkT_\perp)$ during the time of the action of the beam on the external magnetic field also has a resonant character (Fig. 6) and the maximum of $\Delta(nkT_\perp)$ coincides with the maximum of the ICW amplitude. When the ICW amplitude is decreased, $\Delta(nkT_\perp)$ decreases and practically disappears (at an unchanged oscilloscope gain) when the wave amplitude is equal to zero. At a constant ICW amplitude, the value of $\Delta(nkT_\perp)$ increases with increasing current of the injected electron beam (Fig. 7). The results can be attributed to the fact that when the frequency of the transverse wave coincides with one of the harmonics of the electron-cyclotron frequency (this takes place when $\omega_{pe} \approx n\omega_{He}$), this wave should be effectively absorbed in the plasma, causing a decrease of its radiation and a simultaneous heating of the plasma. Numerical estimates show that the increment of the gaskinetic pressure and the decrease of the microwave radiation from the plasma occur at $\omega_{pe} \approx 2\omega_{He}$. The plasma density does not change in this case and the increment of the gaskinetic pressure can be attributed to the increment of the electron temperature: $\Delta(nkT_\perp) = n_e k \Delta T_{e\perp}$. It follows therefore that in this case the electron temperature should reach a value ~ 300 eV.

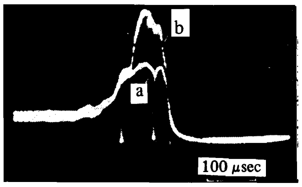

FIG. 5. Oscillograms of diamagnetic signals.

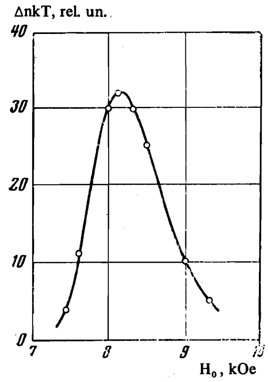

FIG. 6

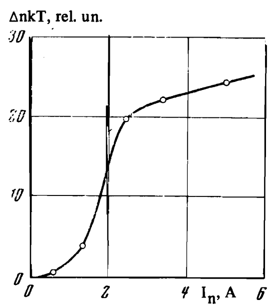

FIG. 7

FIG. 6. Dependence of the increment $\Delta(nkT_\perp)$ of the diamagnetic signal on the value of the constant magnetic field.

FIG. 7. Dependence of $\Delta(nkT_\perp)$ on the beam current.

BRIEF SUMMARY OF RESULTS

1. When an electron beam is injected into a plasma in which external high-frequency currents have excited an intense ICW, the beam-excited Langmuir oscillations are effectively transformed by the ICW in a nonlinear fashion into transverse oscillations with $\omega \approx \omega_{pe}$.

2. When the frequencies of the produced transverse waves are far from the electron-cyclotron frequency, a powerful microwave radiation is emitted from the plasma, with the same polarization as of the extraordinary wave ($\mathbf{E} \perp \mathbf{H}_0$). The amplitude of the microwave radiation is modulated at low frequency as a result of the existence of low-frequency oscillations of the plasma density.

3. When the transverse-wave frequencies are close to harmonics of the electron-cyclotron frequency ($\omega \approx \omega_{pe} \approx n\omega_{He}$), the transverse waves are effectively absorbed in the plasma, and this leads to a vanishing of the microwave radiation from the plasma and to an appreciable increase of the gaskinetic plasma pressure as a result of electron heating.

4. The investigations indicate that combined plasma heating by simultaneous action of ICW and an electron beam is effective.

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