INTERACTION OF ELECTRON AND ION BEAMS WITH A POTASSIUM PLASMA

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Numerous theoretical and experimental works have been devoted to the interaction of charged-particle beams with a plasma [1]. Practically all the experiments with electron beams, however, have been performed with plasmas produced by the beam itself. There have been no experiments with fast ion beams ($v_{0i} \gg v_{Te}$, where v_{Te} is the thermal velocity of the plasma electrons).

In this paper we investigate the interaction of electron and proton beams with a highly ionized potassium plasma created independently of the beam.

Description of the apparatus. A diagram of the apparatus is shown in Fig. 1. The vacuum chamber is a water-cooled stainless steel tube 1 15 cm in inside diameter and 144 cm in length. The tube is connected with vessel 2 by flange 3, which has a window with a moveable shutter and a "gradient tube" 4. When the shutter is closed and the pressure in vessel 2 is 10^{-5} Torr the pressure in the tube can be brought to 10^{-2} Torr by regulation of inleakage. This means that the apparatus can be used for work with a plasma produced by the beam itself. The working pressure in the tube with the shutter open and no inleakage is $1 \cdot 10^{-6}$ Torr.

The magnetic field, directed along the tube axis, is produced by coil system 5. The coils are powered by current pulses ~15 msec in duration. The magnetic field can be varied from 0.6 to 6 kOe. The field inhomogenety along the axis does not exceed 2%. The length of the homogeneous field region is ~100 cm.

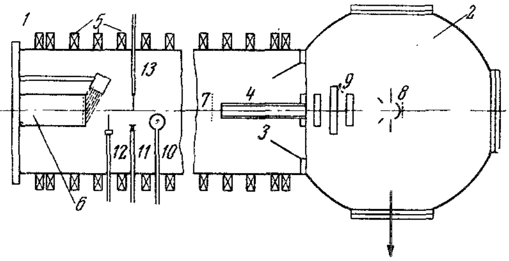

Fig. 1. Diagram of the apparatus: 1) tube; 2) vessel with electron (ion) gun; 3) connecting flange; 4) "gradient tube"; 5) magnetic field coils; 6) ionizer with potassium atomizer; 7) movable tungsten grid; 8) electron (ion) gun; 9) lens of electron (ion) gun; 10) magnetic probe; 11) dipole probe; 12) stub probe; 13) Langmuir probe.

The alkaline plasma is produced by thermal ionization of potassium vapor on tungsten ionizer 6; 4 cm in diameter, at a temperature of ~2000° K. The ionizer is situated in the homogeneous field region. The plasma column is limited in length by movable grid 7, which is usually ~50 cm from the ionizer. A potential equal to that of the plasma is applied to the grid. The plasma density is greatest on the axis and decreases radially. The distribution of plasma density by radius and length is shown in Figs. 2 and 3. The plasma densities in the experiments ranged from $1 \cdot 10^9$ to $7 \cdot 10^{10}$ cm^3 (the density was measured on the column axis at 10 cm from the ionizer).

The electron beam is produced by a three-electrode gun, mounted in vessel 2 outside the magnetic field. The gun produces electron pulses of 100 μsec. The beam energy is 2-23 keV and the maximum current in the ionizer region is ~300 mA (current density ~1 mA/cm^2). The beam diameter is 6 mm, and the energy spread, determined by means of an electrostatic analyzer, is ~1%. The displacement of the beam relative to the tube axis, determined with a fluorescent screen, does not exceed 2 mm.

In work with ion beams the electron gun is replaced by a particular ion source. One of them—a pulsed hydrogen-arc source, developed under the supervision of G. I. Dimov—had the following parameters: beam energy 1.5-6 keV, current in ionizer region 20 mA (current density ~40 mA/cm^2), beam diameter 7-8 mm, and pulse length 100 μsec. The second source—a "duoplasmatron"—had the following parameters: beam energy 20-50 keV, current in ionizer region 30 mA (current density ~40 mA/cm^2), beam diameter 9-10 mm, and pulse length 100 μsec. In both cases the beam was injected exactly along the axis.

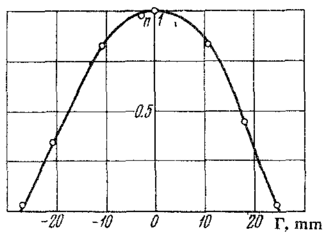

Fig. 2. Radial distribution of plasma density n in relative units.

The plasma density was measured with single Langmuir probes 13, which could be moved in a radial direction.

The high-frequency oscillations in the plasma were measured by stub, dipole, and magnetic probes 10-12. As measuring receivers we used P5-1-P5-7 receivers, which cover the frequency range of 20-7000 mHz and have a sensitivity of 10^{-11} to 10^{-12} W, as well as a selective amplifier, which could measure frequencies in the 0.5-25 mHz range and had a sensitivity of 10^{-12} W.

Experimental Results. It has been shown in several investigations of the interaction of an electron beam with a plasma [2-6] that instability at the electron-cyclotron frequency is excited in a low-density plasma formed by a beam ($\omega_{0e} < \omega_{He}$). Excitation occurs in a limited region of magnetic fields and beam energies. As a control experiment we repeated the experiment in [2], whose parameters were: beam energy 1-4 keV, current 50 mA, beam diameter 5 mm, magnetic field 500-2000 Oe, pressure 10^{-2} to 10^{-3} Torr, and legnth of interaction region $L \leq 40$ cm.

The parameters of our experiment were: beam energy 3 keV, current 50 mA, diameter 6 mm, magnetic field 600-2500 Oe, pressure $4-6 \cdot 10^{-3}$ Torr, and length of the interaction region 50 cm. Practically the only difference was that the beam was pulsed, with a pulse length of 100 μsec.

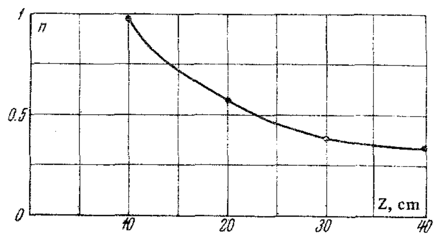

Fig. 3. Distribution of plasma density n by length z; z = 0 is the coordinate of the ionizer.

We obtained satisfactory agreement with the experiment in [2]. In fact, in the range of magnetic fields from 1-2.5 kOe we observed excitation of the cyclotron frequency in a certain region of frequencies and close to it. A typical oscillation spectrum is shown in Fig. 4. The maximum amplitudes, measured by the stub probe (length 6 mm, diameter 0.5 mm), reached 0.5 mW in the region of the beam axis (the passband of the measuring receiver was 3 mHz). The plasma density was not measured in these experiments.

In the investigation of the interaction of an electron beam with a potassium plasma the parameters of the plasma and beam were chosen so that the following inequalities were satisfied: $v_0 \gg v_{Te}$, $n_0 \gg n_1$, $f_{He} > f_{0e}$.

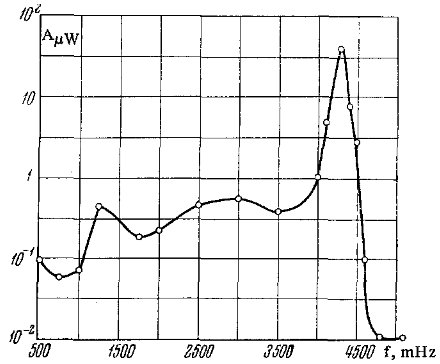

Fig. 4. Spectrum of oscillations of the beam plasma; H = 1.5 kOe, p = $4.1 \cdot 10^{-3}$ Torr, I = 60 mA, U_0 = = 3 kV.

Here $v_0 = 2.5–8.5 \cdot 10^9$ cm/sec is the electron-beam velocity (2–23 kV); $v_{Te} = 2.4 \cdot 10^7$ cm/sec is the thermal velocity of the plasma electrons; $n_1 = 1–3 \cdot 10^8$ cm^{-3} is the electron-beam density (I = 100 mA); $n_0 = 1–70 \cdot 10^9$ cm^{-3} is the plasma-electron density; $f_{0e} = 0.3–2.2 \cdot 10^9$ mHz is the Langmuir-plasma frequency; $f_{He} = 1.7–6 \cdot 10^9$ mHz is the electron-cyclotron frequency (H = 0.6–2.2 kOe).

In such conditions we might have expected excitation of cyclotron instability, as well as instability in the region of plasma frequencies [1,7,8]. Cyclotron instability actually was discovered at low magnetic fields (H < 1.2 kOe) and high energies (~18–20 keV) of the beam electrons. A continuous spectrum of lower frequencies, extending to 150 150–200 mHz, was excited simultaneously with the cyclotron frequency. Typical spectra are shown in Fig. 5. The relationship between the observed frequency of the peak and the magnetic field was in good agreement with the theoretical relationship (Fig. 6). The oscillations were localized close to the axis of the plasma column and occupied a region about 1 cm in diameter (Fig. 7).

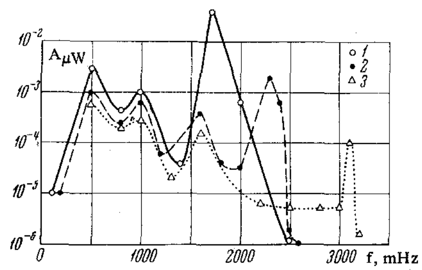

Fig. 5. Spectra of oscillations of alkaline plasma at different magnetic fields; $n_0 = 1.3 \cdot 10^{10}$ cm^{-3}, I = 60 mA, u_0 = 20 kV, 1) H = 0.6 kOe, 2) H = = 0.8 kOe, 3) H = 1.1 kOe.

The amplitude of the oscillations at cyclotron frequency increased with increase in the plasma density (Fig. 8) and in the beam current (Fig. 9), but decreased with increase in the magnetic field (Fig. 10). The maximum amplitudes observed in this experiment did not exceed 10^{-7} W (for the same probe and the same measuring receiver as in the case of the "beam" plasma).

By means of the movable grid, which limited the length of the plasma column, we were able to vary the column length from 66 to 34 cm. The relationship between the cyclotron-frequency amplitude A (in relative units), measured with the fixed stub probe, and the column length L in cm is shown in Fig. 11 (the probe was 20 cm from the ionizer). The figure shows a distinct periodicity in variation of the amplitude with column length; the period is $\lambda_H = v_0/f_{He}$.

We did not find characteristic frequencies, in the region of plasma frequencies or of multiples of them, which depend on the plasma density, despite the fact that in a search for the optimum conditions for their excitation we recorded families of spectral curves at different magnetic fields and electron-beam energies. The magnetic field was varied from 0.7 to 2.5 kOe at steps of 0.4 kOe and the beam energy was varied from 2.5 to 23 keV at steps of 3–4 keV. The plasma density was $1 \cdot 10^{10}$ cm^{-3} and the beam current was 60 mA. We did not find any changes in the nature of the spectra nor in the power of the emission. Typical spectra are shown in Fig. 12. The maximum amplitude did not exceed 10^{-9} to 10^{-10} W. With increase in plasma density the spectrum boundary shifts a little toward higher frequencies and the amplitudes of the oscillations increase slightly. With increase in beam current the amplitudes increase almost in proportion to the current.

In the investigation of the interaction of an ion beam with the plasma the conditions were the same as for the electron beam: $v_0 > v_{Te}$, $n_0 > n_1$, and $f_{He} > f_{0e}$ (in most cases).

Here $v_0 = 5 \cdot 10^7–1 \cdot 10^8$ cm/sec (energy 1.5–6 keV); $n_1 = 2.5 \cdot 10^9–5 \cdot 10^9$ cm^{-3} (current 20 mA); $v_0 = 1.8 \cdot 10^8–2.8 \cdot 10^8$ cm/sec (energy 20–50 keV); $n_1 = 9 \cdot 10^8–14 \cdot 10^9$ cm^{-3} (current 30 mA); $n_0 = 2 \cdot 10^{10}$ cm^{-3}; f_{0e} = 1400 mHz; f_{He} = 560–7000 mHz (200–2500 Oe).

We found no excitation of oscillations in the frequency range 3–4000 mHz.

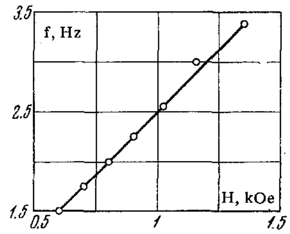

Fig. 6. Excited frequency as a function of magnetic field. The straight line is $f_{He} = eH/2\pi mc$, $n_0 = 1.2 \cdot 10^{10}$ cm^{-3}, I = 60 mA, U_0 = 20 kV.

A beam of faster ions (20–50 keV) excited relatively low-frequency oscillations (up to 2.5–3 mHz) with amplitudes of ~10^{-7} W in the plasma. These oscillations were not investigated in the experiment under consideration, but we can assume that they are due to ion-plasma frequencies.

Discussion of the results. Theoretical investigations by a number of authors of the interaction of a charged-particle beam with a plasma have shown that the plasma-beam system is unstable in relation to oscillations which usually are longitudinal and lie at frequencies close to the characteristic frequencies of the plasma, such as the electron-cyclotron frequency ω_{He}, the electron-plasma frequency ω_{0_0}, the "hybrid" frequency $(\omega_{He}\omega_{Hi})^{1/2}$, etc. [1]. The question of the interaction of a bounded beam with a plasma of the same diameter in a magnetic field was examined in [7]. The unbounded problem was

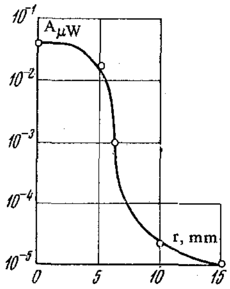

Fig. 7. Radial distribution of cyclotron-frequency amplitude; H = 0.6 kOe, $n_0 = 1.3 \cdot 10^{10}$ cm^{-3}; I = 60 mA, U_0 = = 20 kV.

discussed in [8]. It was shown in both cases that the instability-excitation mechanism can be the Cerenkov effect or an anomalous Doppler effect. The excited frequencies lie close to ω_{He} and ω_0 ($\omega_{He} > \omega_{0e}$). Similar conclusions were formed in [9] in an examination of the interaction of a "thin" beam with a plasma of large diameter. Since the oscillations in the case under consideration are concentrated in the region occupied by the beam we can legitimately use the solution obtained for a beam and plasma of equal diameter [7].

The expressions for the increments of the oscillations near ω_{0e} and ω_{He} for the two excitation mechanisms are:

condition for Cerenkov resonance $\omega \approx k_z v_0$

$$\operatorname{Im} \omega_{0e} \approx \left(\frac{\Omega_0^2 k_z^2 a^2}{\omega_{0e}^2 \lambda_p^2}\right)^{1/3} \omega_{0e} \approx n_0^{1/6} n_1^{1/3} k_z^{2/3},$$

$$\operatorname{Im} \omega_{He} \approx \left(\frac{\Omega_0^2 \omega_{0e}^2 k_z^2 a^2}{\omega_{He} \lambda_p^2}\right)^{1/3} \approx \left(\frac{n_0 n_1 H}{v_0^2}\right)^{1/3},$$

condition for Doppler resonance $\omega \approx k_z v_0 - \omega_{He}$

$$\operatorname{Im} \omega_{0e} \approx \frac{\Omega_0}{2}\left(\frac{\omega_{0e} k_z a}{\omega_{He} \lambda_p}\right)^{1/2} \approx \frac{n_0^{1/2} n_1^{1/2}}{v_0^{1/2}},$$

$$\operatorname{Im} \omega_{He} \approx \frac{\Omega_0}{2} \frac{\omega_{0e} k_z a}{\omega_{He} \lambda_p} \approx \frac{n_0^{1/2} n_1^{1/2}}{v_0},$$

where Ω_0 is the plasma frequency of the beam; k_z is the longitudinal component of the wave vector; v_0 is the velocity of the beam particles; λ_p is a numerical parameter on the order of 1 to 2.4; a is the beam radius.

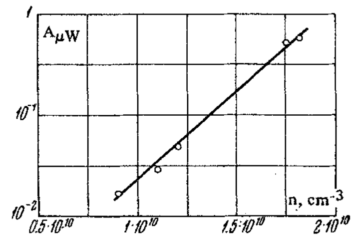

Fig. 8. Cyclotron-frequency amplitude as function of plasma density; H = 0.6 kOe, I = 60 mA, U_0 = 20 kV.

The numerical values of the increments for the parameters corresponding to our experiment have the same order of magntiude for all four cases: $\operatorname{Im}\omega \approx 1\text{–}5 \cdot 10^8$ sec^{-1}, and the ratio of the value of $\operatorname{Im}\omega_H$ for the Cerenkov mechanism to that of $\operatorname{Im}\omega_H$ for the Doppler mechanism is approximately 2.

Thus, we can expect excitation of oscillations in the regions of electron, cyclotron, and plasma frequencies.

In fact, we found that in the case of interaction of an electron beam with a potassium plasma, oscillations were excited in the region of the electron-cyclotron frequency in a fairly narrow interval $\Delta f \approx$ ≈ 100 mHz.

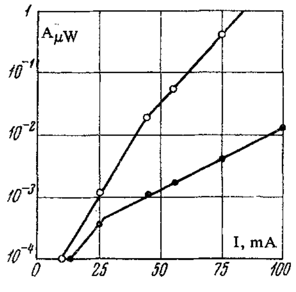

Fig. 9. Cyclotron-frequency amplitude as a function of beam current; U_0 = 20 kV, $n_0 = 9 \cdot 10^9$ cm^{-3}; 1) H = 0.6 kOe; 2) H = 1 kOe.

The wavelength of these oscillations was measured in an experiment which the length of the plasma column was altered. It is obvious that excitation of longitudinal oscillations in a system of bounded length will entail excitation of standing waves with a wavelength which satisfies the condition $L = n\lambda = n v_{ph}/f (n = 1, 2, 3, \ldots)$.

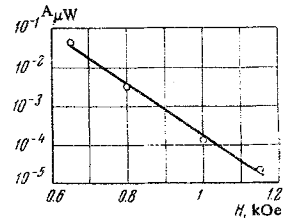

Fig. 10. Cyclotron-frequency amplitude as a function of magnetic field: $n_0 = 1.3 \cdot 10^{10}$ cm^{-3}, I = 60 mA, U_0 = 20 kV.

In our experiments with a given magnetic field the excited frequency was constant $f = f_{He}$. If L varies smoothly this condition can be fulfilled only when the phase velocity of the wave changes. However, when the phase velocity "drifts" from the beam-particle velocity the amplitude of the oscillations will decrease owing to reduction of the increment. When $\Delta L = \lambda$, i.e., $L - \Delta L = (n - 1)\lambda$, v_{ph} again approaches v_0 and the amplitude again increases to the maximum value Thus, the experimentally determined λ_H actually gives the wavelength. We found that $\lambda = v_0/f_{He}$ (measured value $\lambda = (4.6 \pm 0.4)$ cm, calculated $\lambda = 4.5$ cm), from which it follows that oscillations at the electron-cyclotron frequency are excited by the Cerenkov mechanism. We note that the weak dependence of the amplitude of the maxima on the column length can be due to the absolute nature of the instability, and this agrees with theoretical hypotheses [9].

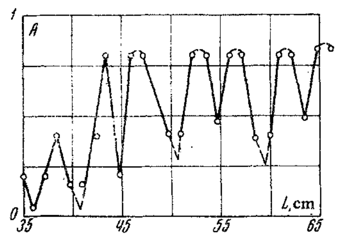

Fig. 11. Cyclotron-frequency amplitude as a function of column length: H = 0.6 kOe, $n_0 = 9 \cdot 10^9$ cm^{-3}; I = = 50 mA; U_0 = 19 kV.

We might have expected that variation in the oscillation amplitude with different parameters would correspond to variation in the increment with them. In fact, we found that, like the increment, the amplitude increased with increase in beam current and plasma density. However, variation in the amplitude with v_0 and H differed from that expected. Instability was observed only at high beam velocities (18–20 kV), whereas $\operatorname{Im} \omega_{He} \approx 1/v_0^{2/3}$. The amplitude of the oscillations decreased sharply with increase in the magnetic field, and $\operatorname{Im} \omega_{He} \approx H^{1/3}$.

In the region of plasma frequencies, according to [7, 9], oscillations will be excited in the region of ω_{0e} and below—$\omega \approx \omega_{0e} k_z a$ ($k_z a < 1$) with increasing increments as $\omega \to \omega_{0e}$. Above ω_{0e} the spectrum will be cut off fairly sharply.

In the experiment we observed excitation of oscillations in a very wide frequency region ($\Delta f \sim 800$ mHz), within which the plasma frequencies lie. In this region, however, we found no peaks whose frequencies might depend on the density. The observed peaks did not depend on any of the parameters (n_0, H, v_0, n_1) and presumbly depended on the frequency characteristic of the probes. The observed shift of the upper (fairly sharp) boundary of the spectrum with increase in density ($f^* \approx n_0^{1/6}$) was much less than expected ($f^* \approx n_0^{1/2}$).

We can postulate that the difference from theory in this case is due to the existence of a longitudinal gradient of plasma density, directed so that the beam moves toward an increase in density. In this case the change in ω_{0e} along the beam can be significant, and the excited waves can be reflected from the region of greater density. All this will lead to broadening and smoothing of the spectrum.

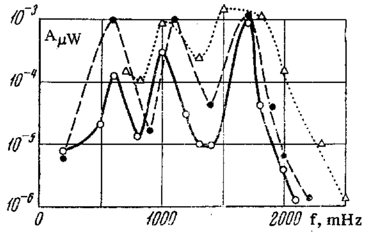

Fig. 12. Spectra of oscillations of alkaline plasma with different densities: H = 1.5 kOe; I = 80 mA; U_0 = 3.5 kV; 1) $n_0 = 9 \cdot 10^9$ cm^{-3}; 2) $n_0 = 1.7 \cdot 10^{10}$ cm^{-3}; 3) $n_0 = 7 \cdot 10^{10}$ cm^{-3}.

When an ion beam passes through the plasma the oscillations will develop with smaller increments due to the greater inertia of the beam ions (in the formulas given above Ω_{0e} is replaced by Ω_{0i}), but the increase in the oscillations along the beam (for convective instability) will be approximately the same as in the case of an electron beam, owing to the increase in the time of beam-plasma interaction. We cannot at present explain the absence of excitation of high-frequency oscillations in the experiment.

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