Instability of a narrow electron-beam interacting with a plasma

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The instability of an electron beam in a rarefied magnetized plasma is investigated experimentally. A special feature of the experiments is a very narrow electron beam (diameter, 0.03 cm), which provides extremely favorable conditions for the observation and identification of drift-type plasma instabilities. The "anomalous" plasma diffusion that appears when instability develops is investigated. Comparison of the experimental results with the theory shows that under the conditions of the experiments the escape of ions from the beam is due to their being accelerated transverse to the magnetic field by the fields of axially nonsymmetric electron-ion oscillations, which develop in the beam as a result of successive kinetic and hydrodynamic buildup of drift-beam instability.

INTRODUCTION

The phenomena accompanying the passage of a narrow electron beam through a plasma are of considerable interest to the plasma physicist: the interaction of such a beam with a plasma provides extremely favorable conditions for the observation and identification of drift-type instabilities. Interest in these phenomena is also stimulated by the wide range of applications of narrow beams in various areas of plasma physics and physical electronics.

The work reported here was an experimental study of the instability of an electron beam in a tenuous magnetized plasma, and of the "anomalous" diffusion transverse to the magnetic field of the positive ions produced by the ionization of the residual gas by the electron beam, whose axis was parallel to the magnetic field. Distinguishing features of these experiments are a very narrow beam (diameter, 0.03 cm) and low electron currents (10^{-6}-10^{-3} A) and ion currents (10^{-11}-10^{-10} A).

Many experimental studies of the interaction of charged-particle beams with plasmas have been devoted to the investigation of beam-instability thresholds (see [1,2] and the literature cited there). These thresholds manifest themselves in sudden (discrete) changes in the characteristics of the plasma–beam system. In each particular case, knowledge of the threshold enables one to identify the type of the developing instability and, what is especially important for us, to determine the nature of the phenomena accompanying the passage of the beam through the plasma.

Our initial assumption was that the investigated phenomena might be associated with collective processes, in particular, with definite electromagnetic oscillations excited in the plasma by the electron beam. In the present work, therefore, we attempted to detect such oscillations and to investigate their relationship to the ion flux transverse to the magnetic field.

APPARATUS

Our apparatus (Fig. 1) was based on the omegatron design[3]. The electrons, emitted by a directly heated tungsten cathode, were accelerated to an energy $W = eU_{acc}$ in the electrostatic field between the cathode and the diaphragm to form a beam whose diameter, limited by the hole in the diaphragm, was 0.03 cm. The beam entered and left a cubical chamber having grounded metallic walls through two 0.1 cm diameter holes, one in the center of each of two opposite walls. The beam was 2 cm long, its length being nearly equal to that of an edge of the cube. The beam current was regulated by varying the cathode heating power. The anode (electron collector) was maintained at a potential of several tens of volts. A uniform magnetic field of strength $H \approx 3000$ Oe was applied in the direction of the beam.

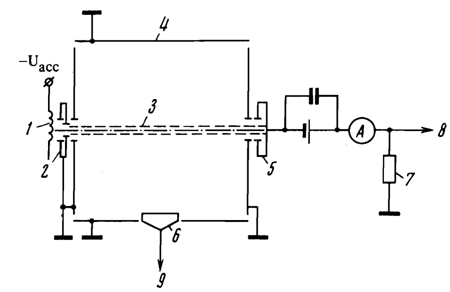

FIG. 1. Diagram of the apparatus: 1—cathode, 2—diaphragm, 3—beam, 4—equipotential region, 5—anode, 6—probe, 7—resistor, 8—to the spectrum analyzer, 9—to the electrometer amplifier.

The entire system was mounted in a vacuum chamber, which was pumped down to 5×10^{-8} mm Hg. The pressure in the chamber was regulated by admitting argon.

To measure the ion current we used a plane ion collector[4] of radius 0.85 cm mounted parallel to the beam with its center in the perpendicular bisector of the beam and at a distance of 0.85 cm from the beam axis. For brevity we shall call this ion collector the "probe." The probe current was measured with an electrometer amplifier.

We used a type S4-8 panoramic spectrum analyzer in conjunction with a broadband amplifier to observe the spectra of the oscillations generated in the plasma–beam system. The spectra of the oscillations were measured in both the anode and the probe circuits.

RESULTS AND DISCUSSION

One well known indicator of the state of a beam is the amplitude of the electron-ion oscillations that develop in it.[1,5] The purpose of the present experiments was to detect such oscillations in the omegatron beam plasma and to investigate their relationship to the ion current transverse to the magnetic field. The ion cur-

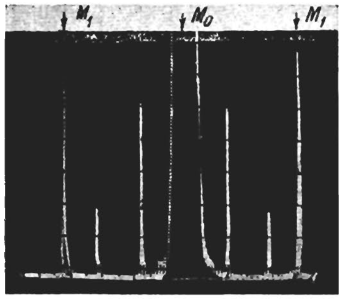

FIG. 2. Spectrum of the electron-ion oscillations in the anode current. Argon, $p \approx 6 \times 10^{-6}$ mm Hg, $U_{acc} = 150$ V, $U_a = 15$ V, I = 350 μA. M_0 and M_1 are frequency markers indicating frequencies of 0 and 700 kHz, repsectively.

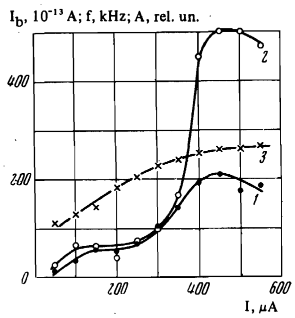

FIG. 3. The probe current I_b (curve 2) and the amplitude A (1) and frequency f(3) of the electron-ion oscillations in the anode current as functions of the beam current I. Argon, $p \approx 6 \times 10^{-6}$ mm Hg, $U_{acc} = 150$ V, $U_a = 15$ V.

rent to the probe, which for brevity we shall call the "background current" and denote by I_b, serves as a measure of the transverse ion current.

Figure 2 shows a typical spectrum of the oscillations observed in the anode circuit. In this case the spectrum consists of a continuum in the low-frequency region, together with a fundamental frequency of ~250 kHz and its first harmonic at twice that frequency. As the beam current is gradually increased, the low-frequency continuum first broadens somewhat, and then there appear oscillations whose frequencies lie between 100 and 500 kHz and satisfy the condition

$$\omega_{Hi} < \omega < k_z v,$$

where ω_{Hi} is the ion Larmor frequency, k_z is the longitudinal wave number, and v is the velocity of the beam electrons. The lines in the spectrum broaden somewhat with increasing beam current. As the pressure is raised, the frequency of the oscillations increases appreciably, harmonics of the fundamental frequency appear, and the lines broaden substantially.

In Fig. 3 we have plotted the background current I_b, as well as the frequency f and the amplitude A of the fundamental harmonic of the oscillations in the anode circuit against the electron current I. The frequency of the oscillations is roughly proportional to $\sqrt{I}$, while the amplitude of the oscillations and the background current are strongly correlated, both rising in two stages. Raising the positive potential U_a of the electron collector increases the threshold current at which the oscillations appear (~50 μA under the conditions of Fig. 3). At low pressures (~10^{-6} mm Hg) the first stage (at $50 < I < 300$ μA in Fig. 3) is lacking.

The observed oscillations can be identified with the axially nonsymmetric electron-ion oscillations investigated by Nezlin and Solntsev[1,5,6]. In fact, the strength H of the magnetic field of the omegatron satisfies the conditions

$$\omega_{He} \gg \omega_1, \quad \omega_{Hi} \ll \omega \ll \omega_{He},$$

where ω_{Hi} is the ion Larmor frequency, ω_{He} is the electron Larmor frequency, ω_1 is the Langmuir frequency of the beam electrons, and ω is the frequency of the electron-ion oscillations excited in the beam.

The quasineutrality of the electron beam in a field of this strength is unstable against both axially symmetric and axially nonsymmetric electron-ion oscillations, which lead respectively to the development of electron-ion[7] and drift-beam[8] instabilities. These instabilities develop only when the beam current reaches certain critical (threshold) values I_{cr}, which are given by the following expressions:

$$I_{cr} \approx \frac{mr^2}{4e} k^2 v^3 \Big/ \left[1 + \left(\frac{mk^2}{Mk_z^2}\right)^{1/3}\right]^3, \qquad (1)$$

for the excitation of axially symmetric electron-ion oscillations[1], and

$$I_{cr} \approx \frac{mr^2}{4e} k^2 v^3 \left(1 + \frac{2k_\varphi v}{r\omega_{He} k_z}\right)^{-1}, \qquad (2)$$

for the excitation of oscillations that are not axially symmetric[6]. Here and below, v is the velocity of the beam electrons, k is the total wave number, k_z, k_φ, and k_r are the longitudinal, azimuthal, and radial wave numbers, r is the radius of the beam, m is the electron mass, M is the ion mass, and L is the length of the beam.

Under the geometric conditions of our experiments, $k_z^2 = (2\pi/\lambda_z)^2 \approx (\pi/L)^2 \approx 2.5$ cm^{-2}, $k_\varphi^2 \approx 1/r^2 \approx 4.5 \times 10^3$ cm^{-2}, $k_r^2 \approx 1/r^2 \ln(\lambda_z/2\pi r)^{1/2} \approx 2.4 \times 10^3$ cm^{-2}, and $k^2 = k_z^2 + k_r^2 + k_\varphi^2 \approx 7 \times 10^3$ cm^{-2}.

We note that expressions (1) and (2) for the critical currents are valid for a system of charged particles consisting of just two components: fast beam electrons, and an equal number of slow ions; i.e., these expressions are valid for a quasineutral electron beam. In our experiments, the criterion for quasineutrality (see, for example,[9] or [1]) is satisfied at argon pressures below 10^{-4} mm Hg.

On calculating the critical currents with formulas (1) and (2), respectively, we find that under our experimental conditions the threshold (2) is considerably smaller than (1).

Nezlin and Solntsev[6] have shown that $I_{cr}^{(2)}$ can be identified with fair accuracy with the limiting beam current.

Under the "extreme" conditions of our experiments the threshold current I_{cr} for the appearance of instability is considerably smaller than the limiting vacuum current[10]. Hence the beam should not be suppressed at $I \geq I_{cr}$. The observed limitation of the beam current at $I \geq I_{cr}$ is due to the fact that the beam expands under the action of the fields of the electron-ion oscillations, so that it is not possible for the entire beam to pass through the hole in the diaphragm and part of the beam current is carried off by the diaphragm itself. This is illustrated in Fig. 4, where the amplitude of the oscillations as measured in the probe circuit, the beam current in the omegatron anode circuit, and the electron current to the end faces of the equipotential chamber are shown as functions of the cathode heating current for a typical case. It will be seen that the onset of oscillations is accompanied by a drop in the beam current and a sharp rise in the electron current to the end diaphragms. It is in this sense that a maximum obtainable omegatron

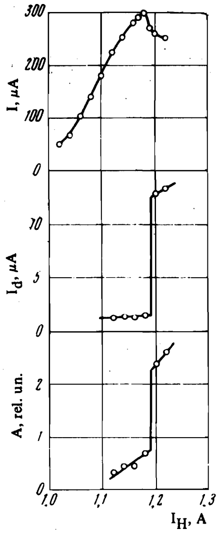

FIG. 4

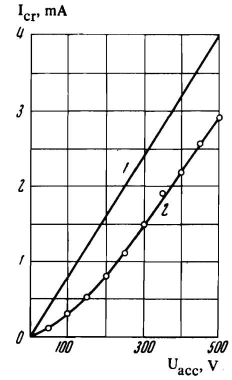

FIG. 5

FIG. 4. Amplitude of the oscillations in the probe circuit (A), electron current to the end diaphragms (I_d), and electron current in the anode circuit (I) as functions of the cathode heating current (I_H). Argon, $p \approx 5 \times 10^{-5}$ mm Hg, $U_{acc} = 90$ V, $U_a = 20$ V.

FIG. 5. Theoretical (1) and experimental (2) curves for the limiting current as a function of the energy of the beam electrons.

beam current can be regarded as indicating the development of instability.

Figure 5 shows the theoretical (expression (2)) and experimental dependences of I_{cr} on the energy of the beam electrons. As the experimental limiting current we took the maximum electron current in the omegatron reached on gradually increasing the cathode heating power. Under the geometric conditions of our experiments, this maximum electron current can differ from the current at which strong buildup of oscillations is observed by as much as 25%, depending on the parameters of the system. Under our experimental conditions, the observed limiting current for a given energy of the beam electrons is independent of the gas pressure over the range from 10^{-7} to 5×10^{-4} mm Hg.

In view of the approximations involved in formula (2), the agreement between the theoretical and experimental curves on Fig. 5 can be regarded as satisfactory. This provides grounds for concluding that under our conditions the limitation of the beam current on gradually increasing the cathode heating power is due to drift-beam instability.

The above conclusion is also confirmed by the observed oscillations, whose spectral characteristics are those of axially nonsymmetric electron-ion oscillations[1,6]. The facts that increasing U_a increases the threshold current at which oscillations appear and that the instability develops in two stages are also consistent with the above conclusion. In fact, the two-stage development of the drift-beam instability is due to successive kinetic and hydrodynamic buildup of electron-ion oscillations[5], and since secondary electrons ejected from the collector by the beam electrons play a decisive role in the kinetic buildup[5], increasing U_a (i.e., decreasing the secondary electron current) increases the beam current at which kinetic buildup of the oscillations sets in.

The behavior of the background current illustrated in Fig. 3 can also be explained without difficulty in terms of the ideas presented above. The excitation of electron-ion oscillations in a quasineutral beam is accompanied by acceleration of ions transverse to the magnetic field[5], and this leads to "anomalous" diffusion of the ions to the walls of the chamber. One would naturally expect the ion flux transverse to the field to be the greater, the higher the energy to which the ions are accelerated. Hence the correlation between the amplitude of the oscillations and the strength of the background current, which is a measure of the ion flux to the probe, can be understood, since the transverse energy of the ions depends directly on the amplitude of the oscillations developing in the beam (because of stochastic acceleration)[5].

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