COLLISIONLESS HEATING OF PLASMA IONS BY AN ION BEAM

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The possible use of an ion beam for the collisionless heating of plasma ions is considered. It is shown that the ion temperature can be increased to a value comparable with the electron temperature through the excitation of high-intensity low-frequency oscillations by an ion beam in a plasma-beam discharge.

THE turbulent heating of plasma is of major scientific and practical importance. This method of heating is based on the nonlinear interaction of waves with plasma particles. One of the most promising collective heating mechanisms is the ion-acoustic instability which arises in plasma, for example, during the flow of a current. This instability can also be effectively excited by an ion beam if the beam velocity u is not much greater than the velocity of nonisothermal ion sound, $c_s \sim (T_e/M)^{1/2}$ (T_e is the electron temperature and M is the ion mass). The interaction between an ion beam and plasma under these conditions is accompanied by the effective dissipation of the beam energy and momentum, and this was discussed in our previous papers.[1-3] In the present report we shall investigate the conditions under which this interaction will lead to the heating of plasma ions.

APPARATUS

The ion-acoustic instability can effectively develop in a plasma containing hot electrons. In our experiments we used a plasma-beam discharge in a uniform magnetic field. The apparatus is illustrated schematically in Fig. 1. The discharge was produced in a grounded metal vacuum chamber 8 (diameter 10 cm) placed in a magnetic field H = 700–1600 Oe. The electron-beam source was the hot cathode 3 separated from the working volume by the collimator 4 (length 7 cm, diameter 1.2 cm). For a beam energy of 100–200 eV, determined by the cathode potential, and an electron current of 5–50 mA in a column 20 cm long (without taking into account the collimator length), it is possible to generate plasma with a density of $n = 10^9–10^{10}\ \mathrm{cm}^{-3}$. The electron temperature was regulated by varying the neutral-gas pressure p (argon). The region in which the electrons were heated corresponded to the pressure range $2 \times 10^{-5}–10^{-4}$ mm Hg, and the T_e maximum (~50 eV) was reached at $p \sim 4 \times 10^{-5}$ mm Hg. The conditions under which the electrons become heated in a discharge of this kind were discussed earlier.[4] A monoenergetic beam of potassium ions was injected into the plasma produced in this way. The ion source was a heated porous-tungsten emitter 1 containing a potassium reservoir. The ions were collected from the emitter surface by the field due to the high-transmission plane grid 2 kept at a negative potential of 300--400 V. This arrangement also prevented the incidence of plasma electrons on the ion emitter. The ion current was introduced into the plasma column through the discharge cathode 3 which is in the form of a series of tungsten wires 100 μ in diameter and 1 mm apart. The beam energy ϵ was determined by the potential difference between the ion emitter and the plasma. The beam current was usually in the range I = 0.5—1 mA and the initial energy could be varied in the range ϵ = 0—1 keV. The electrostatic analyzer 7 which defined the length of the plasma column could be used to control the effectiveness of the interaction (the change in the distribution function) between the ion and electron beams. The moveable probe 6 was used to investigate the plasma parameters and the low-frequency spectra of the excited oscillations. A broadband amplifier (input capacitance 500 pF(and the S4-8 analyzer were employed. The three-electrode electrostatic analyzer 5 placed on the boundary of the plasma column over its central region was designed to measure the distribution of the radial component of the plasma-ion velocity. The diameter of the entrance aperture of the analyzer was 7 mm, the distance between the electrodes (first grid, ion retarding grid, and collector) were 3 mm apart. The "transverse" ion temperature T_i was determined from the slope of the semilogarithmic plot of the collector current as a function of the retarding potential. The resolution of the analyzer was ~3 eV. The analyzer 5 was so designed that ions in the beam could not reach the collector.

RESULTS

The injection of an ion beam into plasma is accompanied by the excitation of a spectrum of ion-acoustic oscillations (Fig. 2). In this frequency region one also observes independently the natural oscillations in the discharge, which are in the form of narrow peaks (frame 1) frequently accompanied by harmonics. Frames 1--7 (Fig. 2) demonstrate the development of

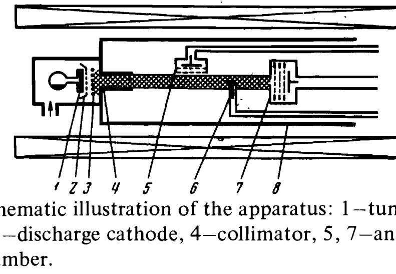

FIG. 1. Schematic illustration of the apparatus: 1—tungsten emitter, 2—electrode, 3—discharge cathode, 4—collimator, 5, 7—analyzer, 6—probe, 8—vacuum chamber.

the ion-acoustic spectrum generated by the ion beam along the length of the beam. The flight distance is indicated without taking into account the length of the collimator. It is clear that the instability has a convective character. Up to distances of about 10 cm the oscillation amplitude increases exponentially. For example, for f = 500 kHz, which corresponds to the maximum growth rate γ, the spatial growth constant is $l \approx 4$ cm, i.e., $\gamma \approx u/l = 9 \times 10^5 \text{ sec}^{-1}$. When $f \lesssim \gamma$, the nonlinear oscillation region is rapidly reached. The growth in the amplitude in the frequency region corresponding to maximum γ then terminates, and the oscillation energy density is redistributed over the spectrum in the direction of decreasing frequency. This type of development of the frequency spectrum of ion-acoustic noise is qualitatively consistent with the prediction of the weak-turbulence theory.[5]

We have investigated the variation of the plasma-ion temperature T_i, measured with the analyzer 5 (Fig. 1), during ion-beam excitation of ion-acoustic oscillations. The thermal energy of the ions under conditions corresponding to the heating of electrons in the plasma-beam discharge was 10–15 eV. By injecting the ion beam into the plasma the temperature T_i could be increased by a substantial factor. Figure 3 shows the ion temperature as a function of the ion-beam energy. The parameter is the neutral-gas pressure which determines the electron temperature. These curves are smooth and exhibit a peak. As the neutral-gas pressure is reduced from 10^{-4} to 3×10^{-5} mm Hg there is an increase both in the maximum T_i and in the ion-beam energy range in which there is heating of the plasma ions. Figure 4 shows the ion temperature corresponding to the peak of the $T_i = T_i(\epsilon)$ curve as a function of the gas pressure in the interaction region. An appreciable increase in the ion temperature occurs only in a relatively narrow gas-pressure range. As was shown earlier,[4] the maximum values of T_e are reached in this range for the plasma-beam discharge we have investigated. The interaction between an ion beam and plasma containing hot electrons may thus lead to the heating of the ion component to a temperature comparable with the mean thermal energy of the electrons.

Probe measurements have shown that the heating of ions is accompanied by a reduction in the plasma density on the column axis. Under these conditions the ratio of the alternating to the constant components of the saturation ion current received by the probe, i.e., the amplitude of the oscillations in the ion density, may reach $\tilde{n}/n = 0.5-1$. A change in the magnetic field within the range indicated above had practically no effect on the oscillation spectra excited by the ion beam or the degree of heating of the ions.

CONCLUSIONS

The heating of the plasma ions in the experiments described above is connected with the electric field of the excited ion-acoustic oscillations. By using an ion beam with a velocity $u \sim c_s$, which excited an instability with a large growth rate ($\gamma \gtrsim f$), we have succeeded in reaching the nonlinear region of oscillation development which is characterized by a high degree of density modulation. The heating of plasma ions and electrons under the conditions corresponding to a developed ion-acoustic spectrum is discussed in the theory of anomalous resistance,[5-10] but the problem cannot be regarded as completely resolved at present. The possibility of increasing the plasma-ion temperature during the relaxation of an ion beam is determined in the first instance by the energy balance, i.e., by the energy taken by the ions from the beam and the energy removed by the ions from the system. The experimental conditions were such that the mean free path of charged particles for binary collisions (Coulomb, charge transfer, elastic scattering) was much greater than the length of the plasma column. The energy w_i removed by ions from the plasma can be estimated on

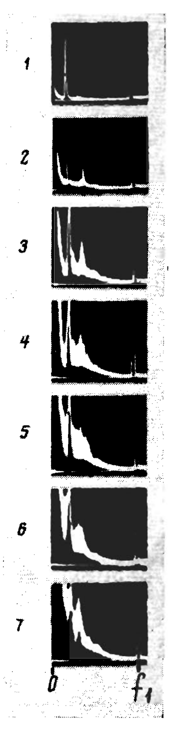

FIG. 2. Spectra of oscillations recorded at different distances along the path of the iom beam (in cm): 1) 2, 2) 6, 3) 10, 4) 12, 5) 14, 6) 18, 7) 20. f_1–2 MHz frequency marker, ϵ = 300 eV, p = 4 X 10^{-5} mm Hg.

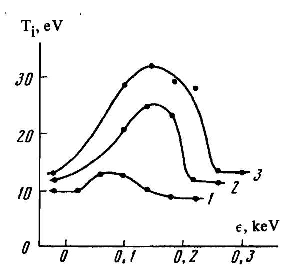

FIG. 3

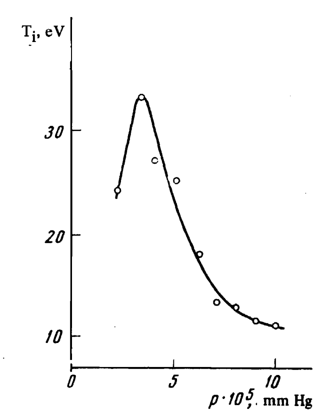

FIG. 4

FIG. 3. Ion temperature as a function of the ion-beam energy. Curves 1, 2, 3 correspond to pressures of 7.1 X 10^{-5}, 5.1 X 10^{-5}, and 3.4 X 10^{-5} mm Hg, respectively.

FIG. 4. Ion temperature as a function of the neutral gas pressure in the plasma column.

the assumption of their collisionless escape with the thermal velocities along the magnetic field, and isotropic T_i. The lifetime of an ion in the plasma column is then $\tau \sim L/2v_i$, $v_i = (T_i/M)^{1/2}$, i.e., the thermal-energy flux at the ends of the system is given by

$$w_i = {}^3/_2 nLST_i / \tau = 3nv_i ST_i,$$

where L is the length and S the effective cross section of the plasma column. This estimate does not take into account energy losses connected with the leakage of ions across the magnetic field toward the walls of the discharge chamber. The ratio of w_i to the initial energy of the ion beam $w_0 = I\epsilon/e$ (e is the ion charge) under typical experimental conditions (T_i = 30 eV, $n = 3 \times 10^9$ cm^{-3}, I = 0.7 mA, ϵ = 150 eV, S = 3 cm^2) is close to unity. At the same time, the total energy losses of the ion beam in the plasma which were determined from the shape of the beam distribution function at exit from the column do not exceed 50%, and a substantial fraction of the energy of the excited low-frequency oscillations may be absorbed by electrons.[7] It follows that to explain the observed plasma ion heating one must assume the presence of an additional energy source for the oscillations, i.e., a source other than the ion beam. In our system, this source was the electron beam. The electron beam in the plasma-beam discharge generates high-frequency oscillations which are responsible for the ionization of the gas and the heating of the plasma electrons. Theory predicts[11-13] that nonlinear processes involved in the interaction between the plasma and ion-acoustic waves can transfer the energy into the low-frequency oscillation region and may substantially modify the dispersion of the oscillations. In particular, such processes lead to an increase in the phase velocities of the low-frequency waves, i.e., to a reduction in the kinetic damping of the waves by ions. This provides an explanation of the observed state of plasma with $T_i \sim T_e$ under the conditions of developed oscillations of the ion-acoustic type.

Our work has thus shown that it is, in principle, possible to obtain plasma with hot electrons and hot ions by the simultaneous longitudinal injection of electron and ion beams into a magnetic system.

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