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DIFFUSION OF A COLLISIONLESS POTASSIUM PLASMA ACROSS A MAGNETIC FIELD IN THE PRESENCE OF A DRIFT INSTABILITY

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A method is proposed for the measurement of the transverse diffusion coefficient of a collisionless plasma; the method is based on the measurement of the longitudinal plasma flux. Experiments carried out on a Q-machine have shown that drift instabilities lead to an anomalous loss of plasma from the system. The diffusion coefficient varies as 1/H and is the same order of magnitude as the Bohm value.

A large number of papers in the literature are concerned with the investigation of drift or universal instabilities and the associated diffusion of plasma across a magnetic field.[1-3] The direct measurement of the absolute value of the diffusion coefficient is difficult and has been frequently found to depend on the method of measurement. At the present writing it appears that there does not exist a reliable method for the determination of the diffusion coefficient. For this reason it is of interest to investigate various indirect methods, one of which is considered in detail in the present paper.

1. The method proposed here consists in the determination of the transverse diffusion flux from measurements of the radial density distribution at various cross-sections along the length of the plasma column. Using the equation of continuity and neglecting recombination, we can express the transverse flux density as follows:

$$j_\perp = \frac{1}{r}\int_0^r \frac{\partial}{\partial z}(nu)\, r\,dr. \qquad (1)$$

On the basis of the results in [4] we assume that the plasma flow rate $u(r, z) = \sqrt{2T_i/M_i}$ is constant in all cross sections. Thus

$$j_\perp(r, z) = \sqrt{\frac{2T_i}{M_i}}\,\frac{1}{r}\int_0^r \frac{\partial n(r, z)}{\partial z}\, r\,\partial r. \qquad (2)$$

By measuring the radial density distribution in various cross sections it is a straightforward matter to obtain the numerical value of $j_\perp$ from (2). Thus, the method proposed here makes it possible to determine the diffusion coefficient $D_\perp = (\partial n/\partial r)^{-1}$ at a given point specified by r and z.

In the course of an experiment a supplementary estimate of the diffusion coefficient can be obtained by a method similar to that used in [1,3]. For this purpose one makes use of a special device which measures the diffusion flux $j_\perp$ at the edge of the plasma column.

2. The experiments have been carried out on a Q-machine [5,6] (Fig. 1a), in which the plasma is produced by thermal ionization of potasium vapor on a tungsten plate heated to 2000°K. The plasma column is 3 cm in diameter and 105 cm long and is located in an axial magnetic field which can be

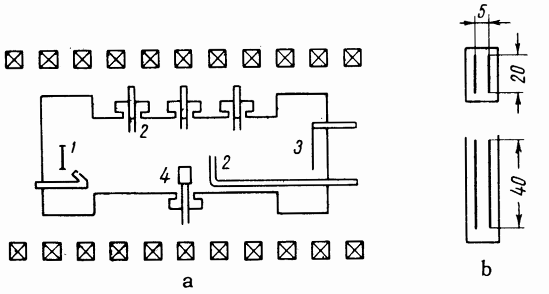

FIG. 1. a) Diagram of the apparatus: 1) plasma source; 2) double probes, 3) copper plate at floating potential, 4) device for measuring the flux $j_\perp$; b) device for measuring the flux $j_\perp$.

varied from 0 to 4.5 kOe. The experiments have been carried out with a low-density plasma $l \gg L$ (l is the mean free path and L is the length of the apparatus). The plasma column is bounded at the ends by a tungsten plate (plasma source) and by a cold copper plate which is at floating potential.

In the course of the experiment we have investigated the low-frequency noise in the plasma potential. The diffusion coefficient is measured simultaneously by the two methods described above. The plasma density and electrostatic noise are recorded by means of one of the two double floating probes. In measuring the plasma density account is taken of the enhancement of the effective probe area[7] because at low values of the density the Debye radius becomes comparable with the probe diameter. The probes are molybdenum wires (0.2 mm) with an open length of 5 mm which are separated from each other by a spacing of 5 mm; the probes are sealed into glass tubes. In some of the experiments we have used probes with electrode lengths of 2 mm. The noise signal from the probe is observed with a standard spectrum analyzer (ASChKh-1 or SCh-8); use has also been made of a tuned microvoltmeter (V6-2).

By means of the electric probe it is possible to measure the oscillations of the potential U_W in the wave being investigated.[8] If the distance between the probe electrodes is d, the field associated with the wave is $\tilde{E} = U_W/d$. When $\lambda \gg d$, the relation between the wave amplitude φ and $\tilde{E}$ is as follows: $\varphi \approx \lambda\tilde{E}/4$ where λ is the wavelength.

The measurement of the diffusion coefficient is carried out as follows: the electric probes are used to obtain the radial plasma density distribution at various cross sections along the length of the column and (2) is then used to obtain the value of the diffusion coefficient. By taking similar distributions for various values of the magnetic field one can obtain the dependence of the diffusion coefficient on magnetic field strength. It should be noted that the determination of $D_\perp$ requires an extremely careful analysis of the probe measurements. Small misalignments of the radial probes can lead to an incorrect determination of the profiles and plasma density gradients and thus to errors in $D_\perp$. Because of the instability of the plasma and the variation of the plasma parameters in time (the change in η_0 in the course of the experiment) the error in the determination of dn/dr and dn/dz is 10—15%. But in the determination of dn/dz the difference in the densities of 10—15% corresponds to a calculated $D_\perp = 10^2$ cm^2/sec. Hence, this value of $D_\perp$ represents the minimum value of the diffusion coefficient that can be measured under the present conditions.

As indicated above, the diffusion coefficient has also been measured by measuring the flux $j_\perp$. The flux-measuring device consists of two metal plates enclosed in a shield, the entire device being located at the edge of the plasma column. The shield is at the floating potential. The principles of operation of the flux-measuring device have been described in detail in[1,3]. As is well known, when the Q-machine is operated with an electron sheath at the tungsten plate, in which case the oscillation amplitude is small, one should observe the classical diffusion coefficient $D_\perp \approx 1$ cm^2/sec. Under these conditions our flux-measuring device yields $D_\perp \approx 50$ cm^2/sec. This value characterizes the accuracy of the method. A more careful arrangement of the plates can yield a higher accuracy.[3]

3. In the presence of an ion sheath at the surface of the tungsten plate one observes waves for which the fundamental frequency lies in the range 8—30 kHz. Similar oscillations have been observed in Q-machines.[1,9-11]

The authors of[1,3,10,11] propose that these oscillations are drift waves. Hence, we shall not dwell in detail on analysis of the electrical noise but note a number of factors which indicate the drift nature of the oscillations observed in these experiments. First of all, one notes the dependence of the oscillation frequency on magnetic field. The oscillation frequency goes as 1/H. Phase measurements carried out by means of a system of probes distributed in the azimuthal direction indicate that the wave propagates in the direction of electron drift with a frequency given by

$$\omega_* \approx -k_y \frac{cT}{eH} \frac{\nabla n}{n}.$$

The phase velocity of the wave lies in the range

$$u_i \ll \omega_*/k_z \ll u_e.$$

Here,

$$k_z = 2\pi/L, \quad k_y = 1/R,$$

where R is the radius of the plasma column, L is the length of the plasma column, u_i and u_e are the ion and electron thermal velocities and T is the plasma temperature.

The component of the wave along the static magnetic field exhibits a maximum amplitude at the center of the plasma column and falls off smoothly towards the ends. No phase variation is observed along the plasma column.

It is well-known that an inhomogeneous plasma is unstable against drift waves.[12,13] This is supported by the diffusion measurements. The dependence of the diffusion coefficient on magnetic field in the regime in which the oscillations appear is given in Fig. 2. The curve denoted by 1 is obtained from (2) while the curve denoted by 2 is obtained from the measurement of $j_\perp$. It is evident from the figures that the diffusion coefficient $D_\perp$ goes as 1/H and that its absolute value is approximately 10^3 cm²/sec, being of the same order as the Bohm value. In these same experiments we have measured the field associated with the wave $\tilde{E}$ at the center of the plasma column. The dependence of $\tilde{E}$ on magnetic field for the fundamental frequency is shown in Fig. 3.

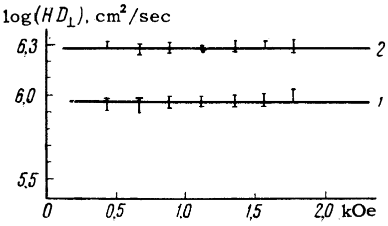

Fig. 2. The dependence of the diffusion coefficient on magnetic field: 1) $D_\perp$ as obtained from (2) in the text, 2) $D_\perp$ as obtained from a measurement of the flux $J_\perp$. The plasma density $n_0 = 6 \times 10^8$ cm^{-3}.

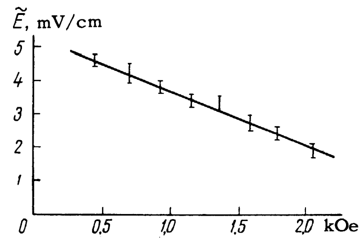

FIG. 3. The dependence of $\tilde{E}$ on magnetic field for the fundamental frequency. The plasma density $n_0 = 6 \times 10^8$ cm^{-3}.

In the regime in which an electron sheath is present at the tungsten plate the amplitude of the oscillations falls off sharply and, simultaneously, the significant plasma density gradient along the axis of the column disappears. Under these conditions, as we have indicated above, the measurement of the flux $j_\perp$ yields a value $D_\perp \approx 50$ cm²/sec while the measurements in accordance with (2) yield a value $D_\perp \leq 10^2$ cm/sec.

Thus, the results reported here indicate that the excitation of oscillations in the plasma leads to an enhancement in the number of effective collisions and causes an anomalous loss of plasma from the system. Measurements of the diffusion coefficient carried out by two different methods give similar results.

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