Formation of an electron loss layer in an open trap plasma in the presence of an anomalous electron diffusion in regular low-frequency oscillations

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This paper presents the results of an experimental investigation of the plasma potential distribution at right angles to the magnetic field in a mirror trap with a minimum in the "Ogra-3B". The results are interpreted on the basis of the S. V. Putvinskiĭ and A. V. Timofeev theory.

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Open traps with an electrostatic barrier[1] have recently been a subject of active discussion. The plasma of open catchers should assume a positive potential with respect to the wall. This is due to the faster departure of the electrons. In the classical electron transport processes, Φ mainly along the axis $\Phi \sim 2\text{–}5T_e$, where T_e is the electron temperature in eV, Φ is the potential in volts. As a rule, an anomalously large positive potential $\Phi \sim 10T_e$ is observed in experiments.

An anomalous potential was also discovered in experiments on the "Ogra-3B" apparatus.[2] In practice the appearance (disappearance) of the anomalous potential is associated with the appearance (disappearance) of low-frequency oscillations (LF-frequency less than the ion cyclotron frequency). The anomalous plasma potential is observed in the "Ogra-3B" even when there are no anomalous ion losses (channel and ion-cyclotron instabilities are suppressed). Measurements showed that the LF plasma oscillations are regular and therefore the anomalous potential is due to an anomalous *transverse* diffusion of electrons in *regular* LF oscillations.

The nature of such an electron diffusion was analyzed in detail in Ref. 3. The basic conclusions of the theory can be formulated as follows: 1) if regular LF oscillations are excited in a plasma, then the rare Coulomb collisions of electrons causes an appreciable transverse diffusion that increases with the oscillation amplitude; 2) the anomalous diffusion coefficient D does not depend on the magnitude of the potential Φ; 3) the diffusion coefficient D decreases with the decrease of the quantity $\kappa = (1/\Phi)(d\Phi/dx)$, characterizing the potential gradient in the transverse direction, $D \to 0$ as $\kappa \to 0$; 4) the transverse electron mobility remains negligibly small.

The low-frequency oscillations by themselves do not cause ion losses in the experiment[2]; therefore the plasma lifetime τ_0 and the transverse density distribution $n(x)$ are given and are independent of the anomalous electron behavior. Quasineutrality of the plasma requires that the following equation be satisfied

$$\tau_0^{-1} = \tau_{\parallel}^{-1} + \tau_{\perp}^{-1}, \tag{1}$$

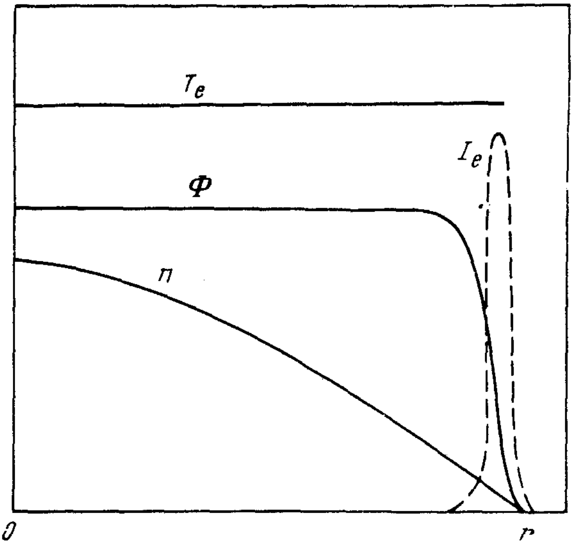


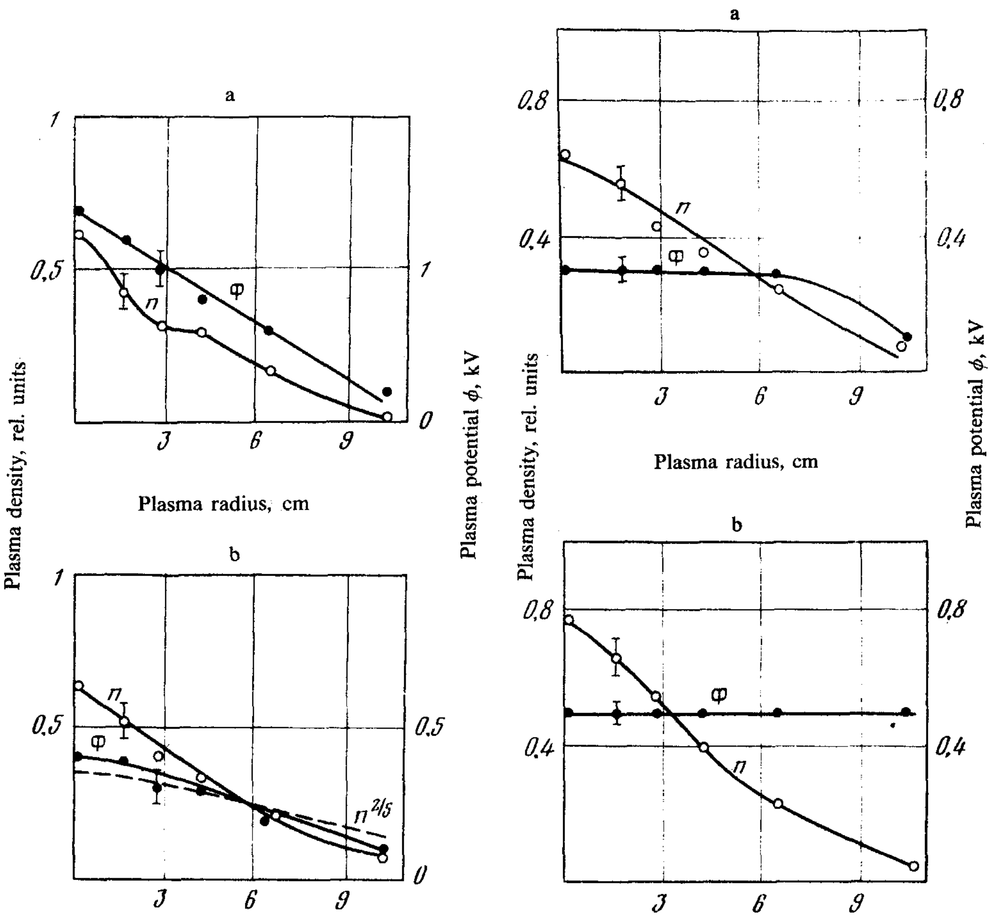
FIG. 1. Transverse distribution of the plasma density n, the flow of electrons leaving the trap I_e electron temperature T_e, plasma potential Φ.

where $\tau_{\parallel}$ is the classical longitudinal lifetime of the electrons, $\tau_{\perp}$ is the anomalous transverse lifetime of the electrons, with $\tau_{\perp} \gg \tau_{\parallel}$ in the absence of LF oscillations. The quantitities $\tau_{\parallel}$ and $\tau_{\perp}$ can be expressed as follow:

$$\tau_{\parallel} \quad f(R)\tau_{ee}\frac{\Phi}{T_e}\exp\left(\frac{\Phi}{T_e}\right), \qquad \tau_{\perp} \sim \frac{a^2}{D}, \tag{2}$$

where τ_{ee} is the electron-electron collision time, a is the characteristic transverse dimension of the plasma, $f(R)$ is a function of the mirror ratio R.[4] Apparently an increase in D for a constant left side in Eq. (1) should lead to an increase in $\tau_{\parallel}$ and, consequently, to an increase in the quantity Φ. At a sufficiently large D (for example, at a high level of LF oscillations) $\tau_{\parallel} \gg \tau_{\perp}$. Experimentally this is exhibited in the form of an anomlaously large value of Φ and absence of electrons leaving along the axis of the trap. The electrons are transported at right angles to the center of the plasma and leave the trap along the force lines in a narrow peripheral region—layer (see Fig. 1). A similar behavior of the electrons was found in the "Ogra-3B" apparatus.[5]

When $\tau_{\parallel} \gg \tau_{\perp}$, a further increase in D is limited since $D \leqslant a^2/\tau_0 = \text{const}$. Therefore a further increase in the LF noise level should lead to a decrease in the value of κ, i.e., the gradient of the potential Φ. Figures 2 and 3 show the measured transverse distribution of the potential Φ and the density n in four operating conditions. *Condition* 1: no oscillations exist in the plasma, the potential has a classical value and the transverse distribution is $\sim n/^{2/5}$ (Fig. 2b). *Condition* 2: LF oscillations are found in the plasma, the potential value is anomalously large[1)] (Fig. 3a). *Condition* 3: the level of LF oscillations is higher than in condition 2; a broad "plateau" of anomalously high potential is observed, changing sharply at the periphery in the layer (Fig. 3b and Fig. 1) *Condition* 4: high-intensity high-frequency ion-cyclotron oscillations develop in the plasma, con-



FIGS. 2 and 3. Distribution of n and Φ along plasma radius. Dashed line-classical potential, calculated from n.

siderably altering the lifetime τ_0 and the transverse density distribution $n(x)$. This leads to an increase in the potential gradient (Fig. 2a).

The intense transverse transport of electrons toward the center leads to an equalization of the electron temperature throughout the entire plasma volume (Fig. 1). Measurements showed that in operating conditions 1–3 the value of T_e and the nature of its dependence on n, τ_0 and the injection energy of the neutrals are predicted quite well by the classical theory. This is understandable since the electrons leave the trap in the layer around the periphery at the classical potential value when $\tau_0 = \tau_{\parallel}$ (Fig. 1).

Thus, the anomalous transverse electron diffusion in regular LF oscillations does not lead to appreciable changes in density, temperature and lifetime of the plasma. This diffusion also determines the magnitude and transverse plasma potential distribution and leads to the formation of a layer around the periphery in which an apprecial potential drop occurs and where the entire flow of electrons, leaving the trap is concentrated.

The conducted measurements and their analysis can serve as an example which shows that the enhanced transverse diffusion *does not lead* to the establishment of a *Boltzmann* potential distribution. This is explained by the fact that the anomalous diffusion is not always accompanied by an anomalous mobility.

The investigated anomalous diffusion *does not depend* on the nature of the LF oscillations (channel-type oscillations, propagating at right angles to the magnetic field). The reasons for their build-up can be very diverse. In our experiments, when the gross channel instability is suppressed by the magnetic well, electron and ion branches of the natural weakly damped channel oscillations are observed. Because of the large Q-factor of these oscillations they are stimulated by external sources, such as the noise of the injected beam. Sudden outbursts (shocks) of ion-cyclotron instability also lead to a "ringing" of the high-Q LF oscillations. A lowering of the beam noise and of the ion-cyclotron instability level can significantly reduce the anomalous electron diffusion, resulting in a reduction of the plasma potential.

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[1)]The electron temperature is significantly different in all the operating conditions.

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