Longitudinal Ion Flux in a Closed Magnetic Trap

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The existence of quasistationary longitudinal ion flux (along the small axis of the toroidal chamber) is observed in a closed magnetic trap (L-1 stellarator). The main dependences of the flux on the characteristics of the magnetic field are studied. The distribution of the flux density within the chamber cross section and its time variation are studied. The mechanism leading to the production of the ion flux is associated with the predominant escape from the plasma of ions "trapped" by the toroidal magnetic field. In the presence of radial electric fields the escape of the trapped ions is accompanied by the production of a recoil momentum in the remaining plasma. Ion flux can be produced similarly in other types of toroidal magnetic traps such as tokamaks.

In our investigation of the confinement of a nearly collisionless plasma in the L-1 stellarator (l = 2) we observed[1,2] the existence of guided ion motion along the small axis of the toroidal chamber (the z axis in Fig. 1). The technique used to measure the guided flux has been described in detail in[3]. The principal characteristics of the axially symmetric flow under the experimental conditions are as follows.

The direction of the ion flux depends uniquely on two factors: the direction of the toroidal magnetic field H_2 and of the angle of twist of the magnetic lines of force (determined by the direction of the helical windings in the stellarator). The reversal of either of these factors reverses the flux.

The direction of the longitudinal ion velocity vector is uniform within each cross section of the chamber; thus the average ion flux within a cross section is not zero. The guided longitudinal velocity v_{0zi} increases towards the periphery. Figure 2 shows the characteristic radial distribution of this velocity, normalized to the thermal velocity $\overline{v}_{T_i}$.

The magnitude of the guided flux is observed to depend strongly on the rotational transform i (Fig. 3). As this angle increases (in the measured range $0 < i < 2\pi$), v_{0zi} grows appreciably.

The experimental data reveal only slight changes in the magnitude of the guided flux as the magnetic field is varied in the experimental range 1.5 kOe $\leq H_z \leq$ 9 kOe. The axial flux is quasistationary and is registered during an interval that exceeds the relaxation time for the ionic component. Depending on the experimental conditions, the ratio $v_{0zi}/\overline{v}_{T_i}$ fluctuates within the range 0.1–0.5. The density of the longitudinal ion current corresponding to this type of guided velocity equals a few times the unit mA/cm^2.

The literature contains no information about the measurement of guided quasistationary charged-particle flux in closed systems. No theoretical investigations predicted the flux first observed in the L-1. Nevertheless, on the basis of the modern "neoclassical" theory of plasma containment in closed systems[4] it can be stated that quasistationary axial motion of charged particles is characteristic of all toroidal magnetic traps. We shall here describe semiqualitatively the mechanisms of the processes leading to the effects observed in the L-1.

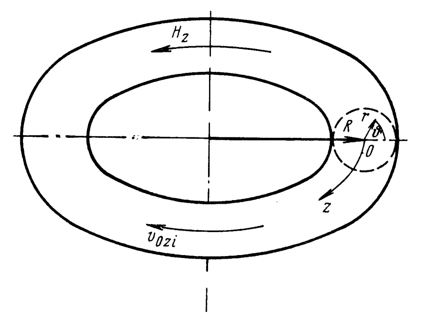

FIG. 1. Schematic representation of the toroidal chamber.

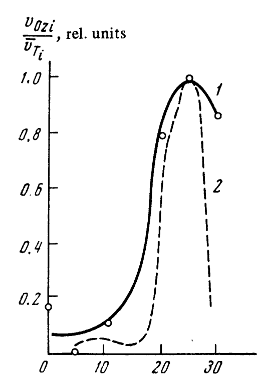

FIG. 2

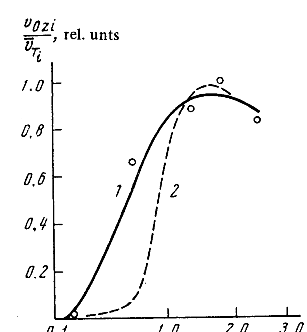

FIG. 3

FIG. 2. Radial distribution of $v_{0zi}/\overline{v}_{T_i}$. 1—experimental, 2—calculated.

FIG. 3. Dependence of the normalized guided ion velocity on the angle of twist of the magnetic lines. 1—experimental, 2—calculated.

We know that the so-called "trapped" and "weakly trapped" particles make the main contribution to the diffusion of nearly collisionless plasmas in closed magnetic traps.[5,6] When a radial electric field $\mathbf{E}_r$ exists in a plasma the trapped particles possess non-zero average longitudinal velocity

$$\bar{u}_E = v_E / \Theta, \tag{1}$$

where $v_E = cE_r/H_z$ and $\Theta = ir/2\pi R$. Therefore, when

$E_r \neq 0$ the escape of trapped particles from the plasma is accompanied by the continuous loss of longitudinal momentum. This must inevitably lead to recoil momentum in the contained plasma.

The flux of trapped particles to the chamber wall is especially large (and therefore the axial acceleration effect in the plasma is especially large) when the deviation of trapped particles from the magnetic surfaces (Δr) is comparable with the transverse dimension of the system (a). In a sufficiently rarefied plasma a particle that has been trapped can escape to the chamber wall without undergoing even a single collision. This regime, in which a "loss cone" is formed in the velocity space of the ions, is characteristic of the L-1 stellarator. Under the experimental conditions for the L-1, calculations indicate fulfillment of the relations

$$\Delta r_i \approx a, \tag{2}$$

$$a / v_{gi} > \tau_0 \approx 1 / \nu_{in}, \tag{3}$$

where v_{gi} is the toroidal drift velocity and ν_{in} is the frequency of collisions between ions and neutral atoms. When (2) and (3) are fulfilled we can roughly estimate the axial velocity of the plasma,[1)] assuming that the momentum acquired by contained ions is proportional to the momentum carried away by trapped ions:

$$n_i v_{0zi} = B n_{\text{trap}\, i} \bar{u}_E, \tag{4}$$

where n_i is the density of transiting ions, $n_{\text{trap}\, i}$ is the density of trapped ions, and B is a proportionality coefficient, dependent on the collision frequency ν_{in}, on the degree to which the "loss cone" is filled with trapped particles etc. (Friction against neutral atoms leads to the establishment of a stationary velocity v_{0zi} that is determined by B as a function of ν_{in}.)

Evaluating $n_{\text{trap}\, i}$ in accordance with[4], we obtain a final expression for the average guided velocity along the z axis:

$$v_{0zi} = B\bar{u}_E(\Phi(t_1) - \Phi(t_2)) \Big/ \left[1 - \frac{\Phi(t_1) - \Phi(t_2)}{2}\right], \tag{5}$$

where $\Phi(t)$ is the error function, $t_{1,2} = (\bar{u}_E \pm \Delta v)/\bar{v}_{Ti}$, $\Delta v \approx 2\sqrt{v_{gi} r \omega_{ci}}$; ω_{ci} is the ionic cyclotron frequency.

From (5) we determine how the guided ion velocity depends on E_r, i, H_z, and T_i. It follows from the results, shown in Figs. 2 and 3, that the calculated dependences of v_{0zi} on r and i resemble the experimental curves. The proposed physical model is consistent with weak dependence of the guided flux on the magnetic field H_z and on time.[2)]

The experimentally determined direction of the axial motion of the ions agrees with what can be expected from the decisive role of the discussed mechanism. In our physical model the guided ion flux must depend strongly on the radial electric field [see (1)]. An increase of E_r must lead to enhancement of the average longitudinal velocity of the trapped ions. However this is accompanied by a very great reduction (which is

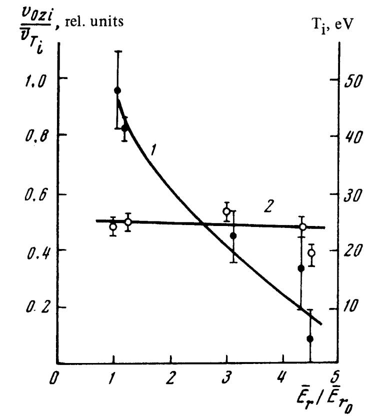

FIG. 4. The normalized guided ion velocity (curve 1) and the ion temperature (curve 2) as functions of the radial average of the normalized radial electric field, $\bar{E}_{r0}$, in the absence of the supplementary negative charge.

almost exponential for sufficiently large values of $\bar{u}_E/\bar{v}_{Ti}$) of the number of trapped ions, because the region of trapping is shifted to the "tail" of the longitudinal velocity distribution. The consequence of this must be an appreciable reduction of the longitudinal momentum carried out of the trap, and therefore of v_{0zi}. In our experiments we changed E_r by placing a supplementary charge on the axis of the chamber.[3)] As expected, the increase of E_r was accompanied by considerable reduction of v_{0zi} (see Fig. 4). With a five-fold increase of the average radial field $\bar{E}_r$ the longitudinal ion velocity becomes so small that it cannot be registered reliably with the technique that was used.

The quite good agreement between the experimental and calculated curves shows that the proposed model can account for the axial ion flux observed in the stellarator: Recoil momentum originates in the plasma through the predominant escape of trapped particles possessing the average velocity $\bar{u}_E$ when $E_r \neq 0$. Since this mechanism is based on the toroidal form of the containing magnetic field and the presence of a radial electric field, it is evident that a longitudinal flux must exist in all types of toroidal magnetic traps containing trapped particles, i.e. in tokamaks, levitrons etc. as well as in stellarators.

The foregoing experimental results describe the behavior of only the ionic component of a plasma (the given technique did not permit us to measure the guided velocities of electrons). However, under conditions that produce $\nu_{ei} \gg \nu_{en}$ the electrons must be carried along in the direction of the ion current up to velocities near v_{0zi}, i.e. the plasma as a whole is involved in the motion. This effect appears to account for the fact that no magnetic field of the ion current could be observed experimentally in the stellarator "Protocleo"[11] (just as in the case of the L-1[2]).

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1)A rigorous theory of the axial acceleration of a plasma has recently been developed by L. M. Kovrizhnykh.[7].

2)Substituting into (5) the experimental values of E_r and T_i obtained in [8,9] (for different magnetic fields and for different moments of time), we find that v_{ozi} is a weak function of both H_z and time.

3)A supplementary negative charge was introduced by means of a "hot" electron emission probe[10], whose potential relative to the chamber wall varied from −50 to −200 V at 10–20 mA. This did not lead to an appreciable change of T_i.

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