Determination of the poloidal rotation rate of plasma in the FT-1 tokamak

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The poloidal rotation rate of plasma in the FT-1 device is determined with use of carbon macroparticles injected into the takamak before the onset of discharge. Its value of $\sim 5\times 10^5$ cm/sec is close to the diamagnetic drift velocity of electrons.

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Theoretical analysis[1,2] shows that poloidal rotation of plasma in a radial electric field has a strong effect on the plasma and impurity transfer processes in toroidal traps. However, the experimental data on the velocity of poloidal rotation v_0 have been obtained only in the LT-3 tokamak for the Pfirsh–Schlüter regime.[3] The determination of v_0 enables us to use the method described in Ref. 4 for plasma diagnostics with use of macroparticles injected into the discharge. Below we describe the results of experiments in which v_0 was determined from the evolution of the impurity ions emitted from the macroparticle.

A $\sim$0.7-mm carbon macroparticle was injected into the discharge from below along the central vertical span at different radii. The onset of discharge was synchronized with the time it was stopped in the upper trajectory. The macroparticle displacement during the discharge was small ($\lesssim 1$ cm).

The interaction of the "suspended" macroparticle with the plasma is characterized by two different stages. First, the macroparticle is heated until the onset of intensive evaporation, and then a small amount of impurities enters the discharge due to cathode sputtering. The particles injected at a distance of $\leqslant 10$ cm from the chamber axis are heated in 5–6 msec. During this period, the discharge parameters (the voltage across the bypass, the current, and the emission intensity of the oxygen lines) are almost undisturbed, which also follows from the estimates in Ref. 4. This stage is analyzed in our paper. The second stage, strong evaporation of carbon, is not examined.

The impurity ions, which escape from the surface of the macroparticle, participate in several motions. They are as follows: 1) flow along the magnetic field lines, 2) drift in the radial electric field, and 3) radial transport. For the slightly ionized CII and CIII carbon ions whose lifetime in the experiment does not exceed 50 msec, the radial shift can be disregarded, and the motion along **B** can be considered collision-free.

For a point source the steady-state density profile of the impurity ions in a particular charge state is given by

$$n_{\mathrm{I}}(Z, \theta) = \left(\frac{m_{\mathrm{I}}}{2\pi T_{\mathrm{I}}}\right)^{1/2} \frac{\dot{N}}{r\theta}\, e^{-r\theta/(v_0 \tau_{\mathrm{ion}}) - \frac{m_{\mathrm{I}}}{2T_{\mathrm{I}}}\left(\frac{z v_0}{r\theta}\right)^2} \delta(r - r_0) \quad . \qquad (1)$$

Here z is the coordinate along the magnetic field, θ is the azimuthal angle measured from the macroparticle in the direction of rotation, m_{I} and T_{I} are the mass and the temperature of the impurity, τ_{ion} is the ionization time of the given charge, and $\dot{N}$ is the injection rate of the impurities into the plasma. The macroparticle coordinates are $r = r_0$, $z = 0$. The distribution function of the ejected particles was assumed to be Maxwellian.

Typical emission intensity distributions of the CII and CIII lines in the cross section $z = 0$ are shown in Fig. 1. The observation was made on the outer side of the torus along the horizontal chords. The main peak corresponds to the macroparticle. A second maximum of the impurity concentration was observed on the opposite side of the magnetic surface of radius r_0. The ratio of the amplitudes of the maxima for the CII line was much larger than that for CIII, and the emission profile of the CV line was symmetrical.

The second intensity maximum for the CII and CIII lines is attributable to the arrival of the impurities on the opposite side of the magnetic surface due to poloidal rotation of the plasma. Measurements of the intensity in the cross section separated from the origin by a quarter of the circumference of the large radius showed a strong ($>$ 10 fold) burn-up of the CII and CIII lines, so that the arrival of the corresponding impurities on the opposite side of the magnetic surface due to the motion along the magnetic field is eliminated.

Integrating Eq. (1) along the horizontal chords and taking into account the finite dimensions of the source—the ionization length of the neutral carbon l_i, we obtain the ratio of the intensity amplitudes A_1 near the macroparticle and on the opposite side of

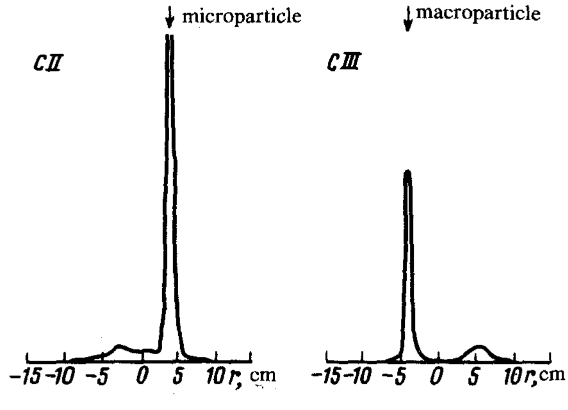

FIG. 1. Distribution of the CII and CIII emission lines.

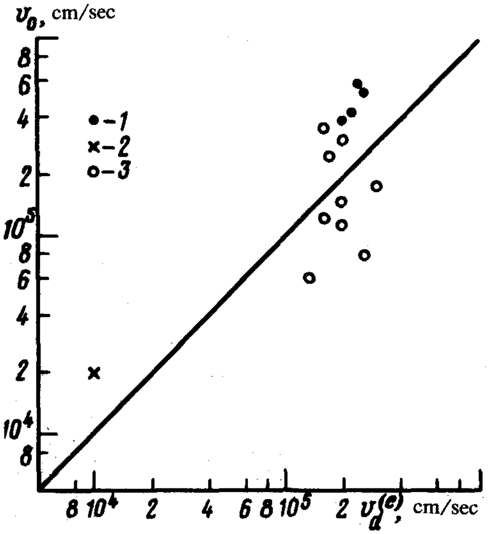

FIG. 2. Dependence of the rotation rate on $v_d^{(e)}$: 1—data obtained by using macroparticles; 2—data obtained by analyzing the emission profiles of the impurities in the Alcator[5]; 3—same for the FT-1 device.

the magnetic surface A_2:

$$v_0 = \frac{\pi r_0}{\tau_{\rm ion}\left(\ln\frac{A_1}{A_2} - \frac{1}{2}\ln\frac{r}{l_i}\right)} . \tag{2}$$

The value of l_i which is determined from the variation of the emission intensity of neutral carbon, is 1 cm near the macroparticle. We note that the uncertainty in the value of l_i is insignificant in the calculation of v_0, since the dependence of v_0 on l_i is logarithmic.

The plasma rotation rate, which is calculated from Eq. (2), is compared in Fig. 2 with the diamagnetic velocity of electrons in the absence of the electron temperature ent $v_d^{(e)} = \dfrac{CTe}{eB}\dfrac{d\ln n}{dr}$. It can be seen that the measured rotation velocity exceeds $v_d^{(e)}$ by a factor of 1.5–2.

Recently, strong asymmetry in the emission distribution of the ion lines of low-charge states $[(A_1 - A_2)/A_1 > r/R]$ was observed in the Alcator,[5] PLT,[6] and FT-1 devices. This asymmetry cannot be explained by the toroidal effects in terms of the existing impurity-transport models (see Ref. 2). Such asymmetry occurs if the ionization time is comparable to the flow time of the impurities along the magnetic surface, and if there is a local source on it. Regardless of the reasons for occurrence of a local source of impurities, their steady-state distribution on the magnetic surface is determined by rotation and ionization. Therefore, the asymmetry data can be used to estimate v_0 on the periphery of the plasma column. In contrast to a macroparticle, the source in this case is distributed along the large circumference of the torus, so that instead of Eq. (2) we have $v_0 = \dfrac{\pi r}{\tau_{\rm ion}\ln A_1/A_2}$.

The asymmetry observed in the oxgen distribution[5] is apparently attributable to the toroidal drift, since its direction changes as a result of reversal of the magnetic field. Our value of v_0, like that of FT-1, which was measured by using macroparticle injection, is of the order of $2v_d^{(e)}$ (see Fig. 2). In the FT-1 device there are other causes of asymmetry in addition to the toroidal drift, since the luminescence maxima of different ions are on the opposite sides of the magnetic surface. The values of v_0 for the FT-1 device are nonetheless close to $2v_d^{(e)}$ (Fig. 2).

The rotation velocity in LT-3,[3] which is close to the velocity of the diamagnetic drift of ions $v_0 = v_d^i = \frac{c}{eB}\frac{dp_i}{ndr}$, corresponds to the radial electric field directed into the plasma, consistent with the assumption about the diffusion of plasma in the Pfirsh-Schlüter regime.[1] In the FT-1 device, where $T_e = 200$ eV and $T_i = 50$ eV, the obtained values of the poloidal rotation velocity indicate that the electric field is determined by the electron temperature, since the drift velocity $v_d^{(i)}$ is almost an order of magnitude smaller than the observed velocity. Unfortunately, the geometry of the experiment made it impossible to determine the direction of the rotation. The sign of the velocity in such experiments can be determined from the direction of the injection.

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