Electric potential and toroidal and poloidal rotation velocities of a tokamak plasma

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The velocities of the toroidal and poloidal rotations and the plasma potential have been measured during ohmic heating in the TM-4 tokamak. The potential at the center of the plasma column lies between − 100 and − 700 V. The velocities at the center of the column agree with the neoclassical predictions, while those at the periphery are much lower.

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The rotation of plasmas in tokamaks is the subject of active theoretical and experimental research.[1–5] A major motivation for this research is a possible relationship between plasma rotation and the radial transport of particles and heat.

The neoclassical theory[1–3] yields the following expressions for the poloidal (V_P)

and toroidal (V_T) velocities of an impurity ion of charge Z (Ref. 3):

$$V_{PZ}^{\mathrm{neo}} = -\frac{cT_i}{eB_T}\left[\frac{\partial}{\partial r}\ln n_i - \frac{1}{Z}\frac{\partial}{\partial r}\ln n_Z + \left(1-k-\frac{1}{Z}\right)\frac{\partial}{\partial r}\ln T_i\right] ; \qquad (1)$$

$$V_{TZ}^{\mathrm{neo}} = -\frac{cT_i}{eB_P}\left[\frac{\partial}{\partial r}\ln n_i + (1-k)\frac{\partial}{\partial r}\ln T_i + \frac{e}{T_i}E_r\right] ; \qquad (2)$$

where n_Z and n_i are the ion and proton densities, T_i is the ion temperature, E is the radial electric field, B_T and B_P are the longitudinal and poloidal magnetic fields, and k is a numerical coefficient which depends on the rate of ion-ion collisions.[1]

One purpose of the experiments which we are reporting here was to compare the experimental values of V_T and V_P with the neoclassical values in (1) and (2). The rotation velocities were determined experimentally from the Doppler shift of the ion lines CV(2271 Å), OV(2781 Å), and CIII(2296 Å), observed along two opposite directions with respect to the rotation. The temperature T_i was simultaneously determined from the Doppler broadening of the spectral lines.

The measurements were taken in the TM-4 with a minor radius (at the limiter) $a_L = 8.5$ cm, a major radius $R = 53$ cm, $B_T = 13$–15 kOe, a discharge current $I_d = 21$–26 kA, an effective plasma charge $Z_{\mathrm{eff}} = 2.0$–2.5, and an average density $n_e = (0.6$–$4.5)\times 10^{13}$ cm^{-3}. Figure 1a shows radial profiles of T_e, T_i, and n_e. The values of T_i and also V_P and V_T for the CV, OV, and CIII ions (Figs. 1b and 1c) were measured on chords corresponding to the maxima of the spatial profiles of the emission of these ions.

In the central part of the plasma column the poloidal velocity is directed along the diamagnetic electron drift, while the toroidal velocity is directed opposite the plasma current. The directions of both the toroidal and poloidal rotations change sign at the periphery. A mirror-image change in the direction of the toroidal velocity is observed when the plasma current is reversed, while a mirror-image change in the direction of the poloidal velocity is observed when the direction of the toroidal magnetic field is changed.

Comparison of the values of V_P^{expt} and V_P^{neo} (Fig. 1b) shows that the neoclassical theory gives a satisfactory description of the experimental results at the center of the plasma column (the CV ion), but there is a qualitative discrepancy at the periphery (the CIII ion).

The field E_r, required for determining V_T^{neo}, is determined from the radial force balance equation,

$$0 = -\frac{\partial}{\partial r}(n_Z T_i) + Zen_Z E_r + \frac{Ze}{c} n_Z (V_{PZ}^{\mathrm{expt}} B_T - V_{TZ}^{\mathrm{expt}} B_P) . \qquad (3)$$

The values found for V_T^{neo} from (2) are $V_T^{\mathrm{neo}}(\mathrm{CV}) = -(6 \pm 3)\times 10^5$ cm/s, $V_T^{\mathrm{neo}}(\mathrm{OV}) = (4 \pm 3)\times 10^6$ cm/s, and $V_T^{\mathrm{neo}}(\mathrm{CIII}) = (10 \pm 5)\times 10^6$ cm/s. Comparison with the

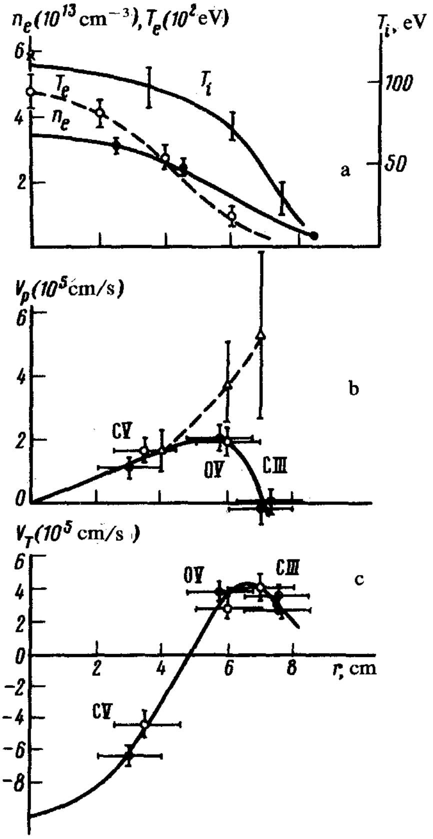

FIG. 1. Radial profiles of various properties. a—Electron density n_e, electron temperature T_e, and ion temperature T_i (x is the value of T_i at the center of the plasma column as determined from the spectrum of charge-exchange neutrals); b—poloidal velocity; c—toroidal velocity. The rotation velocities were measured in experiments without (●) and with (O) displacement of the plasma column. Here Δ is the neoclassical value of the poloidal velocity for the CV, OV, and CIII ions at 4, 6, and 7 cm, respectively.

V_T^{expt} values (Fig. 1c) reveals that the values of V_T^{neo} are also more than an order of magnitude higher than the experimental values at the periphery of the plasma column.

The profile of the plasma potential was determined in the same experiments by using a beam of fast Cs^+ ions as a probe.[6] The potential was measured along the path of the ion beam. The results of these measurements are shown in Fig. 2.

The high negative potential at the center of the column ($|\Phi| \gg T_i$) may be caused by the escape from the plasma of locally trapped superthermal ions with energies $E_i \sim |\Phi|$. To test this possibility we measured $\Phi(r)$, V_P, and V_T under conditions such that the equilibrium position of the plasma column was displaced with respect to the center of the chamber ($\Delta r \sim 0.5$ cm).

In the toroidal plasma of a tokamak, the distribution of levels with identical depth of the local magnetic confinement system, δ, is symmetric, and there are regions with-

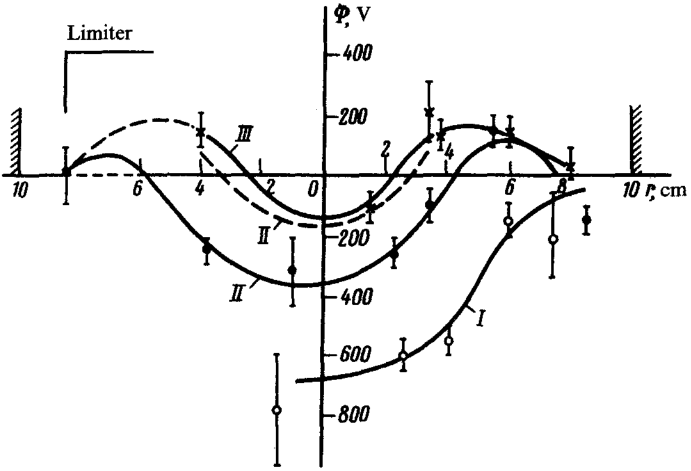

FIG. 2. Radial profiles of the plasma potential. I—$\bar{n}_e = (4–5) \times 10^{13}$ cm^{-3}; II—$\bar{n}_e = 2.5 \times 10^{13}$ cm^{-3} (the solid curves correspond to measurements without a displacement, while the dashed curves correspond to measurements with a displacement in the direction opposite the toroidal ion drift); III—$\bar{n}_e = 0.6 \times 10^{13}$ cm^{-3}.

out these local systems. When the equilibrium position is moved vertically, the picture becomes asymmetric: The region with $\delta = 0$ increases in size on the side opposite the displacement. If the toroidal drift of the locally trapped ions is in this direction, the escape of these ions to the wall is hindered.

Figure 2 shows the results of this experiment (dashed curve). We found that $|\Phi|$ decreases at the center of the plasma, but the magnitude of the electric potential remains essentially constant. Furthermore, there are no changes in the rotation velocities (the open circles in Figs. 1b and 1c).

As $\bar{n}_e$ is increased from 0.5×10^{13} cm^{-3} to 4×10^{13} cm^{-3}, the peripheral zone with the positive potential becomes thinner (Fig. 2), and the energy lifetime increases from 0.4 ms to 1.5 ms. The existence of a positive potential is evidence of an elevated loss of electrons. From other experiments[8] we know that the diffusion coefficients and the electron thermal conductivity in a tokamak increase rapidly at the plasma periphery, in the part of the plasma column with $q(r) > 2$. In the TM-4 experiments this region corresponds to the outer half of the plasma radius. It is thus natural to link the positive potential at the periphery with a disruption of the magnetic structure in this region.

The fact that the values of V_T^{expt} at the periphery are significantly lower than V_T^{neo} may imply a pronounced decrease in the toroidal angular momentum. This braking force should intensify the radial drift of particles.

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