# Intensive transverse transport of fast electrons in a tokamak

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An intensive departure of electrons having an energy exceeding $T_e$ by one order of magnitude, from the center of a tokamak plasma pinch towards its peripheral regions has been observed.

The behavior of fast plasma electrons in a constant magnetic field **E** in toroidal magnetic traps has been considered in[1]. In an ideal torus, on a given magnetic surface, the distribution function and the flux of the runaway electrons are close to those obtained in the case of a spatially homogeneous plasma without the magnetic field. In particular, in a relatively weak field $E \ll E_c$, where $E_c = 4\pi e^3 N \ln\Lambda / T_e$, ($N$, and $T_e$ are the concentration and temperature of the electrons, and $\ln\Lambda$ is the Coulomb logarithm), at not too high electron energies $\mathscr{E} < \mathscr{E}_c = (T_e/2)(E_c/E)$, the distribution function, just as in[2], is given by

$$\ln f \approx -\frac{\mathscr{E}}{T_e} + \frac{E}{E_c}\left(\frac{\mathscr{E}}{T_e}\right)^2 . \tag{1}$$

An important feature of a toroidal system is, however, that the temperature of the electrons and the field $E_c$, which depends on $T_e$ and $N$, can greatly differ on different magnetic surfaces. There is practically no exchange of fast particles between the magnetic surfaces. Therefore, even at relatively small changes of $T_e$ and $E_c/E$, the distribution function of the fast electrons ($\mathscr{E} > T_e$), as seen from (1), varies exponentially rapidly over the section of the torus. It has a sharp maximum near the axis of the torus (if the electron temperature is maximal there). In this case the distribution function of the high-energy electrons, and with it also the flux of the runaway electrons, form a narrow pinch in the center of the plasma.

This simple picture changes noticeably in the case of a toroidal magnetic field that is corrugated along the principal axis. In real tokamaks, the relative depth of the corrugations is $\delta \sim 0.01$–$0.1$ ($\delta = \Delta B/B$, where $B$ is the magnetic field and $\Delta B$ is the depth of the magnetic well in the given corrugation). The presence of corrugations in the magnetic field leads to capture of some of the electrons in the corrugations–supertrapped particles.[3] For these particles, which have short trajectories, the rotational transformation does not hold, so that the drift across the magnetic field becomes important for them. This practically vertical drift leads to motion of the particles

between different magnetic surfaces (something absent in the case of an ideal torus) and to departure of the electrons to the walls of the chamber. Physically, this mixing process can be visualized in the following manner. In the region where the number of fast electrons is exponentially large, the greater fraction of the trapped electrons is transformed, owing to the Coulomb collisions with the bulk of the thermal electrons and ions, into supertrapped particles and drift vertically from the axial region of the pinch to the peripheral magnetic surfaces. There, owing to the same collisions, the supertrapped particles go over into trapped ones that have no vertical drift. The distance covered by the drifting electron during the time it stays in the corrugation increases sharply with increasing particle energy. Therefore the process in question is important only for sufficiently fast electrons with energy $\mathscr{E} > \mathscr{E}_d$, where

$$\mathscr{E}_d(\rho) = \frac{e^2}{2} \left[ \frac{8\pi (1 + Z)BR \ln \Lambda}{c m^{1/2}} \frac{\rho}{\int_0^{\rho}} \frac{N}{\delta} d\rho \right]^{2/5}. \tag{2}$$

Here $R$ is the major radius of the torus and $Z = \Sigma_i(Z_i N_i/N)$ is the average ion charge. An analysis of the solution of the kinetic equation with allowance for the drift transport in the corrugations shows that the $\rho$ distribution function on a given magnetic surface remains unperturbed, (i.e., it decreases with increasing electron temperature in accordance with (1) with $T_e = T_e(\rho)$, and $E_c = E_c(\rho)$) only up to $\mathscr{E} = \mathscr{E}_0(\rho)$, where

$$\mathscr{E}_0(\rho) = k\mathscr{E}_d T_e(\rho) / 2T_e(0) \qquad \begin{cases} k = 2 - \dfrac{\mathscr{E}_d}{\mathscr{E}_{c0}}, & \mathscr{E}_d < \mathscr{E}_{c0} \\ k \approx 1, & \mathscr{E}_d \sim \mathscr{E}_{c0} \end{cases} . \tag{3}$$

Here $T_e(0)$, $E_c(0)$, and $\mathscr{E}_{c0} = T_e(0)E_c(0)/2E$ are the electron temperature, the field $E_c$ and energy $\mathscr{E}_c$ on the pinch axis. From $\mathscr{E} \approx \mathscr{E}_0$ to $\mathscr{E} \approx \mathscr{E}_d$ the distribution function is approximately constant, i.e., it has a "plateau" region. At $\mathscr{E} > \mathscr{E}_d$ it decreases again, but more slowly than (1). Thus, the drift transport alters considerably the distribution function on the periphery of the pinch, enriching the periphery with fast electrons. Near the pinch axis, on the other hand, the transport does not produce a noticeable change. As shown by a detailed analysis, the effect should be most clearly pronounced in the outer side of the torus.

The fast electrons were experimentally investigated in the tokamak T-10. It was observed in[4,5] that the electron temperature distributions over the cross section, measured by two methods–by laser scattering and by x-radiation, differ substantially. An analysis of these data has shown that the relative number of fast electrons that determine the x rays increases strongly towards the periphery of the plasma pinch.[5] This agrees qualitatively with the results of the theory developed above. Figure 1 shows the distribution of electrons with energy 2 keV $\lesssim \mathscr{E} \lesssim$ 8 keV in the T-10 tokamak at different distances $\rho$ from the pinch axis on the outer side of the torus. The experimental points were obtained by reducing the x-ray spectra.
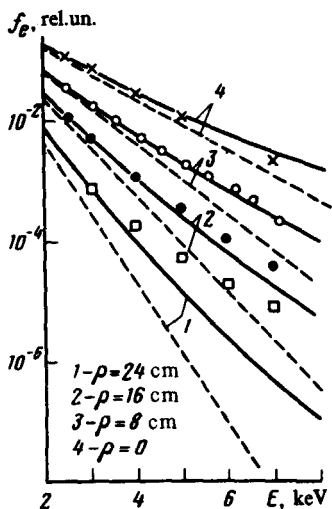
FIG. 1.

$f_e$, rel. un.

$1-\rho = 24$ cm
$2-\rho = 16$ cm
$3-\rho = 8$ cm
$4-\rho = 0$

$E$, keV

Let us compare the experimental data with the theory. The distributions of the electron temperature $T_e(\rho)$ and the electron concentration $N(\rho)$ in T-10, as obtained in[4], are shown in Fig. 2. A Maxwellian distribution with $T_e = T_e(\rho)$ is shown dashed in Fig. 1, while the distribution function (1) perturbed by the electric field is shown by the solid curve. It is seen that the distribution function (1) differs substantially from Maxwellian. On the $\rho = 0$ axis and at $\rho = 8$ cm, the experimental results agree well with the theory that does not take transport into account. This is understandable: the transport is significant only at $\mathscr{E} > \mathscr{E}_0$. The characteristic energies $\mathscr{E}_0$ [Eq. (3)] and $\mathscr{E}_d$ [Eq. (2)], i.e, the lowest and highest limits of the "plateau" region, are shown in Fig. 2. At $\rho \lesssim 18$ cm the energy is $\mathscr{E}_0 > 8$ keV, and the drift transport is immaterial at the experimentally investigated energy range. To the contrary, at $\rho = 24$ cm the energy is $\mathscr{E}_0 \approx 6$ keV. As seen from the figure, experiment shows, approximately in this region, a substantial change in the character of the electron distribution function. Thus, the experimentally observed singularities of the distribution with respect to the electron energy in the peripheral region of the tokamak T-10 pinch can apparently be attribut-
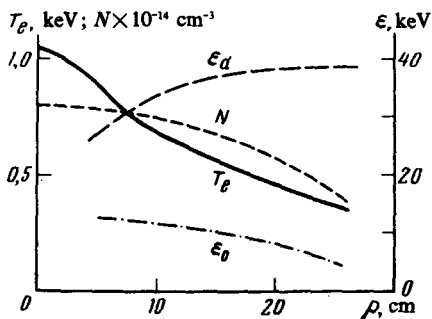


FIG. 2.

$T_e$, keV; $N \times 10^{-14}$ cm$^{-3}$     $\varepsilon$, keV

$\varepsilon_d$

$N$

$T_e$

$\varepsilon_0$

$\rho$, cm

ed to the enhanced drift transport of the fast electrons. At not too high a value of the characteristic energy [$\mathscr{E}_d \lesssim (10-15)T_e$] one can expect the drift transport to lead to a substantial increase of the transverse thermal conductivity of the plasma electrons.

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