Monte Carlo Simulations of $E_r$ on FT-2 Tokamak

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Abstract. Using the Monte Carlo code ASCOT that follows charged particle orbits in five-dimensional phase space we have investigated the formation of transport barriers in the FT-2 tokamak. In such a low current tokamak, a region of a strong (neoclassical ambipolar) $E_r$ can extend over a significant part of the plasma cross section. The generation of $E_r$ appears to be due to finite orbit effects, and its growth is quenched only when the strong poloidal rotation significantly reduces the orbit widths across the steep gradient zone. This field together with the presence of potato orbits in the plasma interior might facilitate the efficient heating of the central plasma observed during improved core confinement mode.

Introduction. In the low current ($I = 22$ kA, $B_T = 2.2$ T) small ($R = 55$ cm, $a = 8$ cm) FT-2 tokamak, when the auxiliary heating (provided by LH-waves) is combined with a global shifting of the plasma column and/or a current ramp-up, a transition into an improved confinement mode has been obtained [1]. In some discharges the plasma profiles and the neutral particle analyzer (NPA) data suggest that the transport barrier associated with the improved confinement is created near the plasma periphery (H-mode with edge transport barrier, ETB), while other discharges indicate improved core confinement (ICC) mode and an internal transport barrier (ITB).

Assuming that the transport barriers are associated with a sheared $E_r$ field, we investigate the formation of the radial electric field in FT-2 plasmas based on purely neoclassical effects. We simulate an Ohmic, an L-mode and an ICC-mode discharge to find the steady state $E_r$ in each case. The direct orbit losses are found to play the dominant role at the edge, in agreement with earlier work carried out for ASDEX Upgrade [2]. Under ICC conditions a strong $E_r$ is created in the plasma interior. It is also shown that even a modest $E_r$ constitutes a super-Mach flow in the plasma, thus dramatically improving the confinement and extending the transport barrier to the plasma interior.

Monte Carlo Simulations of the $E_r$-formation in FT-2. The Monte Carlo code ASCOT follows the guiding center trajectories of test particles in a tokamak magnetic geometry [3]. Test particle collisions with the background plasma are simulated using binomially distributed Monte Carlo operators derived from the Fokker-Planck equation. The effect of LH-waves are included using Monte Carlo operators that give the change in the particle perpendicular energy $W_\perp$, the magnetic surface coordinate $\rho$, and the
toroidal momentum $p_{\phi}$. It is worth noting that the LH-interaction increases only the perpendicular energy and thus it moves ions across the trapped-passing boundary in the velocity space, thereby producing very wide drift orbits and increasing the direct orbit loss probability. The background plasma as well as the magnetic background are assumed stationary. The test particles (hydrogen) are initialized so that they correspond to the bulk plasma. The evaluation of the radial electric field is based on the fact that any non-ambipolar particle flux (including the viscosity drift $v_{\text{visc}} = -(\eta/\Omega B)\partial^2 E_r/\partial r^2$) leads to the appearance of an ambipolar electric field that tends to sustain charge neutrality through the polarization drift $v_{\text{pr}} = (1/\Omega B)\partial E_r/\partial t$. Here, $\Omega$ is the ion cyclotron frequency, $r$ is the radius, $\eta$ is the gyroviscosity coefficient, and $B$ is the magnetic field. Consequently, if we evaluate the non-ambipolar flux across a flux surface as a function of time, we can obtain the radial electric field from the radial current balance [2].

The simulations were carried out using 800 000 test particles that were followed for 0.5 ms. This time is sufficiently longer than both the ion-ion collision time and the bounce time. Radially the region of interest spans from $r = 2$ cm to $r = 8$ cm. In the simulations the radial current balance, including $v_{\text{pr}}$, was solved until a steady-state for the $E_r$-profile was obtained. The simulations were carried out for several sets of plasma profiles: Ohmic phase, characterized by $T(0) = 100$ eV, $T_{\text{edge}} = 10$ eV, $n(0) = 3 \cdot 10^{19} m^{-3}$, and $n_{\text{edge}} = 0.3 \cdot 10^{19} m^{-3}$; L-mode, with $T(0) = 200$ eV, $T_{\text{edge}} = 20$ eV, $n(0) = 4 \cdot 10^{19} m^{-3}$, and $n_{\text{edge}} = 0.3 \cdot 10^{19} m^{-3}$; and ICC-mode, with $T(0) = 300$ eV, $T_{\text{edge}} = 15$ eV, $n(0) = 5 \cdot 10^{19} m^{-3}$, and $n_{\text{edge}} = 0.3 \cdot 10^{19} m^{-3}$.

**Results.** The simulations reveal that as long as the edge temperature and density remain sufficiently high, the direct orbit losses provide the necessary torque to create a strongly sheared $E_r$ in the plasma edge. If the field extends over a sufficiently wide radial region, it can create an ETB. Figure 1(a) shows the $E_r$ profile obtained for the Ohmic phase. The $E_r$ profile agrees well with the standard neoclassical value [4] (for vanishing parallel flow) indicated by the dotted curve. Figure 1(b) shows the $E_r$ profile in the L-mode. The orbit losses induce a radial electric field in the plasma periphery, but only in a very narrow layer. When the pressure gradient at mid-radius gets very high, also conditions relevant for the ITB formation are observed, i.e. during the simulation a deep electric field well is formed around the mid-radius. This field can be significantly stronger than what is formed in the edge region, and it is unlikely that direct losses to the wall or limiter are responsible for its generation. Figure 1(c) shows the $E_r$ profile obtained for the ICC-mode displaying these features.

It is not actually surprising that the obtained $E_r$ deviates from the prediction of the standard neoclassical result in Fig. 1(c). At peak gradient region the poloidal Mach number of rotation exceeds one, and the radial ion current driven by the pressure inhomogeneity exceeds the nonlinear maximum of the current in response to $E_r$, as obtained from ASCOT and shown schematically in Fig. 2. Furthermore, the ion orbits become
Figure 1: The profiles for the radial electric field from ASCOT simulations (solid curves) and from the analytical theory (dotted curves) for (a) Ohmic phase, (b) L-mode, and (c) ICC-mode. The error bars indicate how much the field values fluctuated during the simulation.

Figure 2: The (neoclassical) dependence between the outward flux and the radial electric field. For $E_r > E_{G\max}$ the evolution of $E_r$ becomes unstable.

strongly clamped to the magnetic surface by this large $E_r$, as illustrated in Fig. 3(a). Under these conditions, the standard neoclassical theory is not valid, and only numerical simulation can be used to evaluate $E_r$. The stationary result in Fig. 1(c) was obtained with an anomalous gyroviscosity coefficient (50 times Braginskii coefficient). At a smaller viscosity value the results were essentially the same albeit some differences in the early transitional phase were observed.

The relatively efficient heating of the central plasma in FT-2 could now have two purely neoclassical explanations: before the large $E_r$ is formed inside the plasma, the
Figure 3: (a) A Collisionless ion orbit with and without a uniform $E_r = -10$ kV/m. (b) Different orbit topologies in the central plasma depending on the value of the pitch, $\xi_0 = v_0/v$, at the outer equatorial plane at $r = 4$ cm: A passing orbit ($\xi_0 = 0.4$), a banana orbit ($\xi_0 = 0.3$ and 0.2), and a potato orbit ($\xi_0 = 0.1$).

Low plasma current in the central plasma could actually facilitate the heating. Within the three-centimeter-wide region around the magnetic axis the magnetic topology is such that it only permits passing and potato orbits, see Fig. 3(b). Even up to $r = 4$ cm the phase space volume for banana orbits remains very small. Both the potato and passing orbits have only modest radial excursions and, furthermore, they are not very vulnerable to collisional widening of the orbits. This implies that the fast energy ions produced by LH-heating in this part of the phase space are extra-ordinarily well confined and can be efficiently thermalized thus heating the plasma bulk. Once the large $E_r$ is established around the plasma mid-radius, it can, by clamping the particles to their drift surfaces (see Fig. 3a), confine even those fast ions whose orbits are extended from the center towards the plasma periphery, thus further improving the plasma heating.

Conclusions. Neoclassical ASCOT ion simulations give unexpectedly large radial electric field and its shear for ITB conditions with no external momentum source in FT-2. The field is formed at the region of the highest pressure gradient. Such a large field may be of great relevance for confinement and heating in low current tokamaks.