

Radial Electric Field and Neoclassical Effects in FT-2 Tokamak

T. Kurki-Suonio¹, S.I. Lashkul², and J.A. Heikkinen³

¹Assn Euratom-Tekes, Helsinki Univ. of Tech., P.O. Box 2200, FIN-02015 HUT, Finland

²Ioffe Institute, St. Petersburg, Russia

³Assn Euratom-Tekes, VTT Chemical Technology, P.O. Box 1404, FIN-02044 VTT, Finland

Abstract

Due to its small poloidal field and large magnetic ripple, FT-2 tokamak is ideal for testing the significance of orbit losses in the formation of a radial electric field. Using Monte Carlo based orbit-following code ASCOT we analyze two FT-2 discharges that differ in their confinement properties.

Introduction. On FT-2 tokamak ($R = 55\text{cm}$, $a = 8\text{cm}$) at the Ioffe Institute, a spontaneous transition to improved confinement mode has been observed in the presence of lower hybrid (LH-) heating [1]. In some cases this mode appears to have a transport barrier near the plasma edge (H-mode), and in some cases the barrier is found near the mid-radius (ITB). The barrier is believed to form due to a strongly sheared radial electric field E_r .

FT-2 tokamak has some exceptional features: due to the small plasma current ($I_p = 22\text{kA}$) the poloidal magnetic field is small compared to the toroidal field ($B_T = 2.2\text{T}$, $q = 5-6$). This leads to trapped orbits with very large banana widths, of the order of the minor radius. Also the toroidal ripple is quite large, and the ripple-loss region extends deep into the bulk plasma. Both of these features can lead to significant direct orbit losses, and therefore it is suggested that purely neoclassical effects might explain the formation of a radial electric field with significant enough shear to suppress turbulence.

By simulating FT-2 plasmas we investigate the significance of neoclassical effects in the formation of a radial electric field. We first evaluate the shape and magnitude of the E_r -field that is created due to finite orbit effects. Subsequently we calculate the CX- (charge exchange) neutral fluxes observed by neutral particle analyzers in the presence of this field.

Simulations. The ASCOT [2] code follows the guiding center trajectories of test particles in a tokamak magnetic geometry with a toroidal ripple. Collisions with a stationary background plasma are simulated using binomially distributed Monte Carlo operators derived from the Fokker-Planck equation. The test particles are initialized so that they correspond to the bulk plasma: the particles are distributed uniformly (in poloidal and toroidal directions) on evenly spaced radial shells, and they are assigned weight factors according to the local density and temperature.

The plasma current density is given by a parabolic profile $j(r) = j_0(1 - \rho^2)$ where $\rho \equiv r/a$ is the normalized minor radius, and the stationary hydrogen background plasma is modelled by $n, T = n_0, T_0 (1 - \rho^2)^\alpha + n_{sep}, T_{sep}$. The plasma profiles used in the simulations are shown in Fig.1. The neutral density is assumed to decay exponentially as one moves inwards from the plasma boundary, $n_n = n_{n,0} \exp(-(r-a)/d_n)$ with $d_n = 5\text{cm}$. Here, $n_{n,0}$ is the neutral density at $r = a$. The scrape-off layer (SOL) is modelled by a 2cm wide region outside the separatrix, in which the ion orbits are followed until they either intersect the wall or limiter, or return to the main

plasma. The limiter is simply defined as a region in the SOL limited by two poloidal angles: $\theta_{L,low} < \theta < \theta_{L,high}$. In this work, $\theta_{L,low} = -68^\circ$ and $\theta_{L,high} = -22^\circ$.

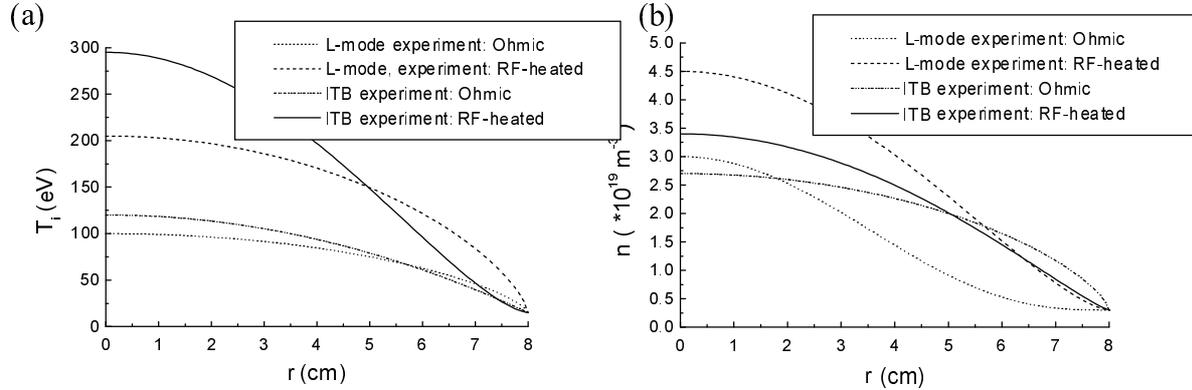


Fig. 1: Temperature (a) and density (b) profiles used in the simulations.

The toroidal magnetic field is $B_T = B_{Tr} / [1 + (r/R_0)\cos\theta]$, where $B_{Tr} = B_0[1 + \Delta(r)\sin N_c\phi]$, and $N_c = 24$ is the number of the toroidal coils. The magnetic field ripple is modelled by $B_0\Delta(r) = B_0\Delta_0 \exp(r/w_B)$, where $B_0\Delta_0$ is the ripple strength on the magnetic axis. Choosing $B_0\Delta_0 = 7.7\text{mT}$ and $w_B = 2.7\text{cm}$, the model fits quite well the ripple strength measurements on FT-2. The external heating in FT-2 is provided by lower hybrid (LH-) waves. In ASCOT, the effect of LH-waves are included using Monte Carlo operators [2] that give the change in the particle perpendicular energy W_\perp , the magnetic surface coordinate ρ , and the toroidal momentum p_ϕ due to the LH-wave during a time step Δt .

The turnable CX-detector in FT-2 is located in the port between the toroidal coils. The detector can be tilted vertically (by an angle θ_{CX}) around a pivot point at $R_{CX} = 89.7\text{cm}$ that lies 9.6cm below the horizontal midplane. The line-of-sight passes through the plasma center for $\theta_{CX} = 15.4^\circ$. The CX-detector is simulated by specifying the viewing angle θ_{CX} and the spot size d_{spot} that is the diameter of the cone seen by the detector at the magnetic axis, $r = 0$. A test particle is registered by the CX-detector, if its coordinates are within the viewing cone and its pitch $\xi = v_{||}/v$ is small enough, $\xi < 0.03$. The test particle's contribution to the CX-signal is determined by its weight factor, which essentially tells how many real particles it represents, and the value of neutral density at the detection point, which gives the neutralization probability.

The evaluation of the radial electric field is based on the fact that any non-ambipolar particle flux leads to the appearance of the ambipolar electric field that tends to sustain charge neutrality through the polarization drift:

$$v_{rp} = \frac{1}{\Omega B} \frac{\partial E_r}{\partial t}$$

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 as [3]

$$\partial E_r / \partial t = - \{ \Omega_0 B_0 / n(r) \} \Gamma(r)$$

where Γ is the non-ambipolar particle flux (polarization flux excluded) across r . If a test particle hits either the vessel wall or the limiter, it is replaced by a thermal particle introduced

at the plasma boundary. This ‘recycling’ of particles assures that the density stays constant during the simulation.

Results. The radial electric field is evaluated for four different plasma conditions in the FT-2 tokamak: We evaluate E_r in both Ohmic and RF-heated phase for the so-called *L-mode* experiment, in which no improvement in confinement is observed. The same analysis is repeated for the so-called *ITB* experiment, in which the confinement is observed to improve due to a transport barrier being formed near the mid-radius.

Figure 2 gives the E_r -profiles, given by a 0.5ms long ASCOT simulation that used 800 000 test particles (protons). Figure 2(a) gives 50 snapshots of the E_r -evolution during the simulation of the RF-heated phase of the ITB-experiment, while Fig.2(b) gives the fitted E_r -profiles in the end of each simulation.

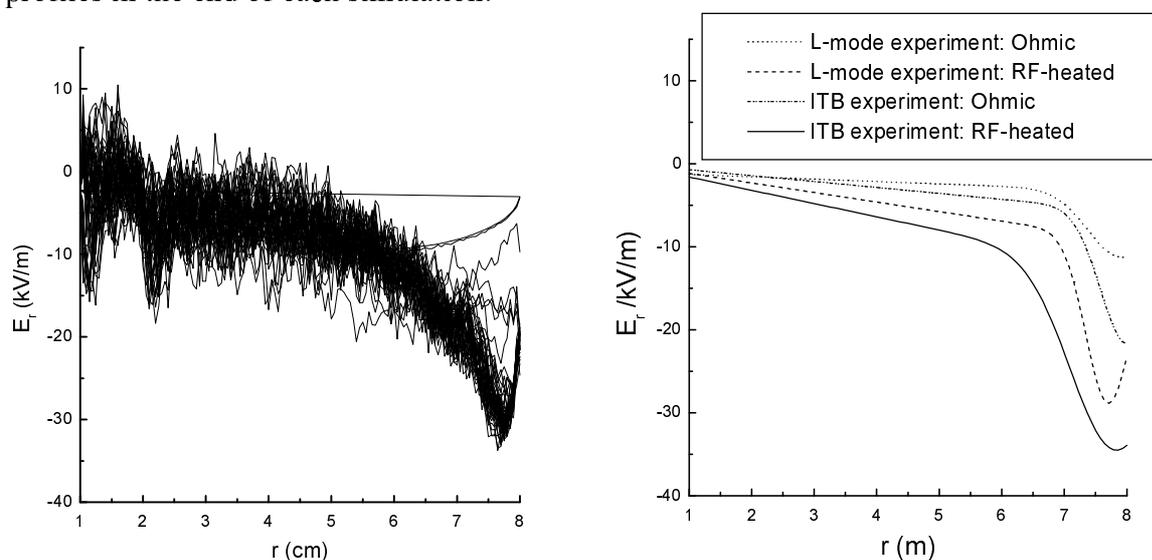


Fig 2: Snapshots of the radial electric field (a) during the simulation for the RF-heated phase of the ITB experiment. The smoothed profiles from all simulations (b), used for the CX-study.

During the Ohmic phase, E_r does not show significant structure in either of the experiments. This is because the temperature remains low while the density is reasonably high. The banana orbit widths are narrow, the collisionality high and, thus, there cannot exist any significant poloidal torque due to orbit losses. Consequently, E_r is close to its ambipolar value.

During RF-heating the L-mode E_r -profile changes only modestly. This is because the temperature does not increase much while the density rises significantly. Thus direct losses remain small. The E_r -profile obtained for the RF-heated phase of the ITB-experiment changes more dramatically, but it does not quite reflect the nature of the confinement improvement: the profile steepens, but most strongly in the vicinity of the plasma edge. This is partially due to the collisionality that remains fairly high, so that the wider banana-orbits can not contribute to the orbit losses except very near the periphery. However, there is a mechanism that could prevent E_r from reaching very high values even with weak collisionality: In FT-2, with its small B_p/B_T -ratio, the Mach number M of the poloidal rotation easily exceeds unity even with a relatively small E_r . At high M , the number of trapped (resonant) ions is strongly reduced, leading to a diminishing Γ and, consequently, to clamping of E_r to the value it had reached.

The CX-signal to a neutral particle analyzer that views ripple-blocked ions above the thermal energy should respond to changes in the radial electric field [4]. The CX-signal was simulated using the plasma profiles and E_r obtained for the ITB experiment in both Ohmic and RF-heated phases. The radial distribution of the collected signal is shown in Fig. 3 for two energy channels: $1.1\text{keV} < E_{kin} < 1.6\text{keV}$, and $1.6\text{keV} < E_{kin} < 2.1\text{keV}$. The overall signal levels are lower in the higher energy channel, as expected due to the low temperature. The signal level in the RF-heated phase is orders of magnitude higher than in the Ohmic phase. To make sure that this increase is due to E_r and not simply because of the different plasma profiles, we also simulate the CX-flux for the RF-phase profiles in the *absence* of E_r . As can be seen, with $E_r = 0$ the CX-signal level reduces to the Ohmic level. It is thus concluded that the CX-detectors on FT-2 should observe changes in the radial electric fields.

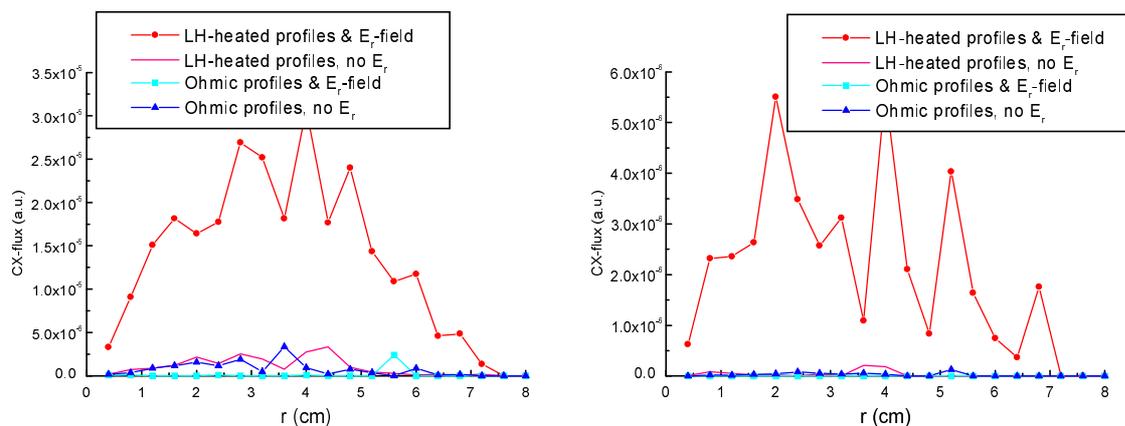


Fig 3: The radial distribution of the CX-signal for (a) $1.1\text{keV} < E_{kin} < 1.6\text{keV}$, and (b) $1.6\text{keV} < E_{kin} < 2.1\text{keV}$. The simulations used the E_r -profiles given in Fig. 2(b).

Conclusions and Discussion. Neoclassical ASCOT simulations of the formation of E_r in FT-2 tokamak indicate that, if the profiles are not very steep, orbit losses alone steepen the E_r -profile mostly at the edge. This is because: 1) The local values of plasma parameters are not sufficient in determining the magnitude of orbit loss current, but all values along the orbit have to be considered; and 2) already a modest E_r provides a poloidal v_{ExB} that completely dominates v_{VB} and, thus, extinguishes the orbit losses altogether. This could also explain the efficiency of the LH-heating on FT-2 tokamak: the rising temperature leads to larger orbit losses and growing radial electric field, accompanied by significant poloidal rotation, which transforms the otherwise wide banana orbits into orbits that closely follow the original flux surface. Consequently the high energy ions generated by LH-heating will be well-confined, leading to an efficient heating of the plasma bulk. With very steep gradients in the central region, a deep (30-40 kV/m) electric field well is formed inside the plasma (to be published).

References

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