Monte Carlo Simulations of Ripple-Trapped Beam Ions in the Presence of a Non-uniform Radial Electric Field

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Abstract. The increase in the neutral flux from the ripple-trapped ions at an L-H transition observed by the CX-detector at ASDEX Upgrade is reproduced by Monte Carlo simulations by turning on E_r near the plasma periphery. For E_r with large enough half-width, the rise-time of the fluxes is shorter than 100 μs, which could make this diagnostic a useful tool for time-resolved measurements of E_r.

Introduction. At an L-H transition, a sudden change in the edge radial electric field has been observed [1], but the question of causality in a spontaneous L-H transition is yet to be resolved. The time resolution of the measurements has not yet been good enough to decide whether the plasma switches to the H-mode before or after the fast changes in the E_r-field [2].

The CX-detector on ASDEX Upgrade monitors the slowing-down ions from the neutral beams that are trapped in the secondary magnetic wells near the plasma surface formed by the discrete set of magnetic coils. These ripple-trapped ions are expected to escape the plasma very fast, in about 50 μs, as a result of the ∇B-drift and, consequently, the CX-detector should receive a negligible flux under ordinary circumstances. However, as the plasma enters the H-mode, these neutral particle fluxes reach levels that are comparable to the signal from nontrapped ions. It has been suggested that the underlying reason for the increased neutral particle flux from ripple-trapped slowing-down ions is a changing E_r-field [3] and, thus, the neutral flux could be used as diagnostic tool for E_r.

We have investigated the effect of a non-uniform E_r on the ripple-trapped neutral beam ions using a Monte Carlo particle tracking code ASCOT [4] that follows the guiding center trajectories of test particles. The tokamak geometry models ASDEX Upgrade, where ∇B-drift is downward. The effects from plasma elongation, triangularity, and Grad-Shafranov shift are omitted for simplicity. The neutral density is assumed to decay rapidly as one moves inwards from the plasma boundary ($a = 50$ cm), $n_n = n_{n_0} e^{(r-a)/d_n}$ with $d_n = 2$ cm. The test particles are initialized according to ions born in the neutral injector beams. The initial energy for the test particles (deuterons) is chosen at the 1/3 power fraction of the beams (20 keV), which is dominant as far as particle source is concerned. The innermost particles are launched at $r = 41$ cm, corresponding to $\rho = r/a = 0.83$. This is well justified, because both the neutral beam flux and the neutralization probability (relevant to the detection) drop very rapidly as the distance to the separatrix increases. The ions are followed until they either escape the plasma ($r > a$), or their energy falls below 2.5 keV.

The magnetic field ripple is modelled by $B_0\Delta(r) = B_0\Delta_0 e^{r/w_B}$, where $B_0\Delta_0$ is the ripple strength on the magnetic axis. Choosing $\Delta_0 = 0.003$ and $w_B = 16$ cm, the model fits quite well the ripple strength obtained from more detailed calculations done on ASDEX Upgrade. In ASDEX Upgrade, the number of toroidal coils is $N_c = 16$ and, thus, the magnetic ripple has a 16-fold periodicity in the toroidal coordinate. The radial electric field is given in a polynomial form $E_r = c_0 + c_1\rho + c_2\rho^2 + c_3\rho^3$, depicted in Fig. 1. The coefficients were chosen so that the profile resembles the experimental profile of E_r measured in DIII-D after an L-H transition (see Fig. 7 in Ref. [5]). We have even allowed a small region inside the separatrix where E_r turns positive (outward). This corresponds to an $E \times B$-drift that is in the same direction as the ∇B-drift and, thus, that is detrimental to the particle confinement. If the separatrix is further in, so that E_r remains always negative inside the plasma, the favorable effects presented in this paper are further magnified.

Results. In Fig. 2 we show the neutral particle flux as a function of toroidal (ϕ^*) and poloidal (θ) angle. The signal is collected on a 20×20 grid that maps the region of interest. Because of the 16-fold periodicity of the system, it is sufficient to look at just one coil period, $0 < \phi^* < \Delta\phi = \frac{2\pi}{N_c}$. The pitch, $\xi = v_{||}/v$, of the ions contributing to the signal satisfies the condition $|\xi| < 0.07$, and their kinetic energy, $\mathcal{E}$, is between 5 and 15 keV. Here, $v_{||}$ is the ion's velocity parallel to the magnetic field, and v is the total velocity at the moment of neutralization. With the present ripple parameters, this guarantees that the detected ions are either ripple-trapped, or they are banana particles near their turning points. Figure 2a, with $E_r = 0$, exhibits a significant depletion of particles near the bottom of the magnetic well due to the fast ∇B -drift losses. Near the coils the detector monitors banana particles for which the ripple-trapping is less probable. Therefore, this region of phase space remains reasonably densely populated, and the signal level is $10-20$ times higher. Poloidally, the signal is enhanced on the lower half due to the downward convection of the ripple-trapped ions [7].

As shown in Fig. 2b, when a non-uniform E_r is introduced to the plasma, the signal depression around the bottom of the magnetic well not only disappears but now the signal has its maximum value there. That the signal from the ripple-trapped ions now exceeds that from the banana-trapped ions can be understood as follows: In the absence of E_r, due to the very narrow neutral density profile, most of the CX-detector signal originates from the very edge of the plasma, where the drift losses efficiently deplete not only the ripple-trapped ions but also banana ions near the ripple-banana boundary. A negative E_r with wide enough profile to affect the orbits of ions residing further inside the plasma contributes an additional drift that opposes the ∇B-drift and, consequently, bends the orbits of these ions outward and, eventually, upward. Therefore, such a radial electric field can force ions from further in to enter the line-of-sight of the detector. Because there are much more ions at these smaller radii, the signal increase due to E_r can dominate the local signal from the banana-trapped ions.

Figure 2c gives the ratio of the neutral flux in the presence of E_r to the flux in the absence of the field, *i.e.*, the ratio of flux in Fig. 2b to that in Fig. 2a. Clearly, the ions that are most sensitive to E_r, reside in the ripple-trapped part of the phase space. Therefore, the presence of a radial electric field can be best observed by monitoring ions near the bottom of the ripple well, for poloidal angles slightly below the mid-plane and, thus, the movable CX-detector on ASDEX Upgrade can monitor the optimal part of the phase space.

In Fig. 3 we show the time evolution of the neutral flux in response to an abrupt onset of E_r at $t = 1$ ms. The detector monitors ions with $|\xi| < 0.07$, $|\theta| < 0.5$ rad, 5 keV $< \mathcal{E} <$ 15 keV, and 0.25 rad$< \phi^* <$ 0.35 rad (with the magnetic well at $\phi^* \approx 0.3$ rad). According to Fig. 2, this window corresponds to ions that are most sensitive to E_r. The simulation is started well before the onset of the field to obtain stationary conditions, and new ions are born steadily throughout the simulation. Also the time evolution in the absence of E_r is shown (dotted line). Before E_r is turned on, only a weak signal is observed but, at $t = 1$ ms, a fast growth is observed for the $E_r \neq 0$ -curve, while the curve corresponding to the fieldless case remains at the low level. Constrained by the statistical accuracy of the simulation, the signal growth can be characterized by a response time of about 50 μs to the field onset. Collisional effects alone are not sufficient in explaing the fast time response to the radial electric field, and some other mechanisms must be involved. Indeed, solving the relevant Fokker-Planck equations for the ripple-blocked ion distribution [6], the fast convective drift of the ripple-blocked ions from the inner, well-filled ripple-orbits to the depletion region is found to be responsible for the fast growth of the ripple-blocked ion distribution by the onset of the radial electric field [8].

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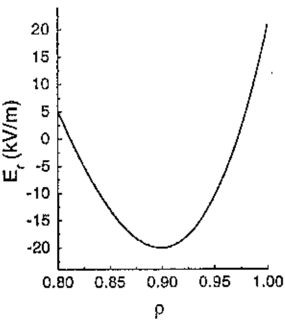

Fig. 1. The radial electric field used in the simulations.

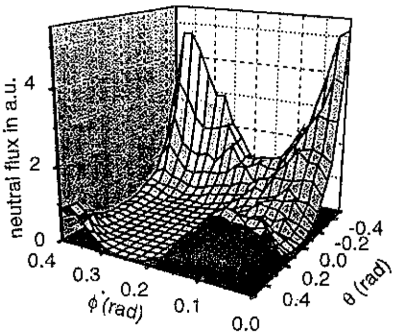

Fig. 2(a). Neutral particle flux Γ in the absence of a radial electric field.

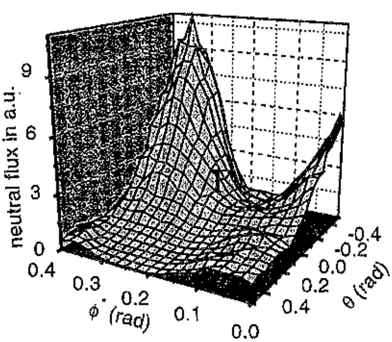

Fig. 2(b). Neutral particle flux, Γ, when the radial electric field of Fig. 1 is present.

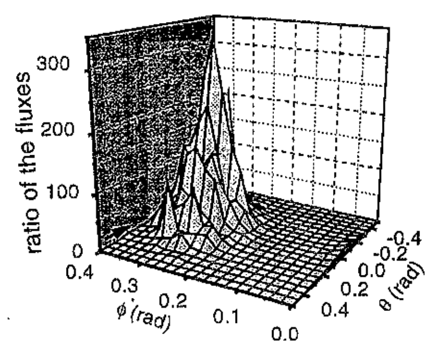

Fig. 2(c). $\Gamma(E_r < 0)/\Gamma(E_r = 0)$, i.e. ratio of the flux of Fig. 2(b) to the flux of Fig. 2(a).

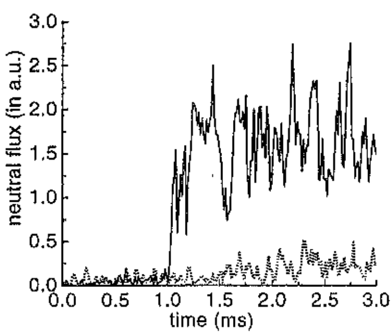

Fig. 3. The time evolution of neutral flux when E_r of Fig. 1 is turned on at t = 1ms.