CX-NEUTRAL FLUX DIAGNOSTICS OF THE RADIAL ELECTRIC FIELD

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1. Introduction

An edge radial electric field in tokamaks is believed to play a crucial role in the L-H transition and, thus, it is important to know when the radial electric field (E_r) appears and how fast it is established. In a recent experiment at ASDEX Upgrade [1], CX fluxes (time resolution <100 μs) from ripple-trapped slowing-down ions from the neutral beams were found to evolve at the L-H transition. The CX-flux growth (by a factor 10-30) was delayed the more the higher was the energy channel, suggesting that a growth of E_r improved the confinement of the ripple-trapped ions. Surprisingly, with ASCOT OFMC simulations of these ions [2,3], the CX-flux characteristics could be reproduced for the experimental conditions only by assuming a slowly (> 1 ms) evolving E_r. In this paper, we study the physics behind the prompt response of the CX flux signal to the E_r variation with the help of Fokker-Planck equations [4] solved self-consistently for the ripple-trapped, banana, and passing ion distributions in time, velocity, and space, and try to specify that E_r variation which best matches the CX flux measurement.

2. Prompt response

Figure 1 shows the stationary ripple-trapped 10 keV neutral beam slowing-down ion distribut-ion in radius and poloidal angle for three electrostatic potentials $V = V_o \exp(-(r-a)^2/r_e^2)$ of different amplitude V_o and width r_e = 2 cm in radius. 20 keV neutral beam ion source with a 15 degrees equatorial angle of incidence with respect to the radial line-of-sight is assumed. The ripple-trapped ion distribution is evaluated at the bottom $\chi = 0$ of the ripple well. The tokamak geometry is chosen to model that of ASDEX Upgrade: The major and minor radii are R_o = 1.5 m and a = 0.5 m, respectively, the magnetic field on axis is B_T = 2.1 T, and the plasma current is Ip = 1 MA. For simplicity, the effects from plasma elongation, triangularity, and the Grad-Shafranov shift are omitted in the present analysis. The toroidal field is clockwise, when viewed from the top, and, consequently, the ∇B-drift is downward. The plasma current is counter-clockwise. The stationary deuterium background plasma is modelled by n , $T = n_o , T_o \times (1 - \rho^2)^{\alpha_n , \alpha_T}$. In the simulations, $n_o = 8 \times 10^{19}$ m^{-3} is the density and T_o = 0.6 keV is the temperature of the plasma electrons and ions at the plasma centre. The profile exponents are $\alpha_n = \alpha_T = 0.5$. The number of toroidal field coils in ASDEX Upgrade is 16, and so the magnetic ripple has a 16-fold periodicity in the toroidal coordinate: $B_{Tr} - B_o = B_o \Delta(r) \sin(16\phi)$.

Near the plasma periphery, at small poloidal angles, a large deficit in the deeply ripple-trapped ion distribution is seen in Fig. la in the absence of E_r. The deficit has been found to be rapidly filled (in less than 100 μs) by the onset of an inward E_r of a sufficient magnitude. The time scale for this filling can be explained by the different ripple ion drift orbit topologies generated by E_r, and it is determined by the convective drift time of the ripple ions from the inner, well-filled ripple region to the depleted region along these orbits. Consequently, the time scale can be much faster than the collisional time scale, and the ripple ion distribution function should faithfully follow the changes in E_r .The mechanism of the fast filling of the ripple loss region can be clearly identified in Figs. lb and lc showing the fully evolved distributions with $E_r \neq 0$.

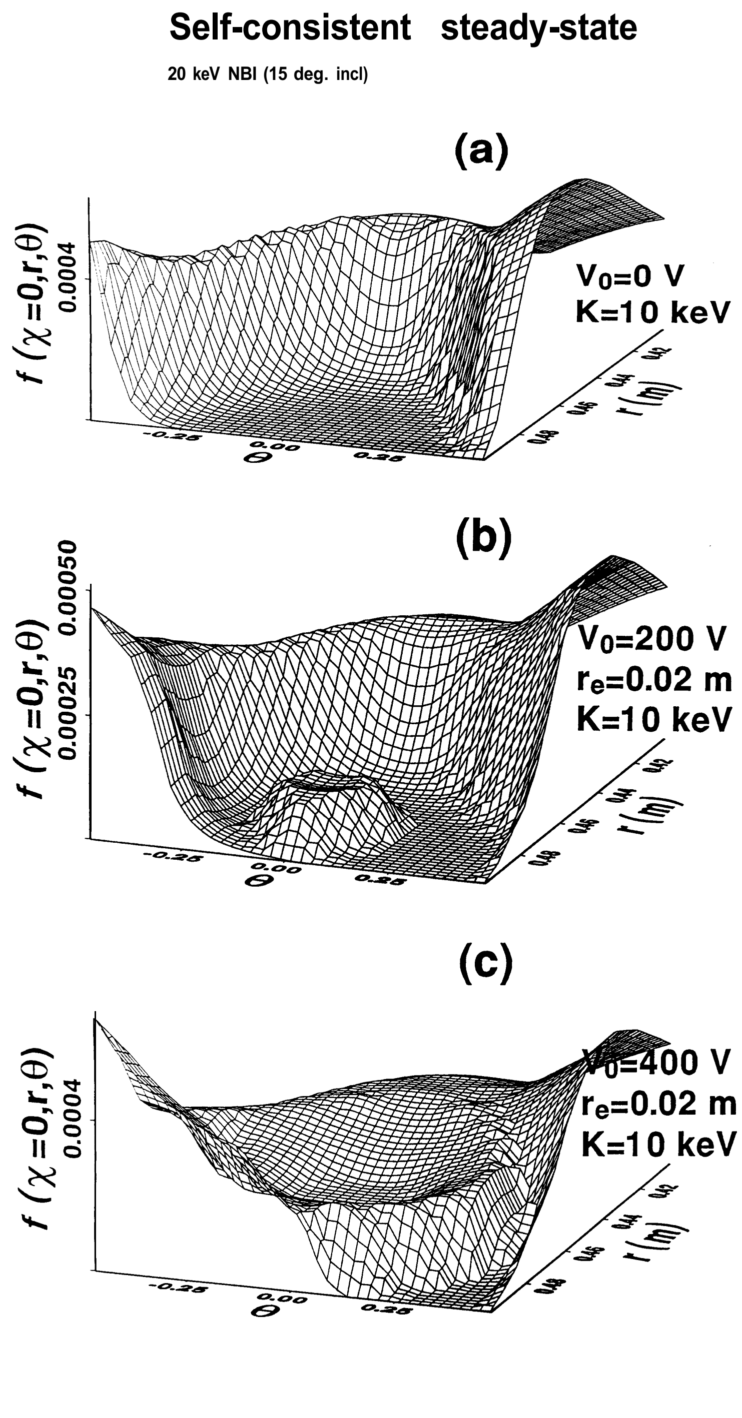

Fig. 1. The stationary distribution function $f(\chi = 0, r, \theta)$ for 10 keV ripple-blocked deuterons obtained with the electrostatic potentials (a) V_0 = 0, (b) V_0 = 200 V, and (c) V_0 = 400 V with the width r_e = 0.02 m.

By modifying the beam source parameters it was observed that the prompt response of the ripple-ion distribution to the radial electric field did not depend sensitively on the source details. To see any effect, it was important to inject the beam near the ripple region. 0therwise, the fast slowing-down would have prevented the beam ions to be ripple trapped during their slowing.

Fig. 2 shows the stationary CX neutral flux collected from 10 keV ions with various field amplitudes and widths as a function of θ. The neutral flux is assumed to emanate along the radial line-of-sight from each point. Even with very narrow profiles, r_e = 1 cm, a large enhancement can be observed.

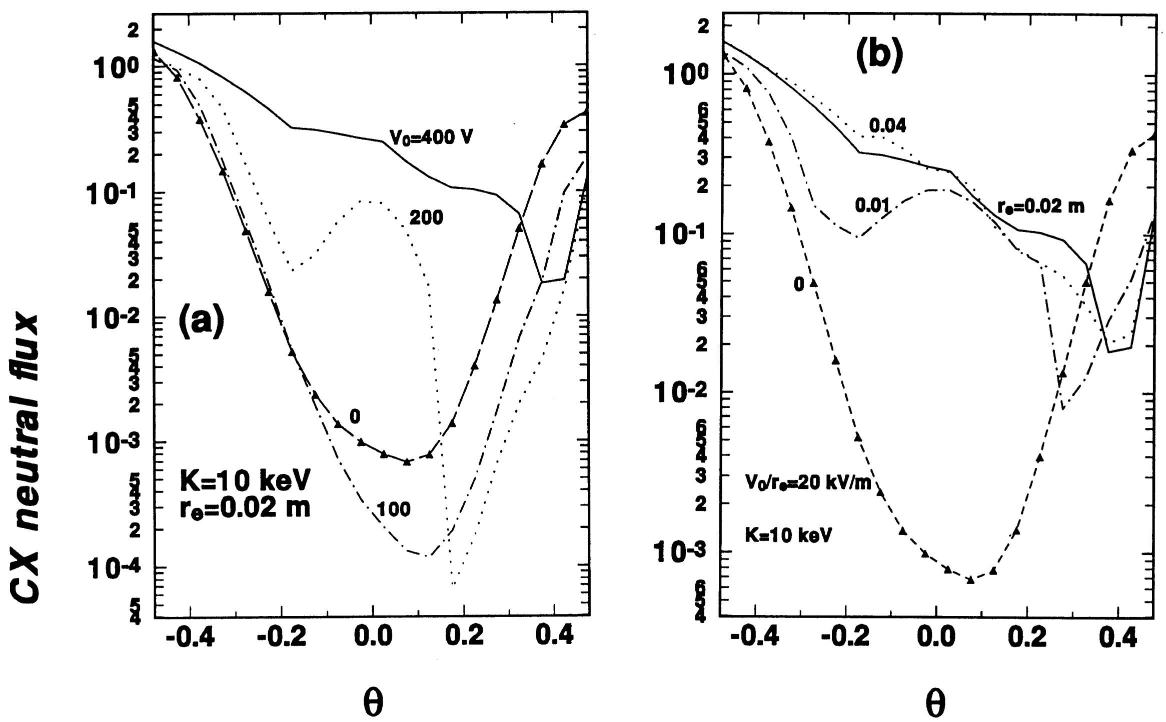

Figure 2. The CX neutral flux (in arbitrary units) as a junction of θ at steady-state after the onset of an electric field as obtained from the consistent Fokker-Planck solution. (a) For various potential maxima, V_o (in Volts), with r_e = 0.02 m and fixed kinetic energy (10 keV). (b) For various electric field widths r_e with the kinetic energy 10 keV, and with the ratio V_o / r_e = 20000 V/m kept constant. The signal in the absence of the electric field is shown with a curve having solid triangles.

3. Discussion

Experimentally the appearance of a radial electric field should thus lead to a strong enhancement in the signal for a neutral particle detector viewing the ripple-blocked part of the phase space for a specific energy range limited by the radial electric field. Indeed, this has been the interpretation of the observations on ASDEX Upgrade experiments at the L-H transition [l]. In these experiments, the CX-signal was found to start growing the later the larger the energy of the detection channel was, indicating a steadily growing electric field after the L-H transition. At first sight, the slow (1 ms) evolution of the CX-flux after the L-H transition observed in Ref. [l] does not appear consistent with any fast jump in the radial electric field because, according to our results, the CX-signal should faithfully follow the field variation, provided that the field strength is appropriate (see Fig. 2a). However, because according to Fig. 2b the CX-flux enhancement becomes stronger for wider and stronger fields (up to some saturation width and strength), a modest fast jump of the field could take place after the L-H transition in a narrow (< 1 cm) region close to the separatrix, with subsequent - further, slow broadening and strengthening of the field. If the background signal in the CX-detection is significantly higher than the flux from the depleted region in the absence of an (or in the presence of a weak) electric field, the initial jump could go undetected. In fact, assuming a background level that is 20 - 30 times higher than the minimum flux level in the absence of an electric field (the $E_r = 0$ -curve in Fig. 2) would indicate a poor flux enhancement by the onset of a narrow electric field, $r_e < 0.01$ m.

In the Monte Carlo OFMC simulations, the banana- and passing-ion distributions were followed in time, simultaneously with the ripple-blocked ions. Also, such mechanisms as neoclassical diffusion, banana orbit losses, and stochastic ripple transport, which are missing in the present Fokker-Planck model, were included in the Monte Carlo simulations. The parameters were the same as in the present analysis, and the radial electric field had a width and magnitude comparable to the ones used in this paper. A fast signal response was observed in the parameter range where, in the absence of a radial electric field, the convective ripple losses are significant. To ensure a sufficient statistical accuracy, the signal was collected for a fairly wide detector window for energy; 5 keV< K <15 keV, poloidal angle; $-0.5< \theta < 0.5$, pitch; $-0.07 < v_{||}/v < 0.07$, and toroidal angle; $-0.05< \phi - \phi_m < 0.05$, corresponding to a broad χ-region (χ <0.4) around the ripple well bottom. Here, ϕ_m corresponds to the bottom of the magnetic well. The steady-state CX-flux was also obtained as a function of θ, within the same χ-region, and the signal enhancement by E_r agrees qualitatively with the present Fokker-Planck results with K = 10 keV and $\chi = 0$.

The convective filling mechanism suggested by the present work indicates a response time $\tau_f = L/v_d$, where L measures the drift length from the undepleted region to the depleted region, and v_d is the drift velocity. To get a rough estimate for the response time, we assume $L \approx a \sin\theta_M$, where θ_M the half-width of the ripple domain in the poloidal angle near the plasma edge. We thus find $\tau_f = a \sin\theta_{Mq} BR/K$. Taking θ_M =0.3, B =1.5 T, R=2 m and K= 10 keV, we find $\tau_f \approx 60$ μs, which is comparable with the present numerical results. Because the threshold electric field for confinement of the ripple orbits scales as $|E_r| > K/qR$ in larger tokamaks higher energy ripple-ions can become confined with the same E_r. Therefore, in order to find small τ_f, in larger tokamaks it is necessary to measure the CX fluxes from higher energy ions and, possibly, for a narrower poloidal angle range.

References

[1] W. Herrmann and the ASDEX Upgrade Team: Phys. Rev. Lett. **75** (1995) 4401.
[2] J.A. Heikkinen, W. Herrmann, and T. Kurki-Suonio: Phys. Plasmas **4** (1997) 3655.
[3] J.A. Heikkinen, W. Herrmann, and T. Kurki-Suonio: Nucl. Fusion **38** (1998) 419.
[4] J.A. Heikkinen and T. Kurki-Suonio: Phys. Plasmas **5** (1998) 692.