Ion Orbit Loss Flux in the Presence of a Radial Electric Field

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Abstract: The multivalued balance between loss of fast ions from the plasma boundary and the neoclassical return current has been proposed to be a reason for L-H transition. By fully toroidal Monte Carlo calculations it is shown that loss cone structure is remarkably modified by strong radial electric field. Effect of the collisionality and direction of the magnetic field to the bifurcation conditions are discussed.

Introduction: In tokamak plasmas, fast increase of the radial electric field E_r is observed near the plasma edge in the context of an L-H transition. The shear flow associated with E_r is believed to suppress fluctuations responsible for anomalous transport. According to one proposal, the multivalued balance between the non-ambipolar loss of fast ions from the plasma boundary and the neoclassical return current could be the reason for the spontaneous transition from low to high electric field. In this work, the ion orbit loss as a function of radial electric field in ASDEX Upgrade geometry is investigated using a fully toroidal Monte Carlo code ASCOT (3D in space and 3D in velocity) [1]. Exact guiding-center orbit trajectories are evaluated, and the loss cone is determined from the condition of intersection of the orbit with the divertor plates or wall structure. Influence of the strong radial electric field to the loss cone structure is presented for thermal and high energy tail particles. Neoclassical return current is calculated with analytical model and it is compared with the ion orbit loss flux. Analysis is done for both directions of toroidal magnetic field and for different temperatures.

Numerical model: With Monte Carlo simulations, the loss of ions of a Maxwellian distribution near the separatrix is determined as a function of E_r. In simulations, constant $E_r(\rho) = -d\phi/d\rho$ is used, to simplify the problem. Here, ϕ is electrostatic potential and ρ is the flux surface label normalized to the value on separatrix. (In tests with more realistic profiles, orbit squeezing due to negative $dE/d\rho$ [2] was found to decrease losses. However, this effect is not remarkable as already noted in [3].) Ensemble of particles with initially local thermal velocity is followed and the particles which are lost due to their orbit width are registered. The lost particles are weighted with the number which corresponds to the relative phase space volume of the initial position of the particle. From the cumulated number of lost particles, loss current density can be determined as an cumulation velocity divided by the flux surface area. Stationary background temperatures and densities are

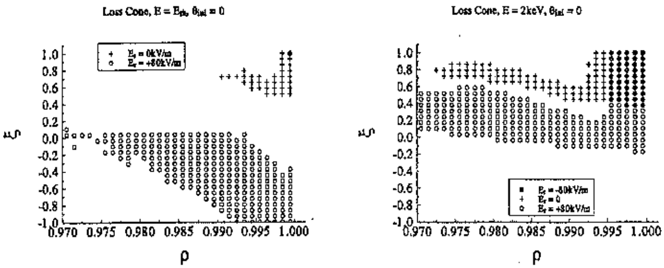

Figure 1: *Loss cone for thermal and tail particles as a function of radius and energy*

assumed. Coulomb collisions are present, including pitch angle scattering and velocity diffusion.

Neoclassical return current density is calculated using expression [4]

$$j_r = \frac{\sqrt{\pi} n T \varepsilon^2}{B r v_{th} B_\theta}(E_r - \frac{T}{e}(\frac{n'}{n} + \gamma\frac{T'}{T}) - B_\theta U_{\|})e^{-(\frac{E_r}{v_{th}B_\theta})^2} \quad (1)$$

where n, T and v_{th} are local ion density, temperature and thermal velocity, respectively, r, ε B and B_θ are minor radius, inverse aspect ratio, total magnetic field and the poloidal component of the magnetic field, respectively, E_r is radial electric field, e is elementary charge, $\gamma = \frac{3}{2}$ in the plateau regime, $U_{\|}$ is the mean velocity along the magnetic field and differentiation with respect to the radius is denoted by prime.

Results: Background data of Asdex Upgrade discharge 8044 is used. Near the separatrix density and temperature profiles of the background ions and electrons on equator are approximately $n, T(r) = n, T(r_{sep}) + (r - r_{sep})n', T'$ with $n_{D,e}(r_{sep}) = 1.2 \times 10^{19}$ m^{-3}, $T_{D,e}(r_{sep}) = 120$ eV, $n' \approx -4 \times 10^{20}$m^{-4} and $T' \approx -6keV/m$. Values $a = 0.5$ m, $R = 1.65$ m, $I_p = 1$ MA and $B_t = -2.5$ T are used for minor and major radius, plasma current and toroidal magnetic field on the axis, respectively. Negative B_t means that ∇B drift is downwards, which is, towards the X-point.

In Fig. 1, loss cone of thermal 120 eV, and 2 keV tail particles is presented as a function of radius and pitch angle. Analysis is done by calculating the trajectories in the absence of collisions for particles initially on outboard equator. Simulation is done in the absence and presence of constant strong radial electric field. For $E_r = 0$, loss happens for for positive pitch angles, i.e., for particles which due to ∇B drift shift outwards from the launching point. For energetic particles with larger banana width, loss cone penetrates deeper into the plasma. With $E_r = -80$ kV/m positively poloidally directed $E \times B$ drift is strong enough to turn particle first to direction where ∇B drift moves particles to inner flux surfaces. No loss orbits were observed. When $E_r = +80$ kV/m, in case of thermal particles, loss cone is shifted to particles with negative pitch angles, i.e., particles which in the absence of E_r are confined. Here again, $E \times B$ drift changes the direction of poloidal motion. Now, the particles leaving from equator with $v_{\|} < 0$, are lost to outer divertor plate. For energetic particles situation is qualitatively different. For pitch angles

$\xi < -0.2$, due to their high energy, direction of poloidal motion is not reversed. However, E_r still shifts and enlarges the loss cone.

In Fig. 2, ion orbit loss flux in the presence of Coulomb collisions is calculated. Simulation is done for both directions of toroidal magnetic field $B_t = \pm 2.5$ T. To get three different collisionalities, the temperature data is multiplied by factors $k = 0.5$, 1 and 2 corresponding to edge temperatures, $T_{sep} = 60$, 120 and 240 eV, respectively. Neoclassical return current is calculated for fluid velocity $U_{\|} = 0$. At strong collisionality, the ion loss current and the neoclassical return current have their L-mode root at low electric field. Reducing the collisionality does not remove this root. In contrast, the return current increases and the loss current reduces, which implies at low collisionality a stable L-mode root even at lower electric field. This analysis was done on separatrix. When going inside the separatrix, non-ambipolar ion orbit loss flux decrease fast and, at the same time, return current obtained from Eq.(1) would increase with increasing density and temperature.

Conclusions: In this work, effect of the strong radial electric field to the loss cone structure and to the amount of the ion orbit loss current was found remarkable. An inward electric field was found to decrease ion orbit loss with both directions of B_t. It should be noted that the loss current does not fit the analytical expression of Shaing [5] (as already noted in [3]), where the loss was independent of the sign of E_r. The ambipolarity of the loss current and the neoclassical return current obtained from Eq.(1) has not been found to produce bifurcated solutions for E_r as the edge plasma becomes less collisional. In order to check the validity of this calculation, the direct calculation of the return current from the Monte Carlo simulations and with the 3D Fokker-Planck code [6] is in progress. Also, the inclusion of an anomalous radial ion diffusivity may be important for the calculation of the loss current, because the filling of the loss cone should be determined by the total diffusion of the ions in the configuration space for which the temperature dependence may be different than for the neoclassical diffusion simulated by ASCOT here.

References

[1] J.A. Heikkinen, S.K. Sipilä, Phys. Plasmas 2 (1995) 3724.

[2] K. Itoh, S. Itoh, Plasma Phys. Contr. Fusion 38 (1996) 1.

[3] A.V. Chankin, G.M. McCracken, Nucl. Fusion 33 (1993) 1459.

[4] T.E. Stringer, Nucl. Fusion 33 (1993) 1249.

[5] K.C. Shaing, E.C. Crume Jr., Phys. Rev. Lett. 63 (1989) 2369.

[6] T.P. Kiviniemi, J.A. Heikkinen, submitted to Comput. Phys. Comm.

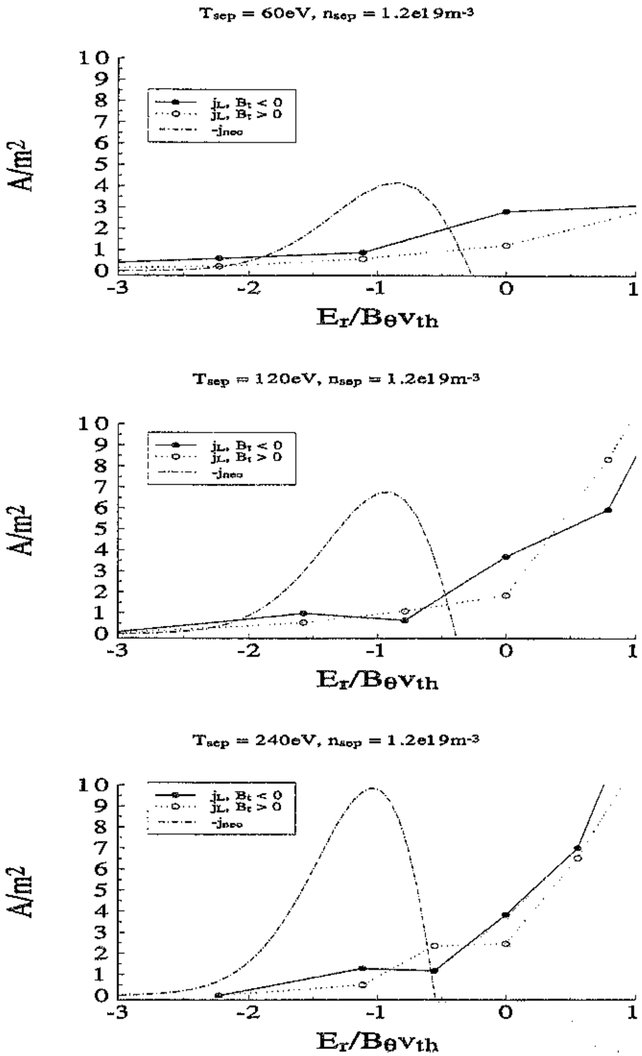

Figure 2: *The dependence of the ion orbit loss flux and the neoclassical return current on the radial electric field. Collisionality decreases from (a) to (c). Here, the numerical value of* E_r *is the radial electric field* $E_r(r_{sep}) = -(d\phi/d\rho)\nabla\rho$ *on the equator.*