Plasma Phys. Control. Fusion **40** (1998) 693–696. Printed in the UK PII: S0741-3335(98)91611-6

# Ion orbit loss current in ASDEX Upgrade

J A Heikkinen†, T P Kiviniemi‡, A G Peeters§, T Kurki-Suonio‡, S K Sipilä‡, W Herrmann§, W Suttrop§ and H Zohm‖

† VTT Energy, TEKES-Euratom Association, P.O. Box 1604, FIN–02044, VTT, Finland
‡ Helsinki University of Technology, TEKES-Euratom Association, P.O. Box 2200, FIN–02015 HUT, Finland
§ Max-Planck-Institut für Plasmaphysik, Euratom Association, D-85740 Garching, Germany
‖ Institut für Plasmaforschung der Universität Stuttgart, D-70569 Stuttgart, Germany

Received 24 September 1997

**Abstract.** The orbit loss current is calculated for the ASDEX Upgrade geometry using the 5D (3D in configuration space and 2D in velocity space) Monte Carlo code ASCOT. The balance between the obtained current and the analytical estimate of the return current shows an L–H transition for the normalized collision frequency $\nu_{*i} \approx 1$ as expected from analytic theory. The transition in ASDEX Upgrade, however, occurs at larger values of $\nu_{*i}$.

## 1. Introduction

During the L–H transition a fast increase in the magnitude of the radial electric field $E_r$ is observed in the plasma edge. In the H-mode the shear flow associated with the gradient in $E_r$ is then believed to suppress the anomalous transport. The process which is the cause of the change in the electric field at the transition, however, is still a subject of discussion in the literature. According to one proposal, the multivalued balance between the non-ambipolar loss of fast ions from the plasma boundary and the neoclassical return current is the reason for the spontaneous transition from low to high electric field [1]. The orbit loss current is usually calculated in cylindrical geometry, and a number of approximations are made to obtain an analytically tractable system. In this paper we present Monte Carlo calculations of the orbit loss current which where calculated using the 5D (3D in configuration space and 2D in velocity space) code ASCOT [2].

The remainder of the paper is structured as follows. In the section 2 the model is presented, then the results of the numerical calculations are given in section 3 and their meaning is discussed in the concluding section 4.

## 2. The model

The ion orbit loss current is evaluated using the exact gyro-centre trajectories, and the loss cone is determined from the condition of the intersection of the orbit with the divertor plates or wall structure. We aim to simulate the orbit losses within the model of Shaing [1], which is different from that of Itoh and Itoh [3]. Shaing assumes the ion distribution has approximately zero parallel velocity. For Shaing the plasma rotates poloidally, whereas the plasma rotates in toroidal direction within the model of Itoh and Itoh. The former assumption, in fact, demands that some external force damps the parallel motion of the

0741-3335/98/050693+04$19.50  

ions. Such a force can, for instance, be supplied by viscosity or neutral friction. In our model the external force is provided by the ion–ion collision operator which does not conserve momentum. The collision operator contains pitch angle scattering as well as velocity diffusion and collisions are evaluated using a Maxwellian background. Since the background should rotate with the $E \times B$ -velocity, the influence of the electric field on the test particle velocity is omitted when evaluating the effect of collisions. Temperature and density profiles are taken from the experiment, but collisionality in the calculations is varied by scaling the temperature. Although the fluctuations may cause the transition from L- to H-mode when both solutions exist, we assume here that the transition occurs only if the L-mode solution disappears.

At present a loss current can only be calculated for low values of the radial electric field. At higher values numerical problems lead to non-stationary density profiles and the interpretation of the obtained current is at least difficult. It will be assumed that the orbit loss current does not vary as strongly with the radial electric field as the return current. This assumption is validated by the analytic calculations of the orbit loss current [1].

The equilibrium electric field is obtained from the balance between the orbit loss current $j_{\mathrm{L}}$ and the neoclassical return current $j_{\mathrm{neo}}$. The latter can be expressed in poloidal viscosity using an equation due to Shaing [1]

$$j_{\mathrm{neo}} = \frac{\langle \boldsymbol{B}_\theta \cdot \nabla \cdot \boldsymbol{\pi} \rangle}{B_\theta B} = \frac{\sqrt{\pi}\epsilon^2}{4 r B_\theta} n m v_{\mathrm{th}} (I_{\mathrm{p}} U_{\mathrm{p}} + I_{\mathrm{T}} U_{\mathrm{p0}}) \tag{1}$$

in which $\boldsymbol{\pi}$ is the ion viscosity, $m$, $n$, $r$ and $\epsilon$ are the ion mass, particle density, minor radius and the inverse aspect ratio, respectively, $B$ ($B_\theta$) is the (poloidal) magnetic field, $v_{\mathrm{th}}$ the thermal velocity of the ions, $I_{\mathrm{p}}$ and $I_{\mathrm{T}}$ are integrals given in [1], $U_{\mathrm{p0}} = -T'/eB$ with temperature $T$, and the expression for the poloidal flow $U_{\mathrm{p}}$ is $U_{\mathrm{p}} = U_{\mathrm{t}} B_\theta / B - E_{\mathrm{r}}/B + p'/neB$ with $p$ being the pressure $p = nT$ and $U_{\mathrm{t}}$ the toroidal flow speed.

In the Monte Carlo simulations, an ensemble of particles is followed which initially represents the local Maxwellian distribution. In our model, the lost particles, which cross the equator outside the separatrix only once, and are sufficiently collisionless, i.e. $\nu_i/\nu_{\mathrm{b}} < p_{\mathrm{c}}$, when they cross the separatrix, contribute to the non-ambipolar ion orbit losses. Here, $p_{\mathrm{c}}$ is of the order of 1. The ions which at the separatrix have $\nu_i/\nu_{\mathrm{b}} \gg 1$ are expected to be accompanied by an almost equal electron flux across the separatrix while for the ions with $\nu_i/\nu_{\mathrm{b}} < 1$, the radial separation of the ion and electron orbits creates the non-ambipolarity. Here, $\nu_i = \sum_j \nu_{ij}$ is the pitch collision frequency of the $i$th ion species with the $j$th background particle species and the definition of the bounce frequency is $\nu_{\mathrm{b}} = |B_\theta| \max(\sqrt{\epsilon} v_\perp/2, |v_\parallel|)/2\pi r B \kappa$ with $\kappa$, $v_\parallel$ and $v_\perp$ being elongation, parallel and perpendicular velocity, respectively. A 'particle' in the Monte Carlo simulation represents a group of particles and 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 a cumulation velocity divided by the flux surface area.

## 3. Results

The simulations are performed for plasma parameters obtained from ASDEX Upgrade discharge 8044. These data are obtained under H-mode conditions. Near the separatrix, the density and temperature profiles of the electrons measured on the midplane are approximately $n, T(r) = n, T(r_{\mathrm{sep}}) + (r - r_{\mathrm{sep}}) n', T'$ with $n_{\mathrm{D,e}}(r_{\mathrm{sep}}) = 1.2 \times 10^{19}$ m$^{-3}$, $T_{\mathrm{D,e}}(r_{\mathrm{sep}}) = 120$ eV, $n' \approx -5 \times 10^{20}$ m$^{-4}$ and $T' \approx -5$ keV m$^{-1}$. Temperature and density

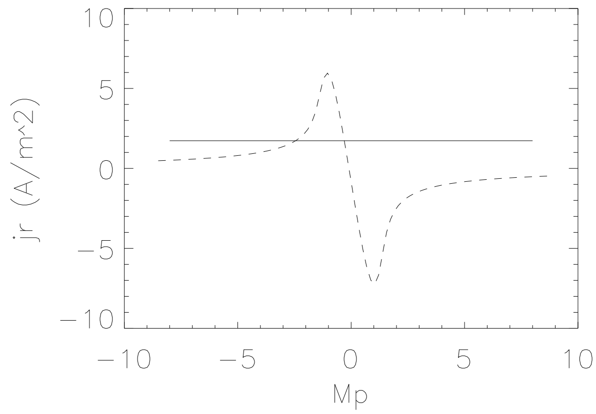


**Figure 1.** Neoclassical return current $j_{\text{neo}}(E_{\text{r}})$ (– – –) and $j_{\text{L}}$ for $E_{\text{r}} = 0$.

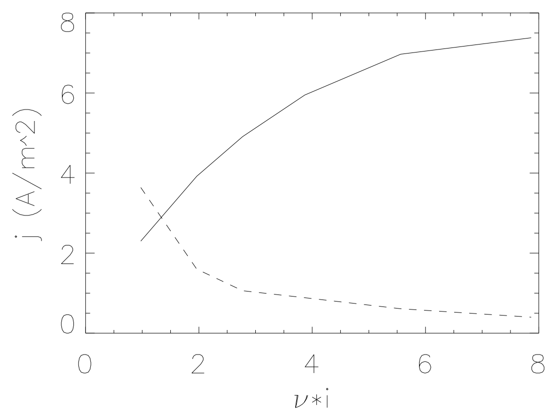


**Figure 2.** Ion orbit loss current for $E_{\text{r}} = 0$ (- - -) and the maximum of $j_{\text{neo}}$.

profiles of the ions are assumed to be equal to the electron profiles. The values $a = 0.5$ m, $R_0 = 1.65$ m, $I_{\text{pl}} = 1$ MA and $B_{\text{t}} = -2.5$ T are used for minor and major radius, plasma current and toroidal magnetic field on the axis, respectively. Negative $B_{\text{t}}$ means that $\nabla B$ drift is downwards, which is, towards the X-point. At the separatrix, the value of the collisionality parameter is $\nu_{*i} = \nu_{ii} Rq/v_{\text{th}}\epsilon^{3/2} \approx 3.8$. In figure 1, the neoclassical return current calculated from equation (1) for toroidal fluid velocity $U_{\text{t}} = 0$ as a function of the poloidal Mach number $M_{\text{p}} = E_{\text{r}}/v_{\text{th}}B_\theta$ is compared to the $j_{\text{L}}$ calculated only for $M_{\text{p}} = 0$, which is assumed to give the maximum of the orbit loss. It can be clearly seen that the maximum of $j_{\text{neo}}$ is much bigger than our estimate for $j_{\text{L}}$, meaning that the L-mode solution still exists for the discharge 8044 although it is in H-mode.

In figure 2, the loss current $j_{\text{L}}$ is presented as a function of $\nu_{*i}$ and is compared to the maximum of the neoclassical return current. Different collisionalities are obtained through a multiplication of the temperature by the factors $k = 0.7$, 0.83, 1, 1.2, 1.42 and 2, corresponding to edge temperatures $T_{\text{sep}} = 85$, 100, 120, 143, 170 and 240 eV, respectively. Decreasing collisionality increases the ion orbit loss and at the same time $j_{\text{neo,max}}$ decreases. In the banana regime ($\nu_{*i} < 1$), $j_L > j_{\text{neo,max}}$ and the L-mode solution disappears. This is in agreement with the analytical theory.

## 4. Conclusions

We have presented Monte Carlo simulations of the ion orbit loss current for the ASDEX Upgrade geometry with the plasma parameters taken from a H-mode discharge (8044). In the simulations, the ion orbit loss current is too small for the L-mode solution to disappear. In fact, we have found a good agreement with the analytic theory in which the transition occurs for $\nu_{*i} \approx 1$.

In the absence of measured data on the ion temperature and density, data for the electrons are also used for the ions. There are some indications that the ion temperature may be higher than the electron temperature which would make our results too pessimistic. In the simulations, the velocity distribution of the test particles near the edge was essentially Maxwellian with the local temperature, since the transit time of the ions in the absence of anomalous diffusion is slow here when compared with the energy diffusion or slowing-down time. Inclusion of an anomalous radial ion diffusivity as well as strong NBI or ICRF heating, may modify the Maxwellian distribution near the edge remarkably. If a strong hot ion tail is formed, the thermal ion collisionality may become an irrelevant bifurcation parameter [4]. However, quantitative analysis is beyond the scope of this paper.

In future, the dependence of the loss current on the radial electric field also has to be determined to enable us to determine more accurately when the L-mode solution disappears. Furthermore, the neoclassical return current is calculated here using an analytical estimate for circular geometry but should be evaluated for real ASDEX Upgrade geometry.

## References

[1] Shaing K C and Crume Jr E C 1989 *Phys. Rev. Lett.* **63** 2369
[2] Heikkinen J A and Sipilä S K 1995 *Phys. Plasmas* **2** 3724
[3] Itoh S-I and Itoh K 1989 *Nucl. Fusion* **29** 1031
[4] Shaing K C and Christenson P J 1993 *Phys. Fluids* B **5** 666