Diffusion of energetic particles due to charge changes and neoclassical tearing modes

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Abstract. The effect of charge changes on the transport of alpha particles is studied with a numerical code that follows the exact particle trajectories and includes the effect of elastic and inelastic collisions. It is shown that charge changing processes can produce significant fluxes in the edge-SOL region. The redistribution of high energy ions by (2,1) NTM modes is studied using a simple cylindrical equilibrium. It is shown that the electric field produced by the rotation of the mode can have a large effect and should be properly calculated.

1. Introduction

Various mechanisms for anomalous alpha particles transport have been considered. These include large scale MHD fluctuations, microturbulence, toroidal ripple and perturbations produced by ELM control coils. We show that processes that change the charge state of the alpha particles (i.e. charge exchange), and therefore their Larmor radius, can also produce a significant particle flux.

We study the redistribution of high energy ions produced by NBI using a simple analytical equilibrium. The perturbed magnetic and electric fields are calculated using Ampere’s law and Ohm’s law respectively, and the experimental information available. It is shown that the electric field produced by the rotation of the mode can have a large effect and should be properly calculated.

2. Alpha particle diffusion due to charge changes

When the charge of an alpha particle changes so does its Larmor radius, and random changes in the Larmor radius can result in particle diffusion. To illustrate this mechanism, we show, in Fig. 1, how charge changes can produce a diffusion process. In this figure, a particle rotating around a uniform magnetic field interacts with a uniform background of thermal and cold species. This interaction produces changes in the charge of the particle and “jumps” in the position of the guiding center, from “0” to “1,” then “2,” etc. We call this process “inelastic diffusion”.

Inelastic diffusion was first studied by Fussmann [1], who only included radiative recombination (RR) processes and concluded that it was not important for alpha particles in the core of a fusion reactor. Recently, Clauser and Farengo presented analytical calculations and
particle simulations that show that charge changing processes can significantly increase the diffusion of alpha particles in the pedestal-edge-SOL regions [2]. A simple 1D model was employed in [2], and only the interaction of the alpha particles with the plasma species, He$^+$ and neutral deuterium (both atomic and molecular) and helium were included. The numerical code employed calculates the exact alpha particle trajectories and introduces the probability of charge changing events via a Monte Carlo type method, where the probability of each process is taken proportional to the corresponding collision frequency. The cross sections of these processes were obtained from the existing databases [3] but it is clear that more, and more accurate, atomic data are needed. The code runs on a GPU, thus allowing calculations with a large number of particles in a short time using modest computational resources.

The main conclusion of Ref. [2] is that once the alpha particles reach the pedestal region, charge changing processes become important and therefore calculations of the alpha particle flux to the wall and divertor should include them. Another important finding is the existence of an inward flux of alpha particles that further reduces their density near the separatrix, which is the region where the confinement can be significantly affected by the toroidal field ripple and the perturbations produced by ELM control coils.

Here we present new results obtained with the same numerical code but a more realistic (2D) equilibrium and improved initial conditions. In addition, classical Coulomb collisions have been added.

2.1 Equilibrium and initial conditions

The 2D equilibrium employed was obtained from a numerical solution of the Grad-Shafranov equation and reproduces the main features of the standard ITER inductive scenario [4]. Figures 2-4 show, respectively, the cross section, with the flux surfaces and the chamber wall, the safety factor profile and the density and temperature profiles. In these figures the "radial" coordinate ($\rho$) is the square root of the toroidal flux. The density and temperature profiles are the same used in [2], and very similar to those shown in [5]. Note that the density of the neutrals is multiplied by a factor 100 and increases towards the wall.

Fig. 2. Cross section and flux surfaces of the equilibrium employed.

Fig. 3. Safety factor profile.
Our simulations cover the region above the oblique dashed red line that touches the lower tip of the separatrix (green), including the area between the separatrix and the wall. Particles that cross the dashed line are assumed to be lost to the divertor. The inner plasma region, with $\rho < 0.6$, is not included because the effect of inelastic collisions is negligible in this zone. The initial velocity distribution of the alpha particles is isotropic and follows a slowing down distribution function, while the spatial distribution has a Gaussian shape with a width of approximately 0.33.

2.2 Results

Figure 5 shows the loss rate of alpha particles as a function of time for simulations with and without inelastic collisions. The curve labeled 1 was obtained including only elastic (Coulomb) collisions, while curves 2 and 3 include both elastic and inelastic collisions. The difference between curves 2 and 3 is that curve 2 was obtained with the neutral density profile shown in Fig. 4 while curve 3 was obtained with a uniform neutral density profile with half the maximum value used for curve 2.

Comparing curves 1 and 2, we note that the initial loss rate is much higher when inelastic collisions are included, but the stationary value is higher when both types of collisions are included. This surprising result can be explained by noting that two competing effects determine the net flux of alpha particles when inelastic collisions are included in the presence of a neutral density gradient. The first one is a large diffusion coefficient that tends to increase
the flux in the direction opposite to the alpha particle density gradient and the second one is a particle flux in the direction opposite to the neutral density gradient. The physical mechanism responsible for the second effect was discussed in [2], where simulations performed with monoenergetic alpha particles clearly show an inward displacement of the particles (see Figs. 7 and 8 in [2]). The results shown in curve 3 provide additional evidence about the mechanisms involved. In this case the use of a uniform neutral density profile eliminates the inward flux, leaving only the much increased diffusion produced by inelastic collisions.

The results presented above clearly show the importance of the neutral density profile in the edge and SOL regions for the confinement of alpha particles. In what follows we only show results obtained with the non uniform neutral density profile.

Figure 6 shows the initial alpha particle density profile (black curve) and the final profiles obtained with elastic (red curve) and elastic plus inelastic collisions (blue curve). We can see that elastic collisions (alone) produce a small reduction of the density near the edge but no significant changes in the shape of the profile. When inelastic collisions are added the shape of the density profile changes significantly. The region near the separatrix is depleted of alpha particles and a gentle maximum appears between $\rho=0.8$ and $\rho=0.9$. This maximum is produced by the inward flux described above and in [2]. The maxima observed in [2] were sharper for two reasons: first, all the particles had the same energy and second, there were no elastic collisions.

Inelastic collisions modify the loss rate of alpha particles and also their spatial and energy distribution. When there are only elastic collisions almost all the lost particles reach the divertor and there is a negligible flux to the wall. When inelastic collisions are added, the fraction of particles reaching the wall increases significantly. Considering the situation at the end of the simulations, when the initial transient has disappeared the fraction of lost particles reaching the wall is 5.6% when there are only elastic collisions and 32.1% when inelastic collisions are added. The remaining particles cross the red dashed line of Fig. 2 and are assumed to be lost to the divertor. The lower part of the outer wall receives most of the lost particles flux.

When there are only elastic collisions the energy distribution of the lost particles has a maximum at very low energies, close to the energy of the plasma particles. This is consistent with the increase of the classical collision frequency as the energy decreases. When inelastic collisions are added, the peak shifts to higher energies, around 400 keV, because the rate of inelastic collisions peaks at approximately this energy.
3. Redistribution of energetic particles by NTMs

Neoclassical tearing modes can increase the diffusion of energetic ions produced by NBI. Detailed experimental and theoretical studies of this process have been performed in ASDEX-U [5-7]. The theoretical studies presented in [5-7] follow the evolution of a large number of beam ions by solving the guiding center equations and using different assumptions for the equilibrium and perturbed fields. A circular cross section equilibrium and a static magnetic perturbation was used in [5], while [6] used a similar perturbation in a realistic 2D equilibrium. Finally, Ref. [7] used basically the same equilibrium as [6] and a time dependent magnetic perturbation. The electric field produced by the rotation of the mode was included in [7], and its parallel component cancelled by introducing a potential. However, the effect of the perpendicular components of the electric field, produced by the gradients of the potential, is not discussed and the changes introduced by including the rotation of the mode do not seem to be very important. Although a general agreement with the experimental results was obtained in [5-7], the results are very sensitive to the spatial extent of the perturbation and only particles initially located very close to the separatrix (outside the NTM magnetic islands) are lost.

We employed the full orbit code already used to study the effect of kink modes on alpha particles [8] to study the effect of (2,1) NTMs on energetic ions produced by NBI. An analytic equilibrium with circular cross section was used [8]:

$$
\psi(x, \theta) = \psi_0(x) + \psi_1(x, \theta) = C \left( J_0 + \frac{\cos \theta}{2} \left[ xJ_0 + \frac{\alpha J_1}{k} (1 - x^2) \right] \right)
$$

$$
J_0 = J_0(kx) \quad J_1 = J_1(kx)
$$

where $\psi$ is the poloidal flux, $J_0$ and $J_1$ are Bessel functions, $x$ is the normalized minor radius coordinate and $\theta$ the poloidal angle. To study the effect of (2,1) modes the current was adjusted to have the $q=2$ surface at approximately the same position as in the experiment.

Ampere’s law was used to calculate the perturbed vector potential from the perturbed current and the resistive Ohm’s law to calculate the perturbed electric field. All perturbed quantities were assumed to have a space and time dependence of the form:

$$
f(r,t) = \tilde{f}(r) \exp \left[ i \left( m\theta - n\phi - \omega t \right) \right],
$$

where $\omega$ is the mode frequency and $\theta$ and $\phi$ are the poloidal and toroidal angles, respectively. The perturbed current was parametrized as in [9], and the parameters adjusted to reproduce the size and location of the observed island. Figure 7 shows the radial profile of the toroidal component of the perturbed vector potential.

The resistive Ohm's law is

$$
E_1 = -\frac{v_1 \times B}{c} + \eta J_1 \quad \frac{\partial \xi}{\partial t} = v_1
$$

were $\xi$ is the displacement and $\eta$ the resistivity (the neoclassical value was used). Due to the relatively slow evolution of the tearing mode we can assume that the plasma motion is incompressible. If, in addition, we assume that the toroidal dependence of the perturbation is very weak, the condition $\nabla \cdot \xi = 0$ allows us to write $\xi_\theta$ in terms of $\xi_r$. The radial component of the displacement, that was also parametrized as in [9], is shown in Fig. 8.
To test the effect of different assumptions we performed simulations with a static magnetic perturbation, a time dependent magnetic perturbation and a time dependent magnetic perturbation plus a time dependent electric field. Figure 9 shows the results of a calculation for a 30 keV beam with a 45° pitch. The normalized frequency is $\frac{\omega}{\Omega_0} = 3.8 \times 10^{-4}$ and the exact particle orbits were followed during 0.5 ms. The curves show the initial density profile and the final profiles obtained for the different conditions. It is clear that the addition of the electric field increases the spreading of the particles. Although not clear from the figure, it also increases the fraction of lost particles. Simulations for longer times and other energies and pitch are currently underway.

Fig. 7. Radial profile of the perturbed vector potential.

Fig. 8. Radial profile of the displacement.

Fig. 9. Initial and final densities for different conditions.