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Collisionless Loss of Transitioning Energetic Ions in Optimized Stellarators

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Introduction

At present, several ways are suggested to avoid severe losses of alpha particles from reactor plasmas of stellarators, which are attributed to the conventional machines of this type. One of them is to optimize the magnetic configuration of the system [1, 2]. In the optimized stellarators (which can also be referred to as Helias configurations) the effects of plasma diamagnetism are sufficiently strong to make closed and weakly deflecting from the magnetic flux surfaces the contours of the longitudinal adiabatic invariant, $J = \oint v_{\|} dl$. This implies that superbanana orbits will not arise, and thus, the locally trapped particles, which constitute the main fraction of escaping alphas in conventional stellarators, will be confined in the optimized systems. However, we will show in this work that a considerable fraction of energetic ions can be lost even in the optimized stellarators. The reason for this is the stochastic diffusion of the so-called "transitioning particles", i.e., particles whose orbits are transformed from locally trapped to locally passing ones and vice versa.

Stochastic diffusion and concomitant loss of alpha particles

We study the diffusion of the transitioning particles arising due to the following. The adiabaticity of the particle motion in the phase space breaks down near the separatrix between the regions of the locally trapped and locally passing orbits (see Fig. 1). Because of this the adiabatic invariant J acquires a phase dependent jump each time when a particle crosses the separatrix [3]-[5]. The phases of the motion do not correlate for successive transitions. Therefore, the multiple crossings of the separatrix are accompanied by the random walk of particles in the J space, resulting in spatial diffusion. Note that stochastic diffusion having the same nature may take place also in tokamaks, where, however, it plays a minor role, being associated with the presence of the ripple wells [6].

The corresponding diffusion coefficient can be written as follows:

$$D = \frac{\langle(\Delta r)^2\rangle}{\tau}, \tag{1}$$

where Δr is the change of the particle radial coordinate caused by the orbit transformation, r is the effective flux surface radius defined by the equation $\psi = \bar{B}r^2/2$; τ is the characteristic time,

$$\tau = \frac{1}{2}(\tau^l + \tau^p), \tag{2}$$

τ^l and τ^p are the characteristic times of the particle motion in the locally trapped and passing states. The factor 1/2 takes into account that a particle crosses the separatrix twice per a full period of a hybrid passing-localized orbit. The time τ^l is essentially the precession time of a localized particle, whereas $\tau^p = (2/P)\int_{-\theta(\kappa^2=1)}^{\theta(\kappa^2=1)} d\theta/\dot{\theta}$ where $\dot{\theta}$ is the frequency of the poloidal motion of a passing particle, P is the probability of the orbit transformation resulting in the trap of a passing particle. The probability P and the radial jump caused by the separatrix crossing can be expressed in terms of the longitudinal invariant [3]-[7].

All ingredients in Eq. (1) were calculated with using the bounce-averaged equations of the particle motion in the magnetic field

$$B = \bar{B}[1 + \epsilon_0(\psi) + \epsilon_m(\psi)\cos N\phi - \epsilon_h(\psi)\cos(\theta - N\phi) - \epsilon_t(\psi)\cos\theta], \tag{3}$$

where ψ, θ, ϕ are the magnetic flux coordinates with ψ the toroidal magnetic flux; ϵ_0 describes the change of the vacuum magnetic field due to finite β; ϵ_m, ϵ_h, and ϵ_t are the amplitudes of the mirror, helical, and toroidal harmonics, respectively, ϵ_m being dominant in the plasma core; $N \gg 1$ is the number of the field periods along the large azimuth of the torus. As a result, a diffusion coefficient was obtained. Its magnitude for $\epsilon_t \ll \epsilon_h \ll \epsilon_m$, which is the case in the plasma core of a Helias, can be evaluated as

$$D \approx \frac{4}{\pi}\frac{R^2\omega_B\rho_B^4}{N^2ar^3}\frac{\epsilon_h^2}{\epsilon_m}\epsilon_0', \tag{4}$$

where ω_B is the energetic ion gyrofrequency, ρ_B is the gyroradius; a, R are the minor and major radius of the torus, respectively; $\epsilon_0' \equiv d\epsilon_0/dx$ with $x = r/a$. Equation (4) is relevant to particles with the pitch-angle parameter $\alpha \equiv \mathcal{E}/\mu\bar{B} - 1 \sim \epsilon_m + \epsilon_0$.

The condition that an energetic ion will be lost because of diffusion (rather than displaced within the plasma) is $\tau_d \ll \tau_s$, where τ_s is the characteristic slowing down time, and τ_d is the diffusion time defined by

$$\tau_d(r) \sim \frac{(a-r)^2}{D}. \tag{5}$$

It is of importance to know the fraction of transitioning particles, which is essentially the stochastic-diffusion-induced loss fraction of alpha particles when the condition $\tau_d \ll \tau_s$ is satisfied. This quantity relevant to a flux surface is given by

$$\nu(r) = \sqrt{\frac{\alpha_{max}}{1+\alpha_{max}}} - \sqrt{\frac{\alpha_{min}}{1+\alpha_{min}}}, \tag{6}$$

where $\alpha_{min} = \epsilon_m + \epsilon_0 - \epsilon_h - \epsilon_t$, $\alpha_{max} = \epsilon_m + \epsilon_0 + \epsilon_h + \epsilon_t$.

Let us evaluate τ_d and ν of α-particles in a Helias reactor with $N = 5$, $R/a = 10$, and $\beta \sim 5\%$. At first, we make a simple estimate by approximating Fourier harmonics of the magnetic field as follows:

$$\epsilon_m = 0.1, \quad \epsilon_0 = 0.08x^2, \quad \epsilon_t \simeq 0.05x, \quad \epsilon_h = 0.08x. \tag{7}$$

Then at $r = a/2$ we find:

$$\tau_d(a/2) \approx \frac{5}{\omega_B}\left(\frac{a}{\rho_B}\right)^4, \quad \nu(a/2) \approx 15\%. \tag{8}$$

Assuming $B = 5T$ and using Eq. (8) we obtain $\tau_d \approx 0.02s$ for $a/\rho_B = 30$, and $\tau_d \approx 0.06s$

for $a/\rho_B = 40$. On the other hand, the slowing down time of a $3.5 MeV$ alpha particle in a plasma with the electron density $n_e = 2{\div}3{\times}10^{20} m^{-3}$ and the temperature $T = 10{\div}15 keV$ is $\tau_s \sim 0.1 sec$. This means that an essential fraction of alphas will be lost to the wall from a flux surface of the radius $r/a = 0.5$ in a system with $a/\rho_B = 30$, but particles can hardly escape from the $r/a = 0.5$ surface when $a/\rho_B = 40$. Furthermore, if profile shapes of the plasma density and temperature change in a way that τ_s strongly decreases with the radius, the condition $\tau_d \ll \tau_s$ may violate near the plasma edge. Then energetic ions will diffuse to the periphery and thermalize in that region. In this case the main effect of the stochastic diffusion will be the broadening of the radial profile of the power deposition of energetic ions rather than their loss. As $\tau_s \propto T^{3/2}/n_e$, this will be the case when the temperature strongly decreases with r, whereas the $n_e(r)$ profile is flat.

The diffusion coefficient, the fraction of transitioning particles and the diffusion time were calculated numerically for a Helias reactor with $\beta = 4.7\%$, using corresponding equilibrium data. In particular, the obtained dependence of τ_d on α at $r/a = 0.5$ is presented in Fig. 2. We observe that the dependence of τ_d on α has a rather flat minimum around $\alpha = \epsilon_m + \epsilon_0$ where D was expected to be maximum; the magnitude of τ_d is in qualitative agreement with the estimates above.

In order to verify predictions of the theory, the numerical calculations of confinement of alpha particles in a Helias reactor were carried out. This was done using the code developed by Lotz [8]. The results of the numerical modelling of alpha confinement will be published elsewhere. Here we only note that the obtained results are consistent with the developed theory and the earlier numerical calculations in Ref. [8].

Conclusions

We have shown that transitioning energetic particles in advanced stellarators of Wendelstein line undergo the stochastic diffusion associated with the orbit transformation of localized and passing particles. This diffusion may lead to the loss of α-particles and other energetic ions from the plasma core of a Helias reactor and Wendelstein 7-X for the time $\sim 0.01 s$. A key parameter affecting the magnitude of the diffusion coefficient is the ratio a/ρ_B ($D \propto \omega_B(\rho_B/a)^4$). The fraction of escaping α-particles can be of the order of 10% for α-particles produced at $r \sim a/2$. It can be even more for the injected ions when their pitch angles correspond to transitioning particles, $v_\parallel/v \sim \sqrt{\epsilon_m} \sim 0.3$. However, the diffusion process is relatively slow. Therefore, the diffusion not necessarily leads to the loss of ions of high energy to the wall. When the electron temperature is characterized by strongly peaking radial distribution, whereas the electron density profile is flat, the energetic ions may be thermalized near the edge before being lost.

A general conclusion which follows from our work is that the stochastic diffusion of transitioning particles can represent the dominant mechanism of the loss of energetic ions in optimized stellarators. The dependence of the obtained diffusion coefficient on plasma parameters and the relatively large diffusion time indicate that the loss region and the loss fraction of energetic ions in Helias configurations can be minimized by shaping the plasma temperature and density profiles so that they satisfy certain requirements.

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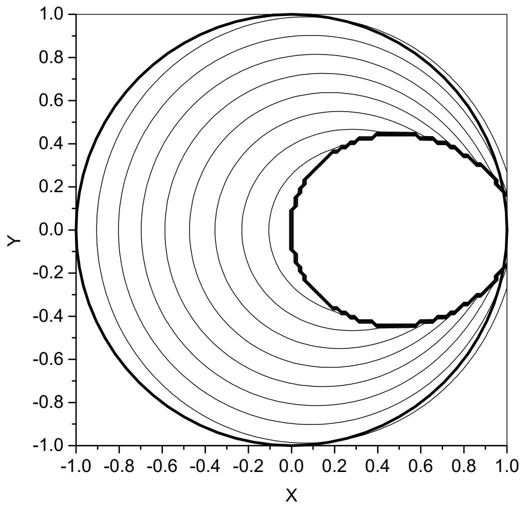

Fig.1.

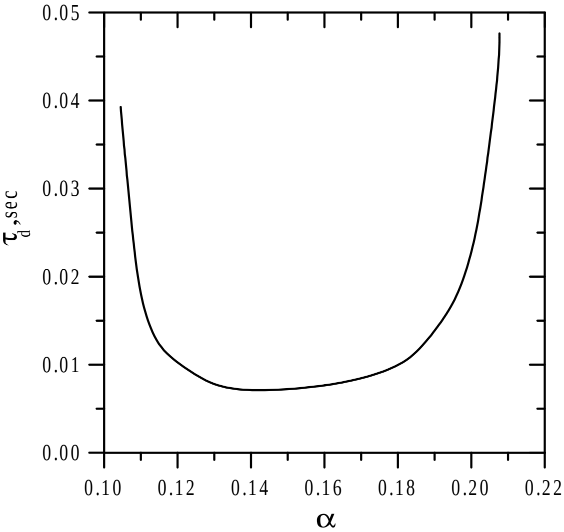

Fig.2.

Fig.1. Sketch of level contours of J for the locally trapped particles (thin lines) and the $\kappa = 1$ contour (bold line inside the plasma) in a Helias. Locally trapped particles moving along the $J = const$ contours become locally passing ones after crossing the bold line.
Fig.2. The diffusion time versus the pitch parameter $\alpha \equiv \mathcal{E}/\mu B - 1$ at $r = 0.5a$ in a Helias reactor with $\beta = 4.7\%$.

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