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IMPURITY CONTROL BY THE RADIAL ELECTRIC FIELD IN A STOCHASTIC LAYER

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IMPURITY CONTROL BY THE RADIAL ELECTRIC FIELD IN A STOCHASTIC LAYER

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Abstract

A decontaminating working régime of the ergodic divertor at low collisionality has been studied : the outwards radial electric field which appears in the laboratory frame when the ergodic divertor is energized, in conjunction with the magnetic ripples action on ions, can produce outwards flux of impurity ions $-Dn_Z(\partial n_Z/n_Z\partial r+Z\partial n_e/n_e\partial r)$. This contrasts with the neoclassical flux $-Dn_Z(\partial n_Z/n_Z\partial r-Z\partial n_H/n_H\partial r)$ which produces the deleterious accumulation of impurity ions in the n_H profile.

I Introduction

The ergodic divertor allows to apply resonant magnetic perturbations which destroy the magnetic surfaces at the edge. The magnetic field lines within that stochastic layer connect the confined plasma to the wall [1]. One expects from this arrangement the same basic effects as from the axisymmetric divertors, e.g. frictional decontamination of impurity ions by recycling hydrogen ions and accumulation of a low temperature high density plasma near the wall [2,3]. In this paper, our interest is focused on the possibility of impurity control by the ergodic divertor in a low collisionality régime. The frictional decontamination effects are then very weak. The only possible action on impurity ions is through the radial electric field. A radial electric field E_r appears indeed [4,5,6,7] in the frame where the ergodic perturbation is static, i.e. in the laboratory frame, to ensure the confinement of electrons in the stochastic layer : $E_r = (T_e/e)/(\partial n_e/n_e\partial r)$. This effect takes place as soon as the stochastic flux lines are connected to the wall because of the fast parallel motion of electrons along the field lines, even if the magnetic perturbation has pratically no direct effect on the ion transport. The basis of the effect we consider is that the ions tend to be extracted outwards by the radial electric field E_r.

Effective extraction necessitates however that the average motions of ions along θ, φ are hindered by resonant static electromagnetic perturbations. Then, the balance of the radial force $n_{ion}e_{ion}E_r$ by the Lorentz force due to average θ and φ motions results into θ and φ frictions forces, which in turn produce an outwards radial diffusion. We will study the effect of magnetic ripples $\delta B_{ripple}/B=b.\cos N\varphi$ acting together with the poloidal magnetic modulation $\delta B_{pol}/B=(r/R)\cos\theta$.

II Neoclassical fluxes in presence of the ergodic divertor

A very convenient presentation of the mecanism of ion diffusion is obtained by considering that each ion assembly exhibits average velocities v_θ, v_φ in the poloidal (θ) and toroidal (φ) directions, and that these velocities produce frictions $-f_\varphi v_\varphi$ and $-f_\theta v_\theta$ due to the magnetic pumping effects [9,10]. The calculation of the friction coefficients f_φ and f_θ is based on neoclassical theory. For each type of perturbation, taken alone, the friction force is effective in the kinetic régime : $k_{//}\lambda_{coll} > 1$ where λ_{coll} is the parallel mean free path and $k_{//}=1/qR$ for $\delta B_{pol}/B=(r/R)\cos\theta$ and $k_{//}=N/R$ for $\delta B_{ripple}/B=b\cos N\varphi$. The values of the coefficients k_θ and k_φ depend whether the perturbations $\delta B/B$ produce trapped particles or not [11]. Two different régimes of low collisionality are investigated. In the Landau régime (plateau régime as far as k_θ is concerned), $1<k_{//}\lambda_{coll}<(\delta B/B)^{3/2}$, one has :

$$k_\theta \text{ or } k_\varphi = \frac{n\sqrt{\pi}}{\left(\frac{1}{qR} \text{ or } \frac{N}{R}\right)} \frac{m^2}{4T} \left(\frac{r}{R} \text{ or } b\right)^2 v_{th}^3 \left(\frac{1}{r} \text{ or } \frac{N}{R}\right)^2$$

where m is the particle mass and v_{th} the thermal velocity $(2T/m)^{1/2}$. In the Zakharov-Karpman régime [8] (banana régime for k_θ), $(B/\delta B)^{3/2}< k_{//}\lambda_{coll}$, it comes

$$k_\theta \text{ or } k_\varphi = n\sqrt{\pi}\left(qR \text{ or } \frac{R}{N}\right)^2 \frac{m^2}{4T} \left(\frac{r}{R} \text{ or } b\right)^{\frac{1}{2}} v_{th}^2 \left(\frac{1}{r} \text{ or } \frac{N}{R}\right)^2 \frac{1}{\tau_{coll}}$$

where $1/\tau_{coll}=<(\Delta v_\perp)^2>_{th} / v_{th}^2$ and $<(\Delta v_\perp)^2>_{th}$ is the Spitzer coefficient for the considered species at the thermal velocity v_{th}. For both species, light ions (H) and impurity ions (Z), in the stochastic layer, the mechanical balance equations yield :

$$(1) \qquad n.e.(E+v\wedge B) - \nabla P + F = 0$$

where F represents the friction forces $-k_\theta v_\theta$, $-k_\varphi v_\varphi$ and the collisional forces along θ, φ between the two ions assemblies proportional to the differences $v_{\varphi,\theta H}-v_{\varphi,\theta Z}$. The radial particle fluxes $\Gamma=nv_r$ arise to balance these friction forces. The set of equations (1) for H and Z ions along the radial, poloidal and toroidal directions allows to calculate the velocities v_θ, v_φ and the flux Γ for given density gradients $\partial n_{H,Z}/\partial r$ and a given electric field $E_r=(T_e/e)/(\partial n_e/n_e\partial r)$. In the limit of strong magnetic ripple, $k_\varphi(H)>>(B_\theta^2/B_\varphi^2)k_\theta(H)$, we find that the static ergodic divertor perturbation leads to a radial impurity flux of the form :

$$(2) \quad \Gamma_Z= -Dn_Z[(\partial n_Z/n_Z\partial r)+Z(\partial n_e/n_e\partial r)] \qquad (D>0)$$

which creates an outwards accumulation of the Z ions outside the n_e profile. This result contrasts with the neoclassical flux :

$$(3) \qquad \Gamma_Z=-Dn_Z[(\partial n_Z/n_Z\partial r)-Z(\partial n_H/n_H\partial r)]$$

which produces the deletetrious concentration of impurities within the n_H profile.

III **Discussion**

The form (3) is a consequence of the friction effects between light ions and impurity ions which tend to set the two assemblies of ions in thermodynamical equilibrium in the same frame rotating around the major axis, and this, independently of the value of the radial electric field E_r. On the contrary, the form (2) reflects that all assemblies are in thermodynamical equilibrium, locked in the laboratory frame from, the ions by the magnetic ripple and the poloidal modulation, the electrons by the static magnetic perturbation of the ergodic divertor. The desired decontaminating régime (2) applies only at low collisionality. It appears from calculations that both assemblies H and Z must be in the plateau or banana régime. If the Z assembly is in the Pfirsch-Schlüter régime, one recovers the form (3), independently of the E_r value in the laboratory frame and of the magnetic ripples level. At very low collisionality, the Z ions may be trapped in the magnetic ripples and then experience a radial diffusion because of the vertical drift combined to the effect of collisions. In that case, the structure (2) applies.

Numerical application with typical Tore-Supra paramaters $n=10^{18}m^{-3}$, $T=1$ keV, $b=0.1$, $B=4T$ shows that a flux of the form (2) occurs with $D\sim0.1m^2.s^{-1}$ comparable to neoclassical values. In a steady state where the flux Γ_Z is balanced by a turbulent flux Γ_t of the form $\Gamma_t=-D_t(\partial n_z/\partial r)$, ones finds that $n_z=n_e^{-\alpha}$, $\alpha=Z(D/(D+D_t))$, implying that a significant decontamination effect only occurs across the layer for steep density gradients at the edge and if $Z(D/(D+D_\upsilon)) > 1$. This contrasts of course with the neoclassical case (3) where one would have $n_Z=n_H{}^{+\alpha}$.

IV Conclusion

We have shown that a decontaminating régime of the ergodic divertor can also be expected at low collisionality. This effect is due to : the stochasticity of the layer and the ergodic connection to the wall create a radial electric field, directed outwards, in the laboratory frame (thermodynamical equilibrium of the electrons), a static resonant perturbation - we have considered the case of magnetic ripple -, by hindering the average ion motions along θ, φ then tends to expell the ions outside the n_e profile. One can expect that the electromagnetic perturbation induced directly by the ergodic divertor has a similar action on impurity transport. The study of this effect and of the corresponding decontamination level is in progress.

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