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Impact of $\vec{E}\times\vec{B}$ Drifts on Impurity Distribution in SOL of a Tokamak

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1. Introduction

It has been demonstrated that a strong electrostatic field exists in the tokamak Scrape-Off-Layer (SOL) and divertor zone [1-4]. The value of an electrostatic potential φ turns out to be of the order of T_e/e with a characteristic perpendicular scale L_y, where T_e is the electron temperature and L_y is the poloidal Larmor radius of main ions. One can expect a strong influence of these drifts on the impurity densities and fluxes in SOL and divertor zone. Such type of influence has been observed in the simulations with the code B2. The purpose of this work is to analyze the relative role of the $\vec{E}\times\vec{B}$ drifts in the impurity flux formation.

2. Impurity fluxes with account of $\vec{E}\times\vec{B}$ drifts

Let us consider the case of a test impurity, when only collisions of the impurity with main ions are taken into account. Here x is the poloidal direction, y is the radial direction, l is the direction along magnetic field, n_Z is the impurity density in the ionization state Z, n_e is the electron density. The temperatures of all heavy species are assumed to be equal to the main ion temperature T_i. The parallel momentum balance for the impurity has the form [5]:

$$m_I \frac{d(n_z u_{z\parallel})}{dt} = -\frac{\partial n_z T_i}{\partial l} - C_z m_i n_e \nu_{iz}\left(u_{z\parallel} - u_{i\parallel}\right) + Zen_z E_\parallel + n_z Z^2\left(\alpha_z \frac{\partial T_e}{\partial l} + \beta_z \frac{\partial T}{\partial l}\right) + S_z . \quad (1)$$

Here $\nu_{iZ} = \frac{4\sqrt{2\pi} e^4 \Lambda Z^2 n_Z}{3\sqrt{m_i} T_i^{3/2}}$, S_Z are momentum sources and sinks due to ionization, recombination and friction with neutrals while coefficients C_Z, α_Z and β_Z are of the order of unity. We assume $m_I >> m_i$. Inertia can be neglected in this equation with respect to the thermal force. Even if the impurity velocity is close to its sound speed, one can estimate

$m_I \frac{d(n_z u_{z\parallel})}{dt} / \left(z^2 n_z\left(\alpha_z \frac{\partial T_e}{\partial l} + \beta_z \frac{\partial T_i}{\partial l}\right)\right) \approx \frac{m_I / m_i}{(\alpha_z + \beta_z) Z^2} < 1$. Fore $m_I >> m_i$ $\alpha_z+\beta_z \approx 3$. In the more realistic case of much slower flow, this inequality is further amplified. Usually the Coulomb collision frequency is significantly larger than the ionization-recombination frequency and the impurity ion-neutral collision frequency. Thus, we can also neglect S_z in Eq. (1). The poloidal velocity is $u_{zx} = b_x u_{z\|} + V_0$, where V_0 is the poloidal $\vec{E} \times \vec{B}$ drift. We omit the diamagnetic drift term

$$u_{zx} = b_x u_{i\|} - \frac{b_x^2}{C_z \sqrt{2} m_i \nu_{ii} n_z Z^2} \frac{\partial n_z T_i}{\partial x} + \frac{b_x^2}{C_z \sqrt{2}} \frac{\partial}{\partial x} \left(\alpha_z T_e + \beta_z T_i + \frac{e\varphi}{Z} \right) \frac{1}{m_i \nu_{ii}} + V_0 \,. \qquad (2)$$

If we assume $u_{i\|}$ to be of the order of the main ion sound speed c_s, then the ratio of the third to the first term in r.h.s. is ~ $\lambda_{mfp}/L_{\|}$, where λ_{mfp} is the main ion mean free path. Hence, the effect of thermal force is important for low main ion velocities $u_{i\|} / c_s < \lambda_{mfp} / L_{\|}$. The ratio of the last to the first term in r.h.s. is of the order of the poloidal Larmor radius to L_y (for $u_{i\|} \sim c_s$) times larger, and can be of the order of unity. So, the last term corresponding to the $\vec{E} \times \vec{B}$ drift can be more important than the third term corresponding to the parallel plasma motion due to the thermal force. Moreover, the $\vec{E} \times \vec{B}$ drift can overcome the impurity velocity caused by the impurity - main plasma friction coupling. Introducing the net impurity density $n_I = \sum_Z n_Z$, we obtain

$$\frac{\partial n_I}{\partial t} + \frac{1}{\sqrt{g}} \frac{\partial}{\partial x} \sqrt{g} \left[n_I b_x u_{i\|} - \frac{b_x^2}{C_{<z>} \sqrt{2} m_i \nu_{ii}} \left(\frac{1}{<Z>^2} \frac{\partial n_I T_i}{\partial x} + n_I \frac{\partial}{\partial x} \left(\alpha_{<z>} T_e + \beta_{<z>} T_i + \frac{e\varphi}{<Z>} \right) \right) \right]$$
$$- \frac{1}{\sqrt{g}} \frac{\partial}{\partial y} \sqrt{g} D \frac{\partial n_I}{\partial y} + \frac{1}{B} \left(\frac{\partial \varphi}{\partial y} \frac{\partial n_I}{\partial x} - \frac{\partial n_I}{\partial y} \frac{\partial \varphi}{\partial x} \right) = n_e \left(I_0 n_0 - R_1 n_1 \right), \qquad (3)$$

where $\sqrt{g}$ is a metric factor and D is a diffusion coefficient. The r.h.s. corresponds to the ionization of neutrals and recombination of impurities with Z=1. We used the model of two most representative ionization states [6]. According to this model, the impurity exists in two ionization states with charges Z and Z+1. In this model with reasonable accuracy we can put $<Z>^k = <Z^k>$, where $-2 \le k \le 2$, and coefficients C_Z, α_Z and β_Z can be considered as functions of $<Z>$. The value of $<Z^k>$ is defined as $<Z^k> = n_I^{-1} \sum_Z Z^k n_Z$.

3. Simple model for net impurity density

The impurity pressure gradient can be neglected with respect to the thermal force. The electric field term is also smaller than the thermal force for the potential of the order of T_e/e, the corresponding parameter is $(\alpha+\beta)<Z>$. Since the temperature spatial scale (and thus the potential spatial scale) in the *y* direction in smaller than that in the *x* direction, the lines φ=const almost coincide with the flux surfaces *y*=const. Therefore, we can introduce the coordinates $\tilde{x}$ along the equipotentials and $\tilde{y}$=const across the flux surfaces. When the diffusion can be neglected, the steady state solution gives the impurity flux, which is directed along the equipotentials:

$$n_I u_{I\tilde{x}} = n_I \left[b_x u_{i\|} + \frac{b_x^2}{C_{<Z>}\sqrt{2} m_i \nu_{ii}} \frac{\partial(\alpha_{<Z>} T_e + \beta_{<Z>} T_i)}{\partial \tilde{x}} + \frac{1}{B}\frac{\partial \varphi}{\partial y} \right] = \Gamma(y)\,, \qquad (4)$$

where the flux Γ is defined by the boundary conditions on the divertor plates. Poloidal flux directions are shown in Fig. 1 for the case when $\vec{E}\times\vec{B}$ drift dominates. This solution is valid if $\frac{DB}{\varphi}\frac{L_x}{L_y} < 1$, where L_x and L_y are the corresponding impurity density scales.

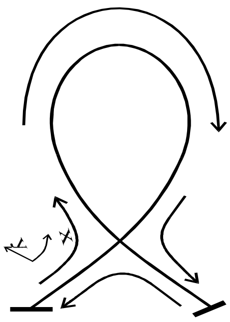

Fig.1 Directions of $\vec{E}\times\vec{B}$ drifts in the edge plasma.

4. Two species model and equation for the average charge state

To the first approximation the terms with <*Z*> can be dropped from equation (3). However, to second approximation one must keep these terms. Moreover, it is often necessary to know the impurity population over ionization states. We shall use two species approximation [6]. Impurity at a given temperature is assumed to exist only in the two ionization states with charges *Z* and *Z*+1. ($Z\geq 1$). The impurity velocities are almost independent on *Z*. The average charge state is defined as $\langle Z\rangle = \frac{n_Z Z + n_{Z+1}(Z+1)}{n_I} = Z + 1 - y_Z$, where $y_Z = n_Z / n_I$. One can get from the continuity equation

$$\frac{\partial\langle Z\rangle}{\partial t}+\vec{V}_I\nabla\cdot\langle Z\rangle=-\nu_Z(\langle Z\rangle-Z_*)\ ,\quad \text{where}\quad \nu_Z=n_e(I_Z+R_{Z+1})\ ;\quad Z_*=Z+1-\frac{R_{Z+1}}{I_Z+R_{Z+1}}\ .$$

Introducing the coordinate along the equipotentials, in the stationary case we find

$$V_{I\tilde{x}}\frac{\partial\langle Z\rangle}{\partial\tilde{x}}=-\nu_Z(\langle Z\rangle-Z_*)\ , \qquad (5)$$

where $V_{I\tilde{x}}$ is $V_{I\tilde{x}}=b_x u_{i||}+\dfrac{b_x^2}{C_{<Z>}\sqrt{2}m_i\nu_{ii}}\left(\alpha_{<Z>}\dfrac{\partial T_e}{\partial\tilde{x}}+\beta_{<Z>}\dfrac{\partial T_i}{\partial\tilde{x}}\right)-\dfrac{1}{B}\dfrac{\partial\varphi}{\partial y}$. Since the velocity $V_{I\tilde{x}}$ and frequency ν_Z are the functions of electron temperature and density only, Eq.(5) can be integrated over $\tilde{x}$.

5. Conclusions

It has been shown that in tokamak edge plasma the $\vec{E}\times\vec{B}$ drifts can compete with the fluxes driven by thermal forces, parallel electric fields and the friction coupling between impurities and main plasma ions. The $\vec{E}\times\vec{B}$ drifts may lead to the impurity flow reversal. This means that in some regions the flows are directed away from the divertor plates, while in others they are directed into them. To first approximation, the impurity fluxes do not depend on the ionization state. To second approximation, the equation for the impurity ion charge averaged over the ionization states was derived. When the ion ∇B drift is directed towards the *X*- point, in the private region, the impurities flow from the outer divertor plate to the inner plate, while in the SOL the impurity flow is directed from the inner to the outer plate.

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