S3-2

"Physics of SOL/divertor plasmas in magnetic fusion"

磁気閉じ込め核融合に於けるプラズマ−壁境界層現象の物理

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Present understanding and open problems of SOL(Scrape Off Layer)/divertor plasmas are reviewed and discussed. A main focus is placed on collisional transport of impurity ions, especially high-Z impurities like tungsten, in SOL/Divertor plasmas. In addition, static and dynamic characteristics of "detachment plasma" will be discussed in the presentation.

1. Introduction

Being based on steady and continuous progress in core plasma performance for magnetic fusion devices, International Thermonuclear Experimental Reactor (ITER) project is now underway and its construction has been started. For ITER and future fusion demonstration reactors, the following research and development items become more significant than before: 1) to control/suppress heat and particle flux from the high temperature and high density fusion core plasma to the wall, and 2) to control/suppress impurity flux from the wall to the core plasma. Therefore, understanding of heat and particle transport phenomena in SOL(Scrape-Off Layer) and divertor plasmas, which are located between fusion core plasma and the solid wall (see Fig.1), is indispensable.

A typical example of self-controlling characteristics in fusion plasmas is "recycling" process in SOL/divertor region (see Fig.1). Plasma heat load can be reduced by the interaction between plasma and neutrals. Moreover, so-called full plasma detachment state from the wall is automatically formed under relatively low input power condition. Plasma ion and electron become a neutral particle before reaching the wall due to ion-electron recombination process in the plasma volume.

Another example of self-regulating characteristics of fusion plasma is impurity generation and their penetration into fusion core plasma. Of course, impurity concentration in the core plasma has to be kept as low as possible for the normal operation to prevent core plasma from radiation cooling by impurities. In case of transient over power, however, increase in fusion power generation possibly enhance heat and particle loads to the wall, which in turn possibly enhance the production of impurities and its transport towards the core. Therefore, understanding of the impurity transport in SOL/divertor region is very important.

2. Impurity collisional transport in closed torus magnetic configurations : Neo-classical Theory

Before proceeding to the impurity transport in SOL/divertor region, a very simple review is given of impurity collisional transport theory in the closed magnetic configuration, i.e., core plasma. It is well known as "Neo-Classical (NC)" theory[1]. Starting from Boltzmann eq. with Fokker-Planck collision operator for

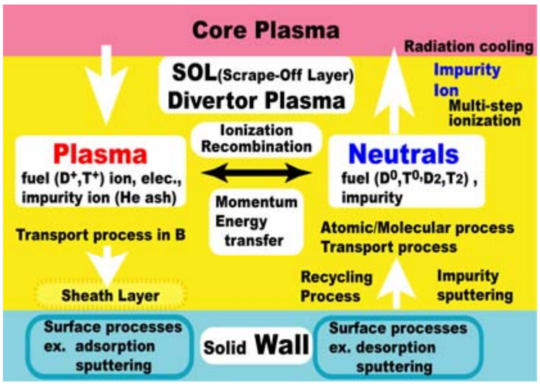


Fig.1 Basic processes in a SOL/divertor plasma.

Coulomb collisions, NC theory provides the linear relation between the macroscopic particle, momentum and heat fluxes and the thermodynamic forces (gradients of density, velocity, temperature). In a simple tokamak configuration with a large aspect ratio (A=R/r>>1) and concentric circular magnetic flux surfaces (Fig.2), NC-theory gives a simple expression for the impurity particle flux averaged over a magnetic surface;

$$< \boldsymbol{\Gamma} \cdot \boldsymbol{e}_r > \simeq \Gamma_{IWP} + \Gamma_{TSE} - D_{NC} \frac{dn_{imp}}{dr} . \qquad (1)$$

The last term in Eq. (1) denotes the self-diffusion flux proportional to the impurity density gradient dn_{imp}/dr, while Γ_{IWP} and Γ_{TSE} are driven by the thermo-dynamic forces of the background fuel ions.

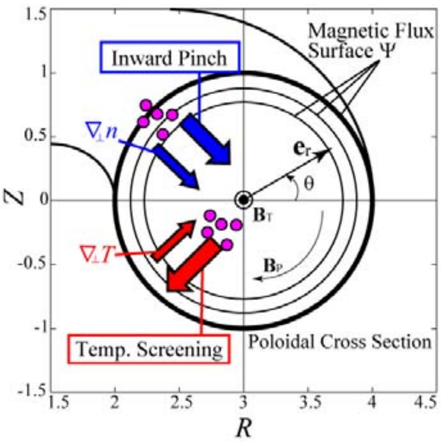
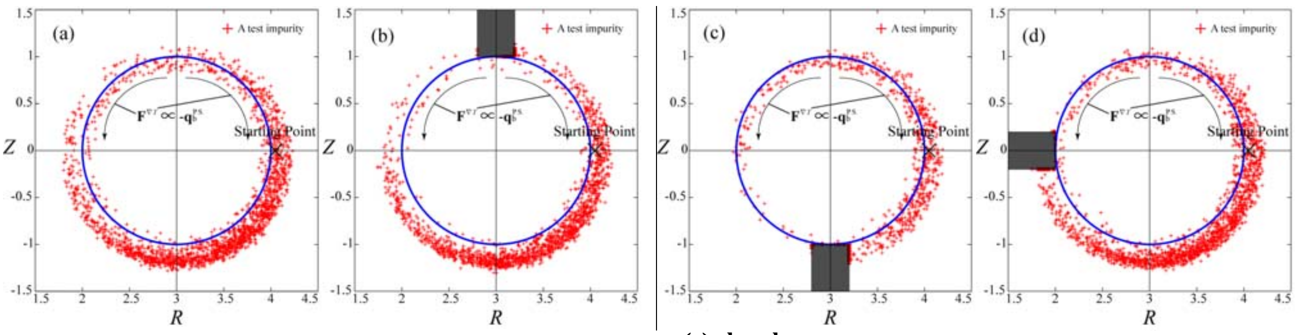


Fig.2 A simple tokamak magnetic configuration



(a) open geometry **(b) closed geometry with a top limiter** **(c) closed geometry with a bottom limiter** **(d) closed geometry with a inner limiter**

Fig.3 Spatial distribution of test impurity ions in the model tokamak geometry (Fig.2). The results are obtained by kinetic modeling [2,3] based on Monte-Carlo Binary Collision Method (MC-BCM) for a given background density and temperature gradient (dn_b/dr=0, dT_b/dr=300 eV/m). In order to simulate the open magnetic configurations, the solid wall structure, which corresponds to so-called limiter or divertor plate, is installed for cases (b)-(d). Test ions have been launched at the same location for all the cases (x). Other detailed input parameters are in Ref. [3, 5]

The flux Γ_{IWP} and Γ_{TSE} in Eq.(1) are given, respectively, by

$$\Gamma_{IWP} \approx D_{NC}\frac{dn_b}{dr}, \quad \Gamma_{TSE} \approx -D_{NC}\frac{n_b}{T_b}\frac{dT_b}{dr}. \qquad (2)$$

Usually the background density n_b and temperature T_b are larger in the core central region, i.e., their gradients are the same sign ($dn_b/dr<0$, $dT_b/dr<0$). Therefore, in Eq.(2), "Inward Pinch (**IWP**)" flux Γ_{IWP} and "Temperature Screening Effect (**TSE**)" flux Γ_{TSE} are in the opposite direction ($\Gamma_{IWP}<0$, $\Gamma_{TSE}>0$) as shown in Fig.2. The IWP Γ_{IWP} drives impurity ions inward to the core center, while the TSE Γ_{TSE} drives impurity ions outward and impurity ions are shielded out from the core.

3. Impurity transport in the SOL/Divertor plasma

Our understanding of impurity transport in the SOL/Divertor plasma is still limited. In most of studies of collisional impurity transport in the SOL/Divertor plasmas, only the impurity transport along the magnetic (*B*) field has been taken into account so far, and collisional transport across *B*-field has been neglected. In other words, it has been believed that only the force balance along *B*-field, i.e., the force balance between "friction force" and the "thermal force" (friction driven by back ground temperature gradient) is important for collisional transport of impurity ions in the open magnetic configuration with the wall boundary.

Recently, however, it is pointed out that collisional transport across *B*-field driven by background thermodynamic forces by Eq.(2) are not negligible on the basis of a new kinetic modeling scheme [2, 3] of impurity transport with Monte Carlo Binary Collision model (MC-BCM[4]), which directly solves Boltzmann equation. Because of the relatively steep gradients of n_b and T_b in the core periphery, and also high charge state Z of impurities, it becomes even comparable with the anomalous transport flux.

A systematic survey of impurity transport across *B*-field is now underway [3, 5, 6] for different collisionalities, and other parameters. Figure 3 shows typical examples. For the closed magnetic flux case in Fig.3(a), our simulation result reproduces the result predicted by NC theory. Most of impurity ions are transported outwards due to TSE. The average radial velocity of test impurity ions becomes positive and almost agrees with that estimated by Eq. (2).

On the other hand, in the open magnetic field, impurity transport depends on the location of the wall structure. It is interesting to note that the locations in case (b) (top) and (d) (inner) are quite different, but the average radial velocities are almost the same as in the closed magnetic flux in Fig.3(a). Even in the open magnetic flux cases [Fig.3 (b) and (d)], TSE effect by NC theory becomes effective in these cases. On the other hand, the average radial velocity becomes almost zero and therefore TSE flux almost disappears in case (c). Physical mechanism which leads to these results are discussed in detail in Ref.[3, 5, 6].

Summary and future outlook

Present understanding and some new results of collisional impurity transport in the SOL/divertor plasma have been briefly reviewed and discussed. For more overall and complete understanding of transport phenomena, further progress in non-equilibrium thermodynamics and transport theory has been demanded, especially for the case where the linear response theory such as Eq.(2) breaks down.

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