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Neoclassical transport modeling of temperature screening effect and inward pinch of high-*Z* impurities in tokamak devices

トカマク型核融合炉における不純物の温度遮蔽効果及びインワードピンチの新古典輸送モデリング

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Effects of the classical and neo-classical impurity transport across the magnetic **B**-field in the Scrape-Off Layer (SOL) of fusion plasmas, have been studied with a new kinetic model using Binary Collision method (BCM). Our model is able to simulate the following two effects, which have been theoretically predicted but neglected in all the existing kinetic impurity transport simulations in the SOL/Divertor plasmas; (1) the inward pinch (IWP) due to density gradient of background plasmas and (2) the temperature screening effect (TSE, outward transport) caused by temperature gradient.

1. Introduction

Understanding of impurity transport in the SOL is one of the most important issues for developing fusion plasma devices, because of its strong influences (both negative/positive) on plasmas such as the radiation cooling. In our recent work [1-3], kinetic Monte Carlo models of IWP and TSE have been developed in the classical limit without toroidicity.

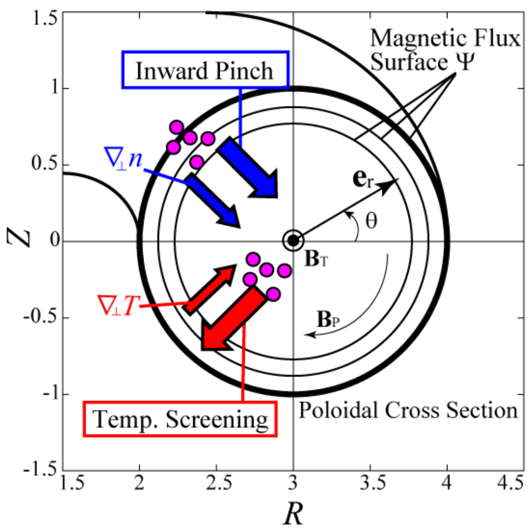


Fig. 1. A simple torus magnetic configuration

In this presentation, we have extended our model to be able to simulate the neo-classical inward pinch (NC IWP) and temperature screening effect (NC TSE) in a torus geometry. Such neoclassical (NC) radial transport is considered as one of the most important processes to determine impurity distribution in the plasma.

Then, the effect of open magnetic **B**-field on the NC impurity transport has been investigated.

2. Neoclassical Transport Theory

In this study, we always suppose a simple torus **B**-field: $B_T = -B_0R_0 / R$, $B_P = \mu_0 Ip\, R_0 / 2\pi rR$, where B_T and B_P are the toroidal and poloidal component. Other symbols are conventional. Under such *closed* **B**-field (i.e. the field line does not intersect with wall boundary), the radial flow velocity $\mathbf{v}_\perp^{NC}$ of impurity is estimated, from the neoclassical (NC) theory[4], as

$$\mathbf{v}_\perp^{NC} = \left(2q^2 n_Z v_Z T_i / e^2 B^2 Z\right)\cdot\left[K\left(n_i'/n_i - Z\, n_Z'/n_Z\right) + H\, T_i'/T_i\right]. \cdots (1)$$

The prime mark means the radial derivative. Other symbols are conventional. In typical fusion plasmas, the numerical coefficients *K* and *H* are estimated as *K*~1 and *H*~(-1/2). In SOL/divertor region, radial gradients n_i'and T_i' are not always in the same direction, e.g. in detachment plasmas. The IWP and TSE are not always canceled out each other.

3. Numerical Model for Test Impurity Particle

Basic characteristics of the model are summarized as follows: (1) Full orbit of each test impurity particle is exactly solved by the equation of motion. (2) Coulomb collisions between impurities and background plasma ions are modeled by the Binary Collision Model (BCM) [5]. (3) In our BCM algorithm, the background ion velocities are randomly sampled from a distorted Maxwellian distribution representing the Pfirsch-Schluter regime which is typical in the SOL. Gradients of the background plasma density and temperature, which have been neglected in the conventional models, are included in our collision model.

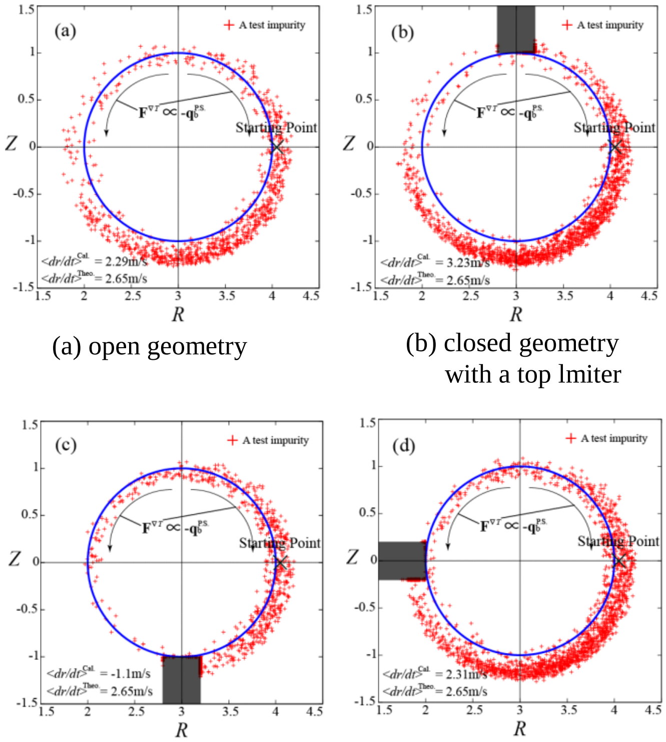
4. Impurity Transport in the SOL plasma

Prior to the case of SOL plasma with open **B**-field, the model validation has been done by checking the IWP and TSE in a simple torus with closed **B**-field in Fig. 1. Background plasma ion is the deuterium (D^+) and impurity is the tungsten ion (W^{4+}). As a result (Fig. 2 (a)), it has been confirmed that impurity radial flow agrees well with the neo-classical theory Eq. (1).

Next, as shown in Fig. 2 (b,c,d), a limiter has been introduced in different position, inner / top / bottom, which produces the SOL region. We have applied our model to investigate whether the impurity transport in the SOL obeys the neo-classical law. It is not obvious because the **B**-field is *open* in the SOL (i.e. intersection with wall boundary).

A systematic test simulation of impurity transport across **B**-field has been performed for different limiter position and different gradients. Figure 2 (a,b,c,d) are the snapshots of simulated impurity profiles showing the TSE, without IWP. In the top and inner limiter case (Fig. 2 (b, d)), the average radial velocities are almost the same as in the closed magnetic flux case in Fig. 2 (a). This means that even in the open magnetic field, impurity transport across the magnetic field can be explained by NC theory. On the other hand, the average radial velocity and therefore flux disappears in case (c), i.e., outward TSE effect is very small in this case.

We have also performed similar test simulations for the IWP case, and confirmed that the IWP has been weakened with the top limiter. Such discrepancy between the simulation and the theory can be explained by the mechanisms of NC IWP and NC TSE.



(a) open geometry

(b) closed geometry with a top lmiter

(c) closed geometry with a bottom lmiter

(d) closed geometry with a inner limiter

Fig. 2 Spatial distribution of test impurity ions in the torus geometry under a given background density and temperature gradient ($dn_b/dr=0$, $dT_b/dr=300eV/m$). In order to simulate the open magnetic configurations, the solid wall structure, which corresponds to so-called limiter or divertor plates, is installed for cases (b)-(d). Test ions have been launched at the same location (symbol:x) for all the cases.

6. Conclusion

We have developed a new numerical model for test impurity transport, which can take into account the neoclassical transport processes such as the inward pinch and the temperature screening effect.

As a result of test simulation in the open magnetic field geometries, we have confirmed that impurity transport can be strongly affected by the location of the wall structure.

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