# Inward Pinch of High-Z Impurity due to Atomic Processes in a Rotating Tokamak Plasma and the Effect of Radial Electric Field

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**Abstract.** The transport of high-Z impurity in a toroidally rotating tokamak plasma is investigated analytically and numerically. It is shown that the inward pinch is driven by the atomic processes of ionization/recombination along the particle orbit both in co- and ctr- rotating plasmas. This inward pinch is enhanced by the radial electric field. It is derived that the negative and positive radial electric fields cause the inward pinch and the outward movement (unpinch) of the high-Z impurity, respectively, under the influence of Coulomb collisions with the rotating background plasma. In the ctr-rotation case, the inward pinch becomes significant with increasing toroidal rotation velocity, because the directions of the both pinches are inward. On the other hand, in the co-rotation case, these pinches have opposite directions. Therefore, the unpinch due to the positive radial electric field is decreased by the inward pinch due to the atomic processes. These tendencies are consistent with the tungsten accumulation observed in the JT-60U rotation scan experiment.

## 1. Introduction

Tungsten is the most promising candidate for a plasma facing material from viewpoints of the low sputtering yield, the low tritium retention, the high melting point, etc. However, large radiation loss in the core plasma might occur because tungsten is not fully ionized even in the core plasma. For an ignited plasma, the tungsten impurity content of the core plasma must be less than $10^{-4}$ against the electron density [1]. Therefore understanding and control of the accumulation process of the high-Z impurity, such as tungsten, is one of the crucial issues for the fusion research and development.

Full tungsten wall experiments have been carried out in ASDEX Upgrade [2]. The tungsten accumulation in the core plasma has been observed in the case without the sufficient heating into the very center of the plasma. It has been considered that the tungsten accumulation is caused by the neoclassical inward flow, which is driven by the density gradient of the background plasma. In JT-60U with local tungsten wall, the toroidal rotation scan experiment using the neutral beams in the co- and ctr- direction to the plasma current was performed. It has been observed that the accumulation of tungsten ions becomes significant with increasing toroidal rotation velocity in the ctr-direction, while the accumulation is not affected so much in the co-rotation case [3]. This result cannot be simply explained by the usual neoclassical theory.

In this study, the transport of the high-Z impurity in the toroidally rotating tokamak plasma with the radial electric field is investigated analytically and numerically.

## 2. Inward pinch of the high-Z impurity due to atomic processes

In the toroidally rotating tokamak plasma, the energy of the high-Z impurity becomes high because the high-Z impurity with large mass is accelerated up to the toroidal rotation velocity $v_t$ of the background plasma by friction. Therefore the deviation of a drift orbit from the magnetic

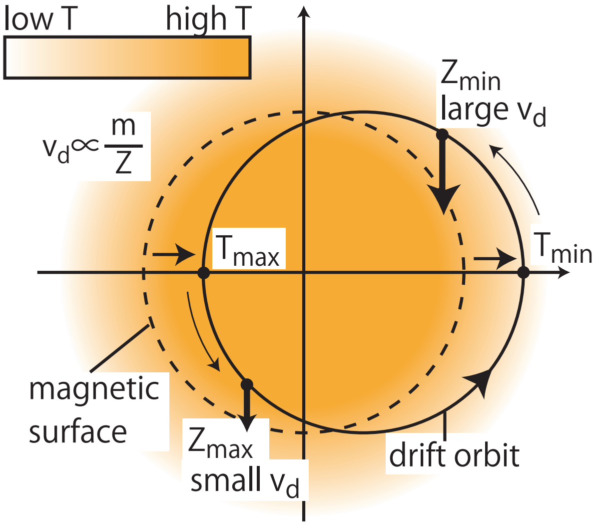


*FIG. 1. Schematic diagram of the basic mechanism of the inward pinch of the high-Z impurity due to the atomic process of the ionization/recombination.*

surface becomes large. As a result, the electron temperature $T$ and the charge state $Z$ vary along the drift orbit. Figure 1 shows that the poloidal variation of $Z$ is deviated from that of $T$ by the time delay of the ionization/recombination processes. The poloidal variation of the magnetic drift velocity $v_d$ in inverse proportion to $Z$ causes the inward pinch [4]. In this paper, such an inward pinch of high-Z impurity due to the atomic processes of ionization/recombination is called the PHZ.

To evaluate the PHZ velocity, an analytic model is derived. The charge state $Z$ along the drift orbit and the position in minor radius $r$ are given by the following equations:

$$\frac{\partial Z}{\partial t} = \frac{\partial \nu}{\partial T}\frac{\partial T}{\partial r}(r - r_0) + \frac{\partial \nu}{\partial Z}(Z - Z_0) \tag{1}$$

$$\frac{\partial r}{\partial t} = v_r = v_d \sin(\omega t) \tag{2}$$

with the poloidal angular frequency $\omega = v/qR_0$ and the magnetic drift velocity $v_d = mv^2/ZeRB$, where, $v$, $q$, $R$, $m$ and $B$ are the velocity of impurities, a safety factor, a major radius, impurity mass and magnetic field, respectively. The subscript "0" represents the initial condition. The net reaction frequency is given by $\nu = \nu_i - \nu_r = n(\langle \sigma v \rangle_i - \langle \sigma v \rangle_r)$, where $n$ is the electron density. The ionization rate $\langle \sigma v \rangle_i$ and the recombination rate $\langle \sigma v \rangle_r$ are taken from Ref. [5]. From Eqs. (1) and (2), the PHZ velocity $v_{PHZ}$ is derived as follows:

$$v_{PHZ} = \langle v_r \rangle = \frac{v_{d0}^2}{2Z_0}\frac{C_T C_{\nabla T}}{C_Z^2 + \omega^2} \tag{3}$$

where $C_T = \partial\nu/\partial T$, $C_Z = \partial\nu/\partial Z$, $C_{\nabla T} = dT/dr$. Figure 2 shows $v_{PHZ}$ estimated by Eq. (3). In the estimation, the following JT-60U like parameters are assumed: $n = 2.0 \times 10^{19}\,\mathrm{m}^{-3}$, $T = 1.5$ keV, $C_{\nabla T} = 5$ keV/m, $B = 3.75\,\mathrm{T}$, $R = 3.2\,\mathrm{m}$ and $r_0 = 0.8\,\mathrm{m}$. From these parameters, $C_T = 8.01\,\mathrm{eV}^{-1}\mathrm{s}^{-1}$, $C_Z = -512\,\mathrm{s}^{-1}$ and $Z_0 = 34$ are obtained for the tungsten impurity. As the toroidal rotation speed increases, the PHZ, i.e., an inward radial velocity increases independently of the rotation direction.

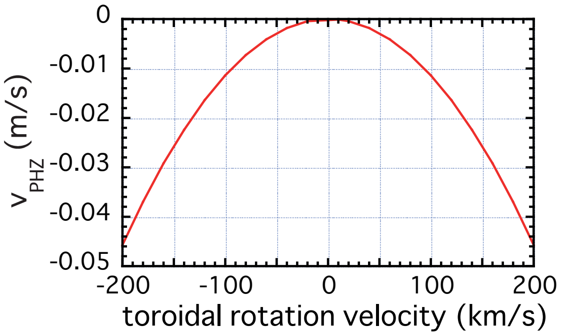


*FIG. 2. The radial velocity by the PHZ estimated by the analytic model.*

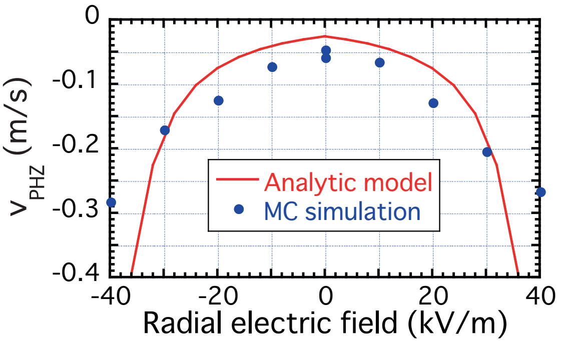


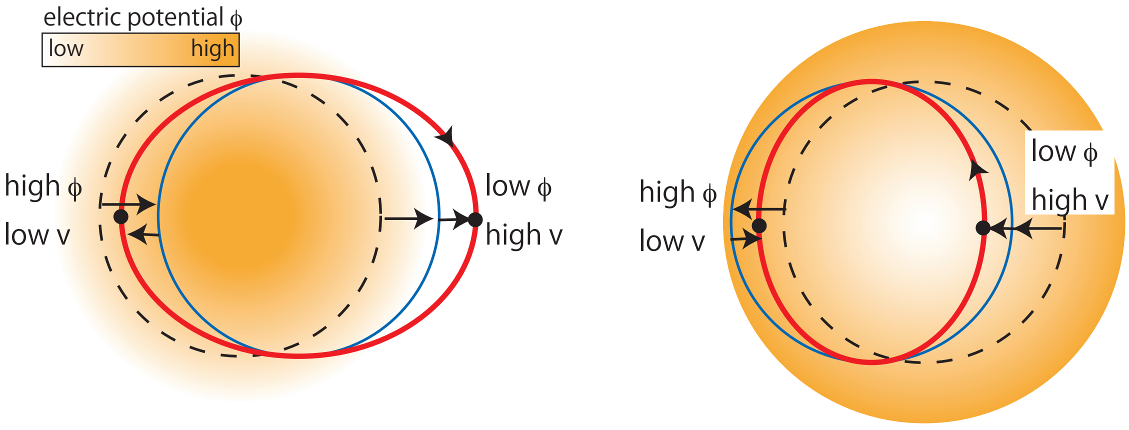
*FIG. 3. The PHZ velocity as a function of the radial electric field.*

In the case that a toroidal rotation speed is high, the positive and negative radial electric fields are formed in the co- and ctr- rotation cases, respectively. These radial electric fields $E_r$ reduce the poloidal rotation by the $E_r \times B$ drift. The resultant increase in the deviation of the drift orbit enhances the PHZ. In Fig. 3, the PHZ velocity with $|v_t| = 150$ km/s is plotted as a function of $E_r$. The sign of $v_t$ is the same as that of $E_r$. As $E_r$ increases, the PHZ velocity increases by more than an order of magnitude. In order to validate the PHZ model and the effect of $E_r$ on the PHZ, the Monte-Carlo (MC) simulation using the high-Z impurity transport code IMPGYRO [6] is performed. In the simulation, the same parameters as the analytic model are used and the Coulomb collision with the background plasma is switched off to focus our attention on the PHZ. The MC simulation results are shown in Fig. 3 by circle symbols. They agree well with the analytic model (solid curve).

## 3. Effect of the radial electric field through the Coulomb collision

In addition to the increase in the PHZ velocity, the radial electric field affects the radial transport of high-Z impurities through Coulomb collisions with the rotating background plasma. The electric potential $\phi$ varies along the drift orbit because of the large deviation of the orbit in the toroidally rotating plasma. Figure 4 shows the deformed orbits. The change in the parallel velocity due to the $\phi$ variation causes the radial expansion of the drift orbit in the co-rotation case (the positive $E_r$), while it brings the shrinkage in the ctr-rotation case (the negative $E_r$). The impurity particle moves by the width of the expansion/shrinkage per the Coulomb collision, i.e., the unpinch/pinch occur with increasing $|E_r|$. (In this paper, "unpinch" is used for the radially outward movement of particles.) However, in larger $|E_r|$ case, the expansion/shrinkage of the drift orbit is cancelled by the increase in the poloidal angular frequency due to the expansion/shrinkage. Therefore, with increasing $|E_r|$, the pinch/unpinch velocity initially increases and then decreases. Henceforth "the $E_r$ pinch" is used for such pinch/unpinch due to the radial electric field through Coulomb collisions.

An analytic model is developed to evaluate the $E_r$ pinch velocity. The magnetic drift velocity and poloidal angular frequency including the effect of $E_r$ are given by $v_d = mv^2/(ZeBR) = (v^2/v_0^2)v_{d0} = (1+2k\Delta r)v_{d0}$ and $\omega = (v - E_r/B_\theta)/qR \sim (1-\alpha+k\Delta r)\omega_0$, respectively, where $B_\theta$ is the poloidal magnetic field, $v^2 = v_0^2 + (2ZeE_r/m)\Delta r$, $k = ZeE_r/(mv_0^2)$ and $\alpha = E_r/B_\theta v_0$. The change in the minor radial position $\Delta r$ and the poloidal angle $\theta$ are given by following



(a) CO-rotation and positive $E_r$ (b) CTR-rotation and negative $E_r$

*FIG. 4. Schematic diagram of the basic mechanism of the pinch/unpinch due to the effect of radial electric field through Coulomb collisions. The broken line indicates the magnetic surface. The thin and thick solid lines correspond to the drift orbit without and with the effect of the radial electric field, respectively.*

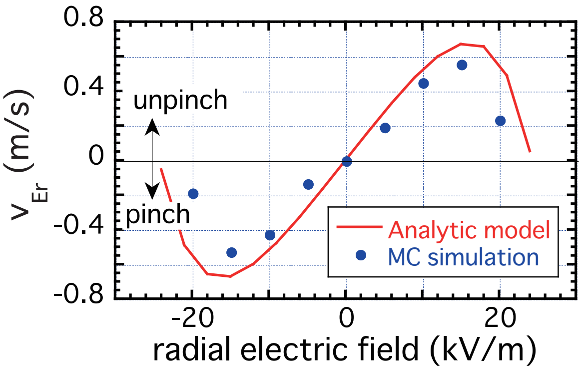


*FIG. 5. Radial velocity by the effect of the radial electric field through the Coulomb collision*

equations:

$$\frac{d\Delta r}{dt} = (1+2k\Delta r)v_{d0}\cos\theta \tag{4}$$

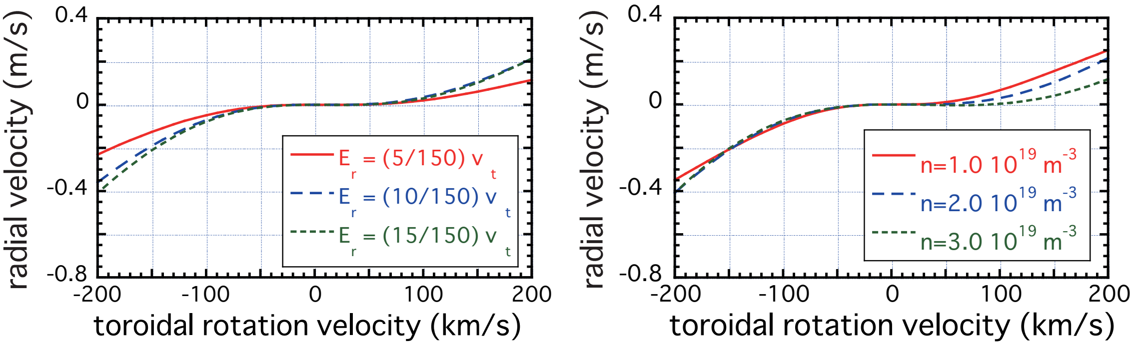
$$\frac{d\theta}{dt} = \omega = (1-\alpha+k\Delta r)\omega_0 \tag{5}$$

From Eqs. (4) and (5), $\Delta r$ is solved and the $E_r$ pinch velocity $v_{E_r}$ is obtained.

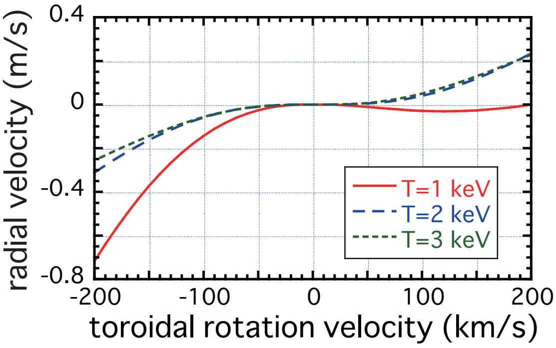
$$v_{E_r} = \Delta r\frac{\nu_c}{1+(\nu_c/\nu_b)^2} = \frac{(1-2\alpha)k\Delta_0^2}{2(1-\alpha)^2}\frac{\nu_c}{1+(\nu_c/\nu_b)^2} \tag{6}$$

where $\Delta_0 = v_{d0}/\omega_0$, $\nu_c$ is the collision frequency and $\nu_b$ is the poloidal rotation frequency.

The radial velocity estimated by Eq. (6) is plotted as a function of $E_r$ in Fig. 5. The same parameters as the $v_{PHZ}$ estimation are used. As mentioned above, as $|E_r|$ increases, the pinch/unpinch velocity initially increases and then decreases. The circle symbols show the result of the IMPGYRO simulation with the effect of the Coulomb collision and the fixed charge state $Z = 34$. The unpinch and the pinch are observed in the cases of the positive and negative $E_r$, respectively. The MC simulation results support the analytic model.



(a) radial electric field dependence (b) density dependence



(c) temperature dependence

*FIG. 6. Dependence of the PHZ and the $E_r$ pinch on the plasma parameters.*

## 4. Parameter dependence of the PHZ and the $E_r$ pinch

In this section, we study parameter dependences of the PHZ and the $E_r$ pinch.

In Fig. 6(a), the dependence of the PHZ and the $E_r$ pinch on the radial electric field is plotted as a function of the toroidal rotation velocity. The radial electric field is estimated by a simple expression $E_r = cv_t$, where $c$ is a constant parameter. The PHZ and the $E_r$ pinch becomes significant with increasing $c$ from $5/150$ to $15/150$. In the ctr-rotation case ($v_t < 0$), the direction of the PHZ and the $E_r$ pinch is inward. Therefore the sum of them increases the inward velocity with increasing toroidal rotation velocity. On the other hand, in the co-rotation case ($v_t > 0$), these pinches have an opposite direction to each other. Therefore, the outward velocity due to the $E_r$ pinch is decreased by the inward velocity due to the PHZ.

The dependence of pinches on the background plasma density is shown in Fig. 6(b). To take into account the $E_r$ effect, $c = 15/150$ is assumed. The PHZ velocity increases with increasing density because of increase in the reaction rate of the ionization/recombination. In the $E_r$ pinch, increase in density enhances the collision frequency $\nu_c$. The poloidal rotation frequency $\nu_b$ is smaller than $\nu_c$ in the present condition. Therefore, from Eq. (6), the increase in $\nu_c$ with small $\nu_b$ decreases $v_{E_r}$. As a result, the total radial velocity decreases in the co-rotation case as the density increases. In the ctr-rotation case under the present condition, increase in $v_{PHZ}$ balances with decrease in $v_{E_r}$.

Figure 6(c) shows the temperature dependence. The PHZ becomes significant with decreasing temperature, because the net reaction frequency $\nu$ is more sensitive to the temperature in the low temperature. As a result, in $T = 1\,\text{keV}$ case, the inward velocity is driven even in the co-rotation case. With increasing $T$, the contribution of $v_{PHZ}$ becomes small, therefore unpinch appears in the co-rotation case.

## 5. Summary

The high-Z impurity transport in the toroidally rotating tokamak plasmas was investigated. The pinch of the high-Z impurity due to the atomic processes of the ionization/recombination along the drift orbit and the pinch/unpinch due to the effect of the radial electric field through Coulomb collisions were analytically derived. These pinch mechanisms are numerically confirmed by the IMPGYRO simulation.

In the ctr-rotation case, the direction of the both pinches is inward. Therefore, the large inward pinch occurs with increasing toroidal rotation velocity. On the other hand, in the co-rotation case, these pinches have an opposite direction to each other. Therefore, the unpinch due to the positive radial electric field is decreased by the pinch due to the atomic processes. These pinches can explain the tungsten accumulation dependence on the toroidal rotation observed in the JT-60U rotation scan experiment.

In future fusion devices, the ctr-rotation is unfavorable for avoidance of the large radiation cooling by high-Z impurities. On the other hand, in the co-rotation case, there is a possibility to control the high-Z impurity accumulation by the toroidal rotation.

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