Analysis of Tungsten Transport in JT-60U Plasmas*)

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In JT-60U plasmas, increasing the toroidal rotation opposite to the plasma current (CTR rotation) enhances tungsten accumulation. Hoshino *et al.* have proposed two pinch models (i.e., PHZ pinch and Er pinch), which account for the effects of toroidal rotation and the radial electric field, respectively. We introduce them to the integrated transport code TOTAL. We study the dependence of tungsten accumulation on the toroidal rotation in TOTAL simulations of JT-60U plasmas. Because the assumptions of the Er pinch model are incompatible with the experimental conditions, we study the effect of the PHZ pinch only. The tungsten accumulation was four times higher at high toroidal rotation velocity than at low toroidal rotation velocity, replicating the experimental trend. The tungsten accumulation in the PHZ pinch model was 1.4 - 2.2 times higher than predicted by neoclassical transport only.

Keywords: tungsten accumulation, toroidal rotation, PHZ pinch, Er pinch, neoclassical transport

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1. Introduction

In tokamak devices, accumulation of impurities from plasma facing materials increases the radiation loss and dilutes the fuel. Tungsten is a promising plasma-facing material in ITER divertor because of its high melting point, high thermal conductivity, and other desirable properties. However, accumulation of tungsten (W) is concerned because of its large radiation loss due to its high atomic number (high Z). In JT-60U H-mode plasma, tungsten accumulation was observed to be enhanced as the toroidal rotation opposite to the plasma current (CTR rotation) increased [1]. This phenomenon cannot be simply explained by the conventional neoclassical transport [2]. From theoretical considerations, Hoshino *et al.* have proposed two pinch models (i.e., PHZ pinch and Er pinch), accounting for the effects of toroidal rotation and the radial electric field, respectively [3]. PHZ pinch is caused by changes in the ion charge state along its drift orbit. Er pinch is caused by the effect of the radial electric field through Coulomb collisions.

In this study, we introduce both pinch models into transport code TOTAL [4] and simulate the JT-60 experiments by TOTAL. We study the dependence of tungsten accumulation on the toroidal rotation. Section 2 explains our impurity transport model and the proposed pinch models. The plasma conditions are described in section 3. Section 4 presents the simulation results of the pinch velocity and the tungsten accumulation. Section 5 summarizes the study.

2. Model

The tungsten transport is solved by the 1.5-dimentinal transport code “TOTAL”. Temperature and density profiles are fixed to the experimental values (described in section 3).

2.1 Transport model

The density of impurities is solved by the rate equation with a transport term. The rate equation in charge state k is given by

$$\frac{\partial n_k}{\partial t} = -\frac{1}{V'}\frac{\partial}{\partial \rho}(V'\Gamma_k) + [\gamma_{k-1}n_{k-1} + \alpha_{k+1}n_{k+1} - (\gamma_k + \alpha_k)n_k]n_e + S_k, \tag{1}$$

where n_k is the density of impurity ions in charge state k, γ_k is the ionization rate, α_k is the recombination rate, and S_k is the particle source term. The ionization rate γ_k and the recombination rate α_k are taken from [5]. The impurity is assumed to be injected from the main plasma surface (last closed flux surface) in the neutral state. $V' = \partial V/\partial\rho$, where V is the volume inside the magnetic surface and ρ is the normalized minor radius. The impurity ion flux is given by

$$\Gamma_k = \Gamma_k^{\mathrm{NC}} - D^{\mathrm{AN}}(\rho)\frac{\partial n_k}{\partial \rho} + V_k^{\mathrm{pinch}}(\rho)n_k,$$

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$$\Gamma_k^{\rm NC} = -D_k^{\rm NC}\frac{\partial n_k}{\partial \rho} + V_k^{\rm NC} n_k, \tag{2}$$

where Γ_k is particle flux of impurities in charge state k. The subscript NC and AN represent neoclassical and anomalous transports, respectively. The neoclassical radial velocity $V_k^{\rm NC}$ and the neoclassical diffusion coefficient $D_k^{\rm NC}$ are calculated with temperature gradient and density gradient by NCLASS module [2] implemented in TOTAL. The anomalous diffusion coefficient $D^{\rm AN}$ is assumed to be uniform.

The total radial velocity is given by

$$V_k^{\rm total} = V_k^{\rm NC} + V_k^{\rm pinch}, \tag{3}$$

$V_k^{\rm total} < 0$ and $V_k^{\rm total} > 0$ correspond to the inward and outward directions, respectively. Pinch models with the toroidal rotation are introduced in the $V_k^{\rm pinch}$ term. The average velocity of all charge state is given by

$$V_{\rm average} = \frac{\sum V_k \times n_k}{\sum n_k}. \tag{4}$$

2.2 Pinch model

In a toroidally rotating plasma, positive radial electric fields are formed in CO-rotation (direction of the plasma current) and negative fields are formed in CTR-rotation. Initially, high-Z impurity ions are accelerated up to the toroidal rotation velocity of the background plasma by friction. Because high-Z impurity ions are relatively massive, their energies become large; consequently, their drift orbit largely deviates from the magnetic surface. PHZ and Er pinches occur by different processes as the impurity ions move along this deformed orbit.

2.2.1 PHZ pinch

The charge state Z varies as the electron temperature T changes along the drift orbit. If the poloidal rotation time approximates the characteristic time of the ionization / recombination, the poloidal variation of the charge state deviates from that of temperature by the time delay of the ionization / recombination processes. The variation of the magnetic drift velocity along the drift orbit causes an inward pinch called PHZ pinch.

The PHZ pinch velocity is given by the following equation [3];

$$V_{\rm PHZ} = \frac{v_{\rm d0}^2}{2Z_0}\frac{C_{\rm T} C_{\nabla \rm T}}{C_{\rm Z}^2 + \omega^2}, \tag{5}$$

where $v_{\rm d0}$ is the magnetic drift velocity; $v_{\rm d0} = {\rm m}V_{\rm t}^2/Z_0 eRB$, ω is the angular frequency of the poloidal motion of impurity ions; $\omega = (V_{\rm t} - E_r/B_\theta)/(qR_0)$, $V_{\rm t}$ is the toroidal rotation velocity, B_θ is poloidal magnetic field, $C_{\rm T} = n_{\rm e}\partial(\gamma_k - \alpha_k)/\partial T_{\rm e}$, $C_{\rm Z} = n_{\rm e}\partial(\gamma_k - \alpha_k)/\partial Z$, $C_{\nabla \rm T} = {\rm d}T/{\rm d}\rho$. Z_0 is the charge state in ionization equilibrium.

Figures 1 and 2 plot the quantity $(\gamma_k - \alpha_k)$ as a function of $T_{\rm e}$ and Z, respectively. When calculating $C_{\rm Z}$, $\partial(\gamma_k - \alpha_k)/\partial Z$ is evaluated for the most fractionally abundant charge state at the electron temperature of each radial location.

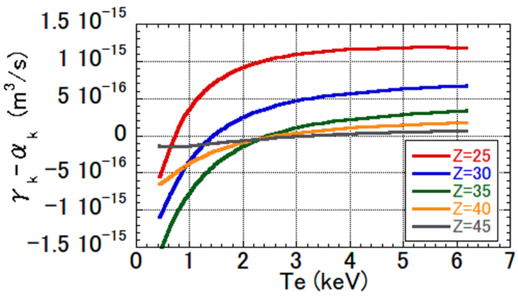

Fig. 1 Relationship between $(\gamma_k - \alpha_k)$ and $T_{\rm e}$.

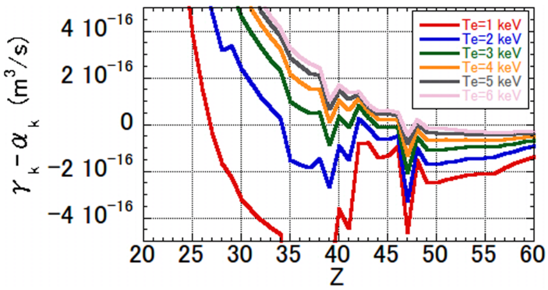

Fig. 2 Relationship between $(\gamma_k - \alpha_k)$ and Z.

2.2.2 Er pinch

The velocity varies along the orbit under the changing electric potential. In the CO and CTR rotation cases, the velocity change expands and shrinks the entire orbit, respectively. Impurity particles move by the width of the expansion / shrinkage per the Coulomb collision. The resulting unpinch/inward pinch is called the Er pinch.

The Er pinch velocity is given by following equation [3];

$$V_{\rm Er} = \Delta r \frac{v_{\rm c}}{1 + (v_{\rm c}/\omega)^2}, \tag{6}$$

where $v_{\rm c}$ is the collision frequency of the impurity ions with the background plasma. Δr is the change in the minor radial position,which is represented as follows:

$$\Delta r = \frac{(1-2\alpha)k\Delta_0^2}{2(1-\alpha)^3}, \tag{7}$$

where $k = ZeE_r/mV_{\rm t}^2$, $\alpha = E_r/B_\theta V_{\rm t}$, and $\Delta_0 = v_{\rm d0}/\omega_0$. The above formula is valid when $\alpha < 1$ and $2k\Delta r < 1$.

In CO-rotation case, the PHZ and Er pinches occur in opposite directions and cancel each other. However, in CTR-rotation case, they are also in the inward direction. Therefore, the inward pinch and impurity accumulation are enhanced with increased toroidal rotation velocity.

3. Conditions

We simulated five experimental data; shot E049530 (t = 7.5 s and t = 9.0 s), E049537 (t = 7.5 s), E049538

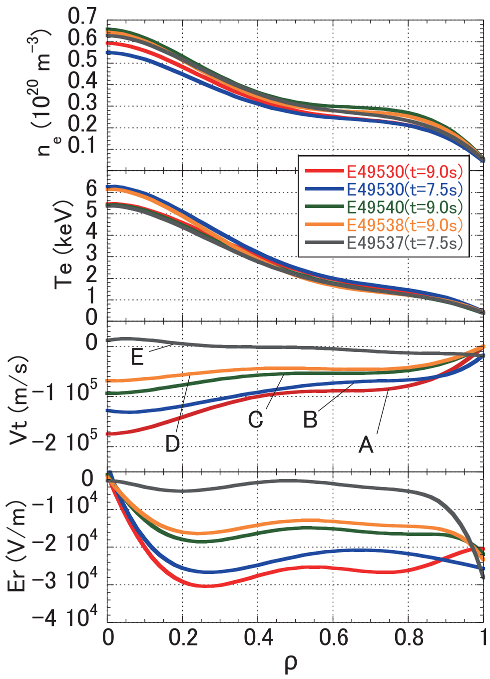

Fig. 3 Radial profile of plasma parameters of the experimental data used in the simulation.

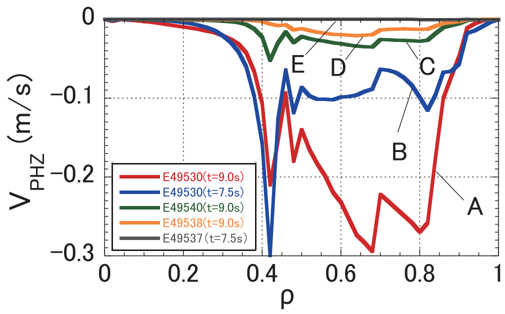

Fig. 4 Average velocity of PHZ pinch.

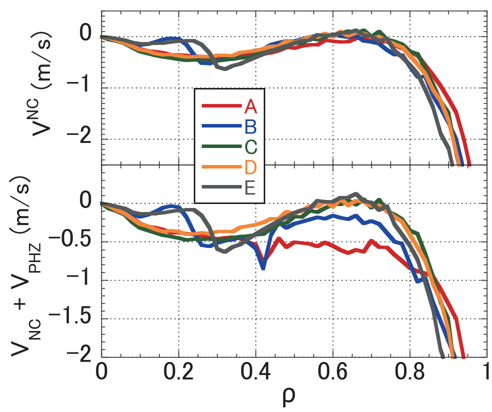

Fig. 5 Neoclassical (top) and total (bottom) radial velocities. Neoclassical and PHZ pinch velocity are the average value of all charge state.

(t = 9.0 s) and E049540 (t = 9.0 s). The plasma parameters were as follows: major radius = 3.35 m, minor radius = 0.85 m, plasma current = 1.6 MA, toroidal magnetic field = 3.5 T, triangularity = 0.32, ellipticity = 1.46, neutral beam (NB) heating power = 15 MW. The radial profiles are shown in Fig. 3. During the experiment, the toroidal rotation velocity V_t was changed by varying the combined tangential NB injection at constant NB power. The radial electric field Er was calculated by integrated transport code TOPICS [6, 7]. To simplify the notation, the experimental shots are labeled from A to E in order of decreasing toroidal rotation velocity. For instance, the largest toroidal rotation shot (E049530 at t = 9.0 s) is labeled A, and the smallest toroidal rotation shot (E049537 at t = 7.5 s) is labeled E.

4. Results

4.1 Pinch velocity

Figure 4 plots the estimated radial velocity of the average PHZ pinch in the 5 cases. In each case, $\alpha > 1$ over the entire range, violating the assumptions of the Er pinch model. Thus, when calculating the tungsten accumulation, we set $V_{Er} = 0$ in this study and investigate only the effect of the PHZ pinch.

As described in the model, PHZ pinch is enhanced at larger toroidal rotation velocities. The PHZ pinch peaks at ρ = 0.4 - 0.8, where ω is almost vanishes due to the Er. The sharp peak at ρ = 0.4 ($T_e \sim 3$ keV) is caused by the small absolute value of C_z at T_e = 3 keV. As shown in Fig. 2, $\partial(\gamma_k - \alpha_k)/\partial Z$ (and hence C_z) is highly sensitive to temperature, so the PHZ pinch velocity exhibits a jagged radial profile although the density and temperature profiles are smooth. The neoclassical and total radial velocities are plotted in Fig. 5.

At $\rho \sim 0.2$, the neoclassical velocity is weaker in cases B and E than in the other three cases. The PHZ pinch is relatively small at the center, so the total velocity in case B (the second largest toroidal rotation velocity) is large over a wide range but remains small at the center.

4.2 Tungsten accumulation

The tungsten accumulation c_w ($c_w = (n_w/n_e)$) is evaluated in steady state. The anomalous diffusion coefficient D^{AN} is assumed as 0.01, 0.001, and 0.0001 m^2/s, approximately equal to or smaller than the average D^{NC} (0.008 - 0.012 m^2/s at the plasma edge in each shot). This assumption is based on the reported similarity between the anomalous diffusion and neoclassical transport diffusion coefficients for high-Z ions [8]. Improved modeling of the anomalous diffusion coefficient will be attempted in future work. The c_w at the plasma center was estimated by the absolute intensity of the W XLVI intensity and the experimentally validated atomic data [1]. The tungsten influx is assumed as constant, and its amount is assumed consistent with the experimental data of case E for each D^{AN}.

Figure 6 shows the radial profile of tungsten accumulation. Tungsten ions accumulate at the center. In cases

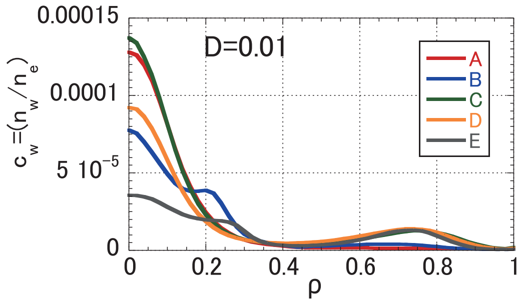

Fig. 6 Radial profile of tungsten ion concentration (D^{AN} = 0.01).

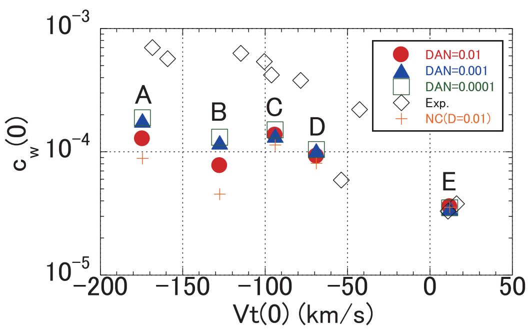

Fig. 7 Dependence of the tungsten concentration on the toroidal rotation. Open diamonds represent experimental data. + signs represent the concentration in each shot assuming neoclassical transport only.

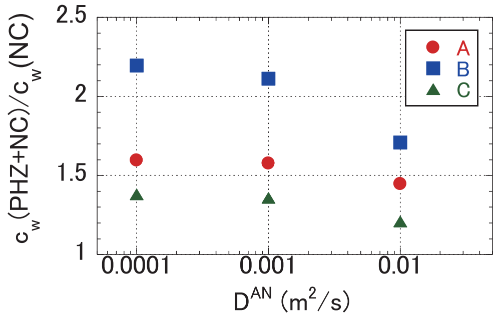

Fig. 8 The effects of PHZ pinch on tungsten accumulation. c_w(PHZ + NC) represents the accumulation due to the total velocity and c_w(NC) represents that due to only neoclassical transport.

C, D and E, tungsten also accumulates at $\rho = 0.6 - 0.8$, the region of neoclassical unpinch. Figure 7 shows the dependence of central tungsten concentration on toroidal rotation velocity. The dependence on toroidal rotation is evaluated by the value of the concentration at the center because the tungsten ions accumulate at the center (Fig. 6). The experimentally observed larger accumulation at higher toroidal rotation was reproduced in the simulation. At the high rotation velocities, the tungsten accumulation is 4 - 5 times larger than at slower rotational velocities. The tungsten accumulation is also enhanced at smaller D^{AN}. The dependence of tungsten accumulation on the plasma rotation velocity is weaker in the simulations than in the experiments. However, because the Er pinch model is invalidated and only the PHZ pinch is considered, the tungsten accumulation might increase if the Er pinch model was included. The PHZ pinch model reproduces the experimental trends.

Next, we investigated how the tungsten accumulation changes by including the PHZ pinch affect in addition to the neoclassical transport. The tungsten accumulation in the absence of PHZ, namely assuming neoclassical transport only, is plotted by crosses in Fig. 7. The central concentration is higher in cases A, C, and D than in cases B and E because the neoclassical pinch differs around $\rho = 0.2$ (Fig. 5). Note that the tendency on the toroidal rotation is also recognized in this analysis, but the trend becomes more pronounced when the PHZ pinch is also included. Figure 8 shows the enhancement ratio of the tungsten accumulation in the presence of PHZ, calculated as $c_w(\mathrm{PHZ + NC})/c_w(\mathrm{NC})$. By including the PHZ pinch, we enhance the tungsten accumulation by 1.4 - 2.2 times relative to neoclassical transport only under the conditions $V_t = -100 \sim -180$ km/s, $D^{AN} = 0.0001\ \mathrm{m^2/s}$.

5. Summary

We introduced two pinch models (i.e., PHZ and Er pinch induced by toroidal rotation and the radial electric field, respectively) into transport code TOTAL and conducted TOTAL simulations of the JT-60 experiments. The PHZ pinch model reproduces the experimentally observed behavior of the JT-60U plasma. The PHZ pinch effect enhanced the tungsten accumulation by 1.4 - 2.2 times relative to neoclassical transport only ($V_t = -100$ to -180 km/s, $D^{AN} = 0.0001\ \mathrm{m^2/s}$).

In this study, we set $V_{Er} = 0$ because the Er pinch model was invalidated under our conditions. In future work, we will plan to develop a new Er pinch model that is valid when $\alpha > 1$. In CO-rotation, it has been observed that tungsten accumulation is small because the PHZ and Er pinches cancel each other. Further validation is required for the CO-rotation case.

Acknowledgments

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