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# Theoretical Study of Structure and Dynamics of Radial Electric Field in Helical Plasmas

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## 1. Introduction

The internal transport barrier has been found in the ECRH plasma in the compact helical system (CHS) and the steep gradient in the profile of the radial electric field is obtained in the inner region [1]. A pulsating behavior of electrostatic potential is also found in CHS heliotron/torsatron [2]. We have examined the one-dimensional transport equations which describe the temporal evolutions of the density, the electron and ion temperatures, and the radial electric field in a cylindrical heliotron configuration [3]. The anomalous transport model for anomalous diffusivities to describe the plasma like L-mode has been used. The stationary structure of the radial electric field with hysteresis characteristic (hard transition) was examined in helical plasmas. The strong reduction of the anomalous transport can be obtained near the transition point. However, in the parameter region examined in a previous study, the anomalous transport is dominant compared with the neoclassical transport because the reduction of the anomalous transport can not be obtained at the radial points which are not near the transition point. Therefore, the reduction of the neoclassical transport due to the large positive $E_r$ is not seen and there is not a clear suppression in the total transport.

To show the clear transport barrier in an analytic result, the dependence of the stationary profile of plasma quantities on the input power profile is mainly studied. The hard transition which is characterized by the rapid change spatially is examined. The clear transport barrier can be obtained theoretically because of the large positive value of $E_r$. When the different external control parameter from the previous analysis is adapted, the neoclassical transport is found to be dominant compared with the anomalous transport in the wide inner region since the gradient of the radial electric field is enough strong to reduce the anomalous transport. Furthermore, we study the dynamics of the radial electric field.

## 2. One-dimensional model transport equations

In this section, model equations used in this study are explained. The cylindrical coordinate is used and r-axis is taken in the radial cylindrical plasma. The total particle flux $\Gamma^t$ is set as $\Gamma^t=\Gamma^{na}-D_a\partial n/\partial r$ in this article, where $D_a$ is the anomalous particle diffusivity and $\Gamma^{na}$ is the radial neoclassical flux associated with helical-rippled trapped particle. The expression for the neoclassical flux here is the connection formula and is applicable from the $\nu_{thj}$ regime defined by $D_j\propto\nu_{thj}$ to the $1/\nu_{thj}$ regime ($D_j\propto 1/\nu_{thj}$), where $D_j$ is the particle diffusion coefficient and $\nu_{thj}$ is the collision frequency estimated by the thermal velocity for species j [4]. The total heat flux $Q_j^t$ of the species j is expressed as $Q_j^t=Q_j^{na}-n\chi_a\partial T_j/\partial r$, where $\chi_a$ is the anomalous heat diffusivity and $Q_j^{na}$ is the energy flux by the neoclassical ripple transport, respectively. The theoretical model for the anomalous heat conductivity will be explained later. The formula for $Q_j^{na}$ are also given in ref. [4]. The anomalous diffusion coefficient for $E_r$ is denoted by $D_{Ea}$ and is given in ref. [5]. The temporal equation for the density is

$$\frac{\partial n}{\partial t}=-\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma^t)+S_n. \tag{1}$$

The term $S_n$ represents the particle source. The equation for the electron temperature is given as

$$\frac{3}{2}\frac{\partial}{\partial t}(nT_e)=-\frac{1}{r}\frac{\partial}{\partial r}(rQ_e^t)-\frac{m_e}{m_i}\frac{n}{\tau_e}(T_e-T_i)+P_{he}, \tag{2}$$

where the $\tau_e$ denotes the electron collision time and the second term on the right-hand side represents the heat exchange between electrons and ions. The term $P_{he}$ represents the absorbed power due to the ECRH heating and its profile is assumed to be proportional to

$\exp(-(r/(0.1a))^2)$ for simplicity. This profile has more central peaking than the previous analysis [3]. The equation for the ion temperature is

$$\frac{3}{2}\frac{\partial}{\partial t}(nT_i)=-\frac{1}{r}\frac{\partial}{\partial r}(rQ_i)+\frac{m_e}{m_i}\frac{n}{\tau_e}(T_e-T_i). \tag{3}$$

The term $P_{hi}$ represents the absorbed power of ions and its profile is also assumed to be proportional to $\exp(-(r/(0.1a))^2)$. The temporal equation for the radial electric field in a helical is expressed by [5]

$$\frac{\partial E_r}{\partial t}=-\frac{e}{\varepsilon_\perp}\sum_j Z_j\Gamma_j^{na}+\frac{1}{r}\frac{\partial}{\partial r}(\sum_j Z_je(D_{Ej}+D_{Ea})r\frac{\partial E_r}{\partial r}), \tag{4}$$

where $\varepsilon_\perp$ is the perpendicular dielectric coefficient calculated as $\varepsilon_\perp=\varepsilon_0((c^2/v_A^2)+1)(1+2q^2)$. The factor $(1+2q^2)$ is introduced due to the toroidal effect.

## 3. Boundary conditions and model for anomalous transport coefficients

The density, temperature and electric field equations (1)-(4) are solved under the appropriate boundary conditions. We fix the boundary condition at the center of the plasma (r=0) such that $n'=T_e'=T_i'=E_r=0$, where the prime denotes the radial derivative. For equation (4), the boundary condition at the edge (r=a) is the ambipolar condition. This simplification is employed because the electric field bifurcation in the core plasma is the main subject of this study. The boundary conditions at the edge (r=a) for the density and the temperatures are those in CHS device: $-n/n'=0.05$m, $-T_e/T_e'=-T_i/T_i'=0.02$m. The machine parameters are similar to those of CHS device, such as R=1m, a=0.2m, the toroidal magnetic field B=1T, toroidal mode number m=8 and the poloidal mode number $\ell=2$. We set the safety factor and the helical ripple coefficient as $q=3.3-3.8(r/a)^2+1.5(r/a)^4$ and $\varepsilon_h=0.231(r/a)^2+0.00231(r/a)^4$, respectively [1]. The particle source $S_n$ is set to be $S_n=S_0\exp((r-a)/L_0)$, where $L_0$ is set to be 0.01m and the value of $S_0$ controls the average density by the particle confinement time. This profile corresponds to the peaking at the plasma edge of the particle source due to the ionization effect. The values for the anomalous diffusivity of the particle and the anomalous coefficient for $E_r$ are chosen $D_a=1\text{m}^2\text{s}^{-1}$ and $D_{Ea}=1\text{m}^2\text{s}^{-1}$. These values are set to be constant spatially and temporally. In this study, we adopt the model for the anomalous heat conductivity based on the theory of the self-sustained turbulence due to the interchange mode, driven by the current difffusivity [6]. This model is chosen because the experiment in CHS device is done in the configuration of the magnetic hill. The anomalous transport coefficient for the temperatures is given as $\chi_a=\chi_0/(1+G\omega_{E1}^2)$, where $\chi_0$ and G are the functions of the magnetic shear, the safety factor, the pressure gradient and so on. The details of the forms $\chi_0$ and G are shown in ref. [6]. The parameter $\omega_{E1}$ represents the effect of the suppression due to the electric field gradient. In order to set the averaged temperature of electrons $\overline{T}_e$ to be around $\overline{T}_e=610$eV and the density to be around $\bar{n}=2\times10^{19}\text{m}^{-3}$, the absorbed power of electrons is 100kW and the coefficient of the source term $S_0$ is $1.5\times10^{24}\text{m}^{-3}\text{s}^{-1}$ for the choice of above values of anomalous transport coefficients. The averaged ion temperature is chosen to be about $\overline{T}_i=430$eV, where the absorbed power of ions is fixed at 50kW.

## 4. Stationary solution with multiple ambipolar electric fields

Using these parameters and boundary conditions given, we analysis the equations (1)-(4). The stationary solutions of the radial electric field are shown in figure 1(a). The profiles of the density and the temperature are shown in figures 1(b) and (c), respectively. In figure 1(c), the dotted line represents $T_i$ and the solid line shows $T_e$. In figure 1(a), the transition of the radial electric field is found at the point $\rho=\rho_T$ (0.49), where $\rho$ represents the normalized minor radius r/a. The circles in figure 1(a) show the values of the electric field which satisfy the local ambipolar condition for the calculated profiles of the density and the temperatures of figure

1(b) and (c). Multiple solutions are found to exist for the local ambipolar condition in the parameter region examined here. In the case of figure 1(a), the electron root ($\rho<\rho_T$) for $E_r$ is sharply connected to the ion root ($\rho>\rho_T$) with a thin layer between them. The transition point should be determined by the Maxwell construction [7]. We confirm that the Maxwell construction is satisfied. The derivative of the radial electric field is observed in figure 1(d). The peak at the transition point $\rho=\rho_T$ is found in figure 1(d). Furthermore, due to the central heating, the gradient of the radial electric field is obtained to some extent in the region $\rho<\rho_T$.

The transport barrier can be shown in both $T_e$ and $T_i$ profiles in figure 1(c). The value of the anomalous diffusivity shown in figure 2(a) is that of $\chi_a$. At the transition point $\rho=\rho_T$, the suppression is obtained due to the strong gradient of the electric field. The neoclassical diffusivities of electrons $\chi_e^{NEO}$ and ions $\chi_i^{NEO}$ are also shown with the solid line and the dashed line, respectively. Because of the large positive value of $E_r$, the reduction of the neoclassical transport is obtained in the region $\rho<\rho_T$. In the wide inner region $\rho<\rho_T$, the anomalous transport is moderately reduced due to the $E_r$ gradient. In figure 2(a), the anomalous transport is suppressed up to about one third in the region $\rho<\rho_T$ compared with the case of no $E_r$

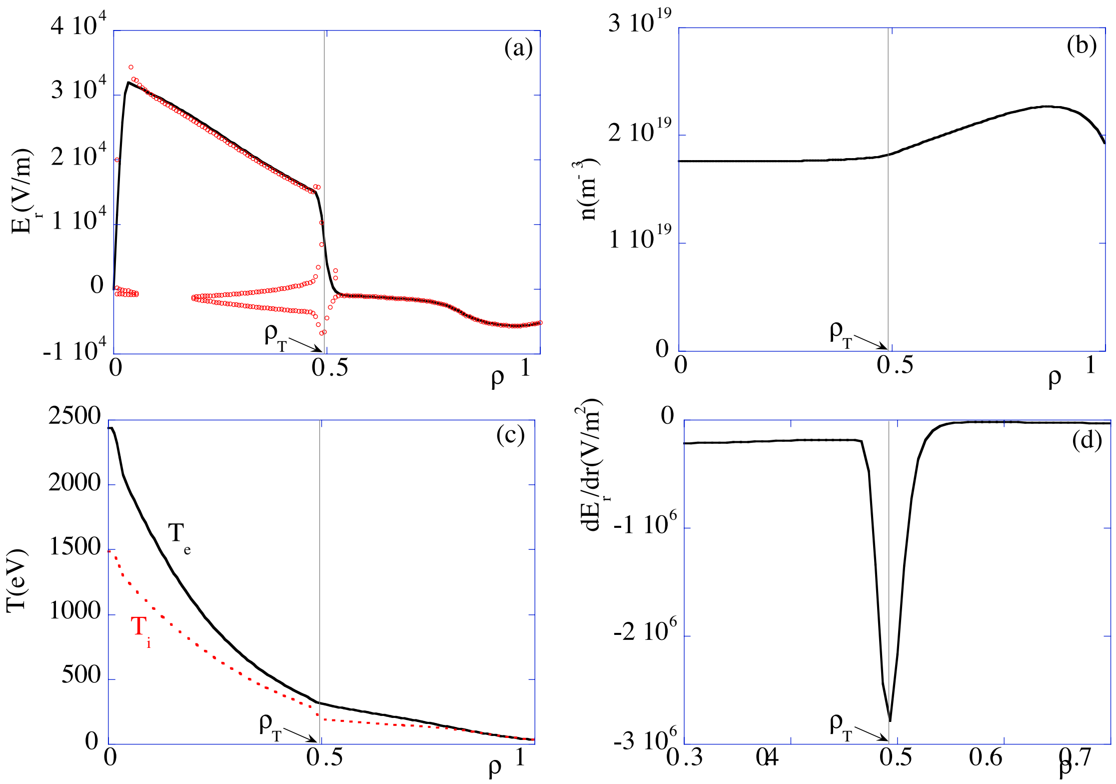


Figure 1 Radial profiles of (a) the electric field, (b) the density, (c) the electron temperature (solid line) and the ion temperature (dotted line) and (d) the derivative of the electric field.

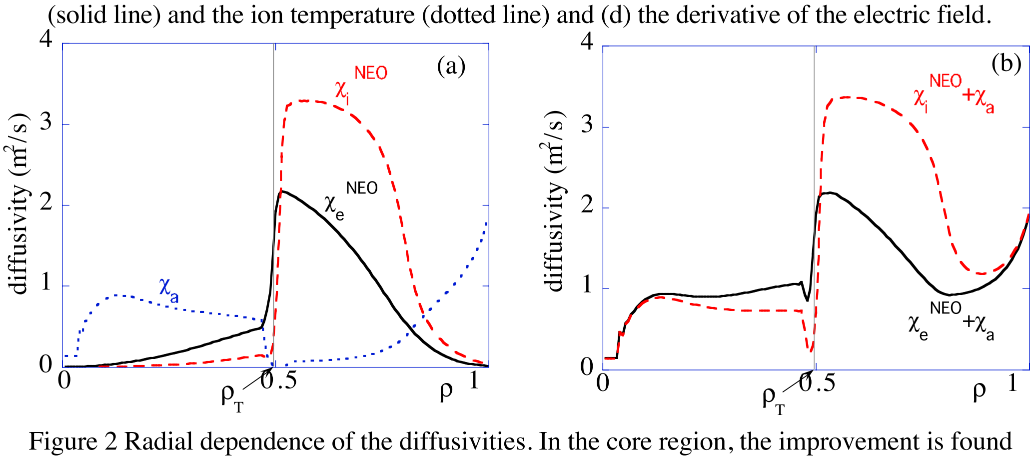


Figure 2 Radial dependence of the diffusivities. In the core region, the improvement is found because of the large positive $E_r$.

gradient. In the region $\rho>\rho_T$, the neoclassical transport is found to be dominant compared with the anomalous transport in the parameter region examined here. In figure 2(b), the sum of the anomalous and neoclassical diffusivities in the case of electrons and ions is obtained with the solid line and the dashed line, respectively. In the electron channel, the total heat conductivity in the region $\rho<\rho_T$ is about one half of that in the $\rho>\rho_T$ region. In the ion channel, the total heat conductivity in the region $\rho<\rho_T$ is around one third of that in the region $\rho>\rho_T$. Therefore, the clear transport barrier is obtained in both profiles of ion and electron temperatures.

## 5. Dynamics of radial electric field

In this section, the dynamics of the electric field is examined in the analysis shown in the previous section. In figure 3, the profiles of the electric field are shown at three times. The profile of $E_r$ (solid line) at t=0.2s corresponds to the stationary one, which is identical to that in figure 1(a). Before the state reaches the stationary one, the dotted line and the dashed line show the profiles of $E_r$ at 0.005s and 0.02s, respectively. When the state approaches to the stationary one, the transition point $\rho_T$ goes inside and the gradient of $E_r$ gets steeper in the case of the initial condition chosen here. The time during which the state reaches the stationary one is about a few times as long as the typical energy confinement time $\tau_E$~0.01s. In this study in which a theoretical model due to the current diffusivity is used, the oscillating solution in time is not obtained in the parameter region examined in this paper.

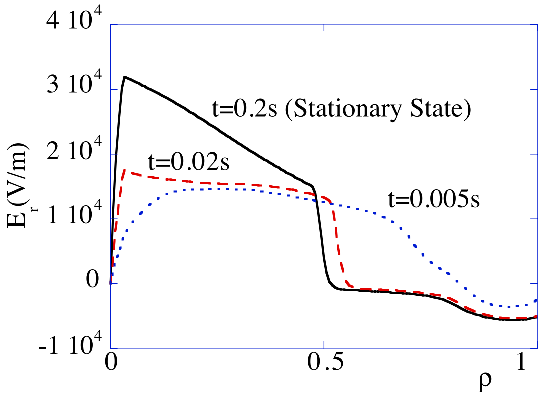


Figure. 3 The temporal evolution of $E_r$ profile is shown. The dotted line represents the $E_r$ profile at t=0.005s, the dashed line represents the one at t=0.02s and the solid line shows the $E_r$ profile at t=0.2s, respectively.

## 6. Summary and discussion

In this paper, the structure of the radial electric field in helical plasmas is theoretically studied in the case of the more central heating profile than the previous analysis. The parameter region in which the neoclassical transport is dominant compared with the anomalous transport is found by use of a theoretical model for the anomalous transport diffusivities. The clear transport barrier is seen in the profiles of the temperatures. Therefore, it is shown that the heating profile is important when the bifurcation characteristic exists even if the values of the heating power are same. In this study, only a theoretical model for anomalous coefficients due to the interchange mode is used. Analyses by use of other theoretical models (e.g., Ion temperature gradient mode) for anomalous coefficients are needed. The continuous study of the dynamics of the electric field should be done to study the electric pulsation observed in CHS device. These are future studies.

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