ANALYSIS OF STRUCTURE OF RADIAL ELECTRIC FIELD IN HELICAL PLASMAS

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1. Introduction

Recently, the internal transport barrier has been found in electron resonance heating (ECRH) plasma in the compact helical system (CHS), and the steep gradient of the radial electric field is observed in the core plasma [1]. To study the existence of the transport barrier in the experimental conditions of helical plasmas, there are two important issues. The first is the formation of the electric field domain interface which is associated with the steep gradient of E_r. This could be investigated quantitatively because the neoclassical transport is found to play the dominant role in generating the structure of the electric field in helical plasmas [2]. The second is the study of turbulent transport and neoclassical energy transport so as to understand the formation of the internal transport barrier.

In order to analyze the structure of the electric field quantitatively, the self-consistent transport study is done in which both the electric field bifurcation and suppression of the anomalous transport are included. The magnitude and the spatial distribution of the transport reduction are studied. The hard transition of E_r which induces the steep gradient is examined. The reduction of the anomalous transport is obtained due to the strong electric field shear at the electric domain. The neoclassical diffusivities are found to have a peak near the domain interface where the electric field vanishes.

2. One-dimensional model transport equations

In this section, the model equations are explained. The cylindrical coordinate is used and r-axis is taken in the radial cylindrical plasma. The total particle flux Γ^t is written as $\Gamma^t=\Gamma^{na}-D_a\partial n/\partial r$, where D_a is the anomalous particle diffusivity and Γ^{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 to both the collisional and collisionless regimes [3]. 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 χ_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 heat conductivity will be explained later. The formula for Q_j^{na} are also given [3]. The neoclassical component D_{Ej} of the diffusion coefficient for the electric field is given in ref. [4]. The anomalous diffusion coefficient for E_r. is denoted by D_{Ea}.

The temporal equation for the density is

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

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

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

where the τ_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 $\exp(-(r/0.2a)^2)$ for simplicity. The equation for the ion temperature is

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

The term P_{hi} represents the absorbed power of ions and its profile is also assumed to be proportional to $\exp(-(r/0.2a)^2)$. The temporal equation for the radial electric field in a nonaxisymmetric system is expressed by [4]

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

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=1(m), a=0.2(m), the toroidal magnetic field B=1(T), 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 0.01(m) and the value of S_0 controls the average density by the particle confinement time. The value for the anomalous diffusivity of the particle is chosen $D_a=10(m^2s^{-1})$. This value is 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 ballooning mode or the interchange mode, both driven by the current difffusivity [5,6]. The anomalous transport coefficient for the temperatures is given as $\chi_a=\chi_0/(1+G\omega_{E1}^2)$, where $\chi_0=F(s,\alpha)\alpha^{\frac{3}{2}}c^2v_A/(\omega_{pe}^2qR)$. The factor $F(s,\alpha)$ is the function of the magnetic shear s and the normalized pressure gradient α, defined by $\alpha=-q^2R\beta'$. For the ballooning mode turbulence in the system with a magnetic well, we employ the anomalous thermal conductivity $\chi_{a,\,BM}$. The details about the coefficients $F(s,\alpha)$ and G, and the factor ω_{E1} which stands for the effect of the electric field shear are given [5] in the ballooning mode turbulence. In the case of the interchange mode turbulence for the magnetic hill, the coefficient F has been given by $F_{IM}=3C(\Omega'/2)^{\frac{3}{2}}(R/a)^{\frac{3}{2}}/(qs^2)$, where $\Omega'=(r/R)^2(m/\ell)(r/a)^{-2}((r/a)^4/q)'$ for the anomalous heat conductivity $\chi_{a,\,IM}$. The factor for the suppression due to the electric field shear is $\omega_{E1}=\tau_{AP}E_r'/B$ and $G=0.52D_0^{-1}$, where $D_0=\Omega'\beta'a^2R^2/(2r^2)$ [6]. For the standard parameters in CHS experiment, the numerical factor C is chosen to be 10. We use this value of C throughout this paper. The greater one of the two diffusivities, $\chi_a=\max(\chi_{a,\,BM},\chi_{a,\,IM})$ is adopted. The approximation $D_{Ea}=\chi_a$ is employed, where the validity of this approximation is shown in ref. [7]. In order to set the averaged temperature of electrons $\overline{T}_e$ to be around $\overline{T}_e=250$(eV) and the density to be around $\bar{n}=1\times10^{19}(m^{-3})$, the absorbed power of electrons is 100kW and the coefficient of the source term S_0 is $7\times10^{24}(m^{-3}s^{-1})$ for the choice of above values of anomalous transport coefficients. The averaged ion temperature is chosen to be about $\overline{T}_i=150$(eV), where the absorbed power of ions is fixed at 50kW.

4. Results of Analysis

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 dashed curve represents T_i and the full curve shows T_e. At the point $r=r_T$ (0.12m), the transition of the radial electric field is found. 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 allowed for the local ambipolar condition in the parameter region examined here. In the case of figure 1(a), the electron root ($r<r_T$) for E_r is sharply connected to the ion root ($r>r_T$) with a thin layer between them. The transition points should be determined by the Maxwell construction [8]. We confirm that the Maxwell construction is satisfied in the case of figure 1(a). The profile of the derivative of the radial electric field is observed in figure 1(d). The peak at the transition point $r=r_T$ is found in figure 1(d). It is found that there is a difference between the half widths at the half maximum of the inner side ($r<r_T$) and the outer side ($r>r_T$) in the profile of the electric field shear. The half width of the inner side is wider than that of the outer side due to the dependence of the neoclassical current on the radial electric field. The magnitude of the peak of the electric field shear in this study is twice as that of the case for the constant D_{Ea} [2] which gives the same half width at the half maximum. The condition for the suppression due to the electric field shear is satisfied where the width in the profile of the electric field shear is smaller than 0.007(m)

The transport barrier is obtained for the both channels of the neoclassical transport and the anomalous transport, although it is not very clear in both T_e and T_i profiles in figure 1(c). The value of the anomalous diffusivity shown in figure 2 is that of χ_a. At the transition point, the suppression is obtained due to the strong electric field shear. The neoclassical diffusivities of electrons χ_e^{NEO} and ions χ_i^{NEO} are also shown with the dashed line and the dotted line, respectively. When the spatial transition occurs, the electric field goes across zero. Therefore, the neoclassical diffusivities have a peak near the surface where the relation E_r~0 holds, because they depend on the value of E_r itself. In figure 2(b), the sum of the anomalous and

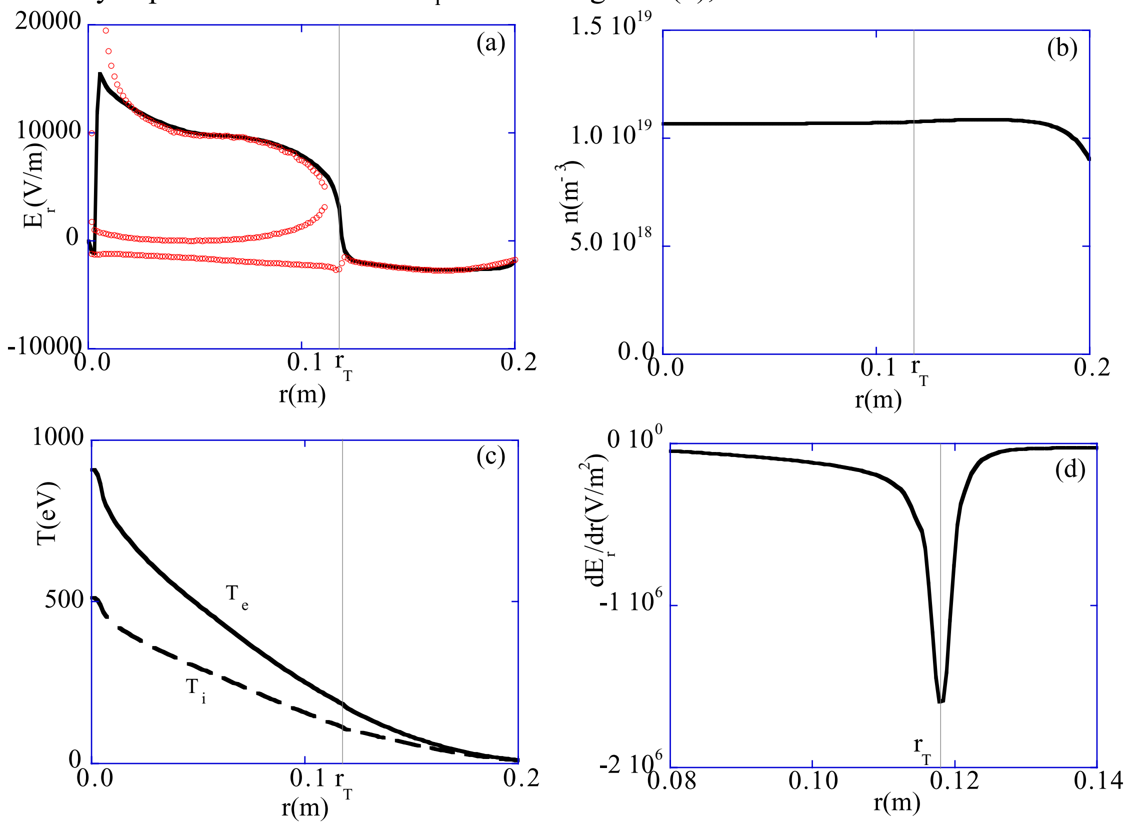

Figure 1 Radial profiles of (a) the electric field, (b) the density, (c) the electron temperature (solid line) and the ion temperature (dashed line) and (d) the derivative of the electric field.

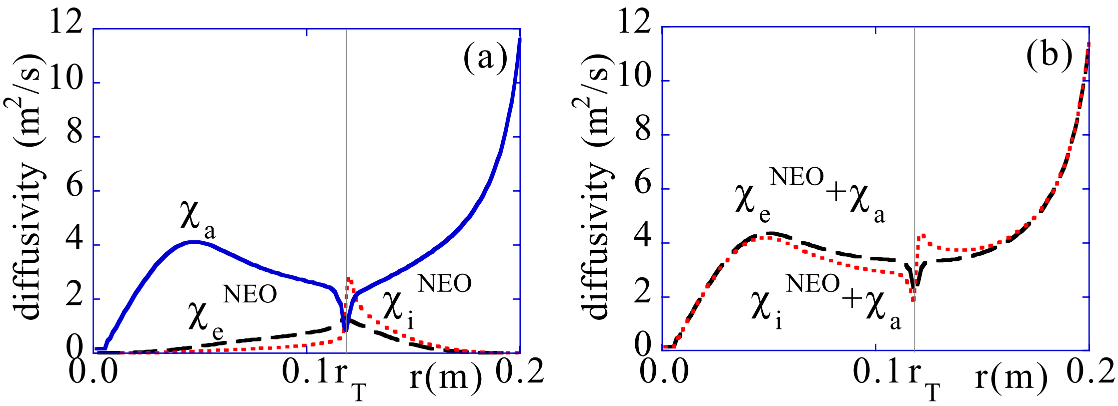

Figure 2 Radial dependence of the diffusivities. The suppression of the anomalous diffusivity is obtained in figure 2(a) due to the strong electric field shear.

neoclassical diffusivities is shown. The case of electrons and the case of ions are obtained with the dashed line and the dotted line, respectively. The total suppression can be seen but is small compared with that of the anomalous diffusivity. This is because the neoclassical diffusivity has a peak near the radius $r=r_T$.

5. Summary and Discussion

In this paper, the structure of the radial electric field in helical plasmas is theoretically studied. The analysis is done by use of one-dimensional transport model equations. Theoretical model is adopted for the anomalous heat diffusivity and the anomalous diffusion coefficient of the electric field. The hard transition with the multiple ambipolar E_r is obtained in the structure of the radial electric field in this study of T_e/T_i~2. The connection from the positive electric field (electron root) to the negative electric field (ion root) is seen with the steep gradient. The reduction of the anomalous diffusivities is obtained at the electric domain due to the strong electric field shear. When the value of T_e is much higher than the value of T_i (T_e/T_i~10) and the transition type becomes soft (without multiple ambipolar solution for E_r), the gradient of the electric field gets weaker at the electric domain interface. In that case, no suppression of the anomalous transport diffusivities is obtained and the transport barrier is not seen. The condition for the suppression of the anomalous diffusivities is found as high T_i ($T_i/T_e>1/3$) in addition to the low density and high T_e. In CHS device, the spatial transition from the larger positive electric field to the smaller positive electric field is observed. Such a spatial transition does not induce a local peak of χ_j^{NEO}, and should be searched for in simulations The analysis of the dynamics of the electric field is needed to study the electric pulsation observed in CHS device [9]. These are left for future studies.

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References

[1] A. Fujisawa et al., Phys. Plasmas **7** 4152 (2000).
[2] S. Toda and K. Itoh, Plasma Phys. Control. Fusion **43** 629 (2001).
[3] K. C. Shaing, Phys. Fluids **27** 1567 (1984).
[4] D. E. Hastings, Phys. Fluids **28** 334 (1985).
[5] K. Itoh et al., Plasma Phys. Control. Fusion **36** 279 (1994).
[6] K. Itoh et al., Plasma Phys. Control. Fusion **36** 123 (1994).
[7] K. Itoh et al., J. Phys. Soc. Jpn. **62** 4269 (1993).
[8] K. Itoh, S. -I. Itoh and A. Fukuyama, Transport and Structural Formation in Plasmas (London, UK: Institute of Physics Publishing) ch 12.
[9] A. Fujisawa et al., Phys. Rev. Lett. **81** 2256 (1998).