Theoretical Analysis of Structure of Radial Electric Field in Helical Toroidal Plasmas

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Abstract

The structure of the electric field is studied by use of the theoretical model for the anomalous transport diffusivities. In this analysis, the thermal diffusivity is employed based on the theory of self-sustained turbulence due to the ballooning mode and the interchange mode, both driven by the current diffusivity. Multiple solutions of E_r for the ambipolar condition are obtained in the structure of the radial electric field. The reduction of the anomalous transport coefficient is examined due to the strong gradient of the radial electric field in the phase diagram of the external sources.

Keywords:

helical plasmas, radial electric field, transport barrier, neoclassical transport, anomalous transport

1. Introduction

Many types of improved confinement states have been found in toroidal plasmas. Among the variety of improved confinement states, the H-mode in tokamaks has been studied most intensively. Through evolution of research, it is widely recognized that the structure of the electric field influences the various improved confinement modes. A study of the confinement mechanisms has also been done for helical plasmas [1]. Nevertheless, quantitative analysis of the generation and the structure of the radial electric field in high temperature plasmas is far from satisfactory.

Recently, the internal transport barrier has been found in electron cyclotron resonance heating (ECRH) plasma in the compact helical system (CHS) and a steep gradient in the profile of the radial electric field has been obtained in the inner region [2]. In Wendelstein-7-AS (W7-AS), studies on the change of the electron transport triggered by the neoclassical transport have also been done theoretically [3] and experimentally

[4,5]. The observation of the internal transport barrier is also confirmed by W7-AS stellarator [6] and the problem of the internal transport barrier in helical systems provides a key to understand the essential nonlinear property of toroidal plasmas. To study the existence of the transport barrier in the experimental conditions of helical plasmas, an investigation of the electric field bifurcation is needed. The interface of domains with different electric polarities has been pointed out for helical plasmas [7]. Furthermore, there is a difference between the bifurcations under the fixed-gradient condition and the flux-fixed condition [8]. It is well known that neoclassical transport is dominant in the bipolar part of the particle flux in helical plasmas and multiple solutions of the ambipolar condition exist [8]. The internal transport barrier in heliotron plasmas, which is induced due to the electric field bifurcation, was theoretically studied based on the zero-dimensional model [9,10]. To study the structure of the radial electric field related with the transport barrier, one-dimensional

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transport analysis is needed. Because the scale length of the steep structure of the radial electric field which induces the transport barrier is determined by the anomalous diffusivity of the electric field [11] and is very different from the global length such as the minor radius of helical plasmas. There are two important issues. The first is the formation of the electric field, which is associated with the steep gradient of the radial electric field E_r . The generation of the electric field in helical systems could be investigated more quantitatively because the neoclassical transport is found to play the dominant role in generating the radial electric field (See articles [5,10] and reviews, *e.g.* [8,12,13]). The second is the study of the turbulent transport and the neoclassical energy transport so as to understand the formation of the internal transport barrier. 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 in order to examine the detailed structure of the electric field [14]. The self-consistent transport study has been done in which both the electric field bifurcation and suppression of the anomalous transport are included in order to analyze the structure of the electric field quantitatively [15]. The transport model (*e.g.* [1]) for anomalous diffusivities was adopted in CHS typical machine parameters.

In this article, types of the structure of the radial electric field are studied and a phase diagram of a bifurcation of E_r profile is investigated. The E_r structure is examined in the both cases by use of the CHS and LHD machine parameters. The parameter region with respect to the density and the temperature is shown to obtain the electron root ($E_r > 0$) in both cases. A reduction of the anomalous transport diffusivities is obtained due to the strong gradient of the electric field. 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 used here are shown. Cylindrical coordinates are used and r -axis is taken in the direction of the plasma minor radius in this article. The region $0 \leq r \leq a$ is considered, where a is the minor radius. The expression for the radial neoclassical flux associated with helical-ripple trapped particle is given as [16]

$$\Gamma_j^{\text{na}} = -\varepsilon_t^2 \sqrt{\varepsilon_h} v_{dj}^2 n_j \int_0^\infty dx x^{5/2} e^{-x} \tilde{v}_j \frac{A_j(x, E_r)}{\omega_j^2(x, E_r)}, \quad (1)$$

where $x \equiv m_j v^2 / (2T_j)$, $A_j(x, E_r) = n_j' / n_j - Z_j e E_r / T_j + (x - 3/2) T_j' / T_j$, $\omega_j^2(x, E_r) = 3 \tilde{v}_j^2(x) + 1.67 (\varepsilon_t / \varepsilon_h) (\omega_E + \omega_{Bj})^2 + (\varepsilon_t / \varepsilon_h)^{3/2} \omega_{Bj}^2 / 4 + 0.6 |\omega_{Bj}| \tilde{v}_j$ and $\tilde{v}_j(x) = v_{thj} / (\varepsilon_h x^{3/2})$. Here, the relations $\omega_E = -E_r / (rB)$, $\omega_{Bj} = -T_j \varepsilon_h' x / (Z_j e r B)$ and $v_{dj} = -T_j / (Z_j e r B)$ are used. The quantities m_j , n_j , T_j , v_{thj} are the mass, the density, the temperature and the collision frequency using the thermal velocity for the species j . The parameters ε_t and ε_h are the toroidal and helical ripple, respectively. The parameter ε_t represents the toroidal modulation of the magnetic field when the toroidal magnetic field is caused by some coils. The prime denotes the derivative with respect to the radial direction. This expression for the particle flux is applicable from the v_{thj} regime defined by $D_j \propto v_{thj}$ to $1/v_{thj}$ regime ($D_j \propto 1/v_{thj}$), where D_j is the particle diffusion coefficient for species j . The form (1) is usable when there is an effect of the orbit squeezing due to the gradient of the radial electric field. The total particle flux Γ^t is chosen as

$$\Gamma^t = \Gamma^{\text{na}} - D_a \frac{\partial n}{\partial r}. \quad (2)$$

The energy flux related with neoclassical ripple transport is given as [16]

$$Q_j^{\text{na}} = q_j^{\text{na}} + \frac{5}{2} \Gamma_j^{\text{na}} T_j = -\varepsilon_t^2 \sqrt{\varepsilon_h} v_{dj}^2 n_j T_j \int_0^\infty dx x^{7/2} e^{-x} \tilde{v}_j(x) \frac{A_j(x, E_r)}{\omega_j^2(x, E_r)}. \quad (3)$$

The total heat flux Q_j^t of the species j is also chosen as

$$Q_j^t = Q_j^{\text{na}} - n \chi_a \frac{\partial T_j}{\partial r}. \quad (4)$$

Here, χ_a is the anomalous heat diffusivity. The theoretical model for the anomalous heat conductivity obtained by the eigenvalue problem for the ballooning mode and the interchange mode is adopted and will be explained later. The neoclassical diffusion coefficient for the electric field is expressed by [17]

$$D_{Ej} = -\frac{e}{\epsilon_{\perp}} \frac{3}{16\sqrt{2}\pi} \frac{Z_j e}{T_j} \frac{n_j v_{thj} T_j^4}{(Z_j e)^4} \frac{\epsilon_{\perp}^4}{\sqrt{\epsilon_h}} \left(1 + \frac{\epsilon_{\perp}}{\epsilon_h}\right) \int_{x_b}^{\infty} \frac{dx e^{-x} x^3}{\left(\left| E_r \right| + \left| x \frac{T_j}{Z_j e} \epsilon_h' \right| \right)^4}, \quad (5)$$

where $x_b = \left\{ v_{thj} / \left\{ \epsilon_h \left[\left| E_r \right| + \left| T_j / (Z_j e) \epsilon_h' \right| \right] \right\} \right\}^{2/3}$. The anomalous diffusion coefficient for the radial electric field is denoted by D_{Ea} .

The equation for the density is

$$\frac{\partial n}{\partial t} = -\frac{1}{r} \frac{\partial}{\partial r} (r \Gamma) + S_n, \quad (6)$$

where the term S_n represents the particle source such as the ionization effect. The equation for the electron temperature is given as

$$\frac{3}{2} \frac{\partial}{\partial t} (n T_e) = -\frac{1}{r} \frac{\partial}{\partial r} (r Q_e) - \frac{m_e}{m_i} \frac{n}{\tau_e} (T_e - T_i) + P_{he}, \quad (7)$$

where the term τ_e denotes the electron collision time and the second term in the right hand side represents the heat exchange between ions and electrons. 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

$$\frac{3}{2} \frac{\partial}{\partial t} (n T_i) = -\frac{1}{r} \frac{\partial}{\partial r} (r Q_i) - \frac{m_e}{m_i} \frac{n}{\tau_e} (T_e - T_i) + P_{hi}, \quad (8)$$

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 radial electric field equation in a nonaxisymmetric system is expressed by [17]

$$\frac{\partial E_r}{\partial t} = -\frac{e}{\epsilon_{\perp}} \sum_j Z_j \Gamma_j^{na} + \frac{1}{r} \frac{\partial}{\partial r} \left[\sum_j Z_j (D_{Ej} + D_{Ea}) r \frac{\partial E_r}{\partial r} \right], \quad (9)$$

where $\epsilon_{\perp}$ is the perpendicular dielectric coefficient as $\epsilon_{\perp} = \epsilon_0 [(c^2/v_A^2) + 1](1 + 2q^2)$. Here, ϵ_0 is the dielectric constant in the vacuum, c is the speed of light, v_A is the velocity of Alfvén wave and q is the safety factor. The parameter Z_j is a charge number of the species j . The factor $(1 + 2q^2)$ is introduced from the toroidal effect. Equation (9) is solved together with the density and the

temperature (ion and electron) equations (6), (7) and (8).

3. Boundary Conditions and the Model of Anomalous Transport Coefficients

The density, temperature and electric field equations (6)–(9) are solved under the appropriate boundary conditions. We fix the boundary condition at the center of the plasma ($r = 0$) such that $n' = T_e' = T_i' = E_r (= -\phi') = 0$, where ϕ is the electrostatic potential of the electric field. For the diffusion equation of the radial electric field, the boundary condition at the edge ($r = a$) is chosen as $\sum_j Z_j \Gamma_j = 0$. 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 ($r = a$) with respect to the density are those expected in the CHS and the LHD: $-n/n' = 0.05$ m, $-T_e/T_e' = -T_i/T_i' = 0.02$ m. Equations (6)–(9) are solved as an initial value problem. The same stationary state is obtained even if the different initial values are chosen in the region of the realistic plasma parameters.

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 $\epsilon_h = 0.231(r/a)^2 + 0.00231(r/a)^4$, respectively [2]. On the other hand, the machine parameters which are similar to those of LHD device are set to be $R = 3.6$ m, $a = 0.6$ m, $B = 3$ T, $m = 10$ and $\ell = 2$. In this case, we set the safety factor and the helical ripple coefficient as $q = 1/[0.4 + 1.2(r/a)^2]$ and $\epsilon_h = 2\sqrt{1 - \{2/[mq(0)] - 1\}^2 I_2^2(mr/R)}$, respectively. Here, $q(0)$ is the value of the safety factor at $r = 0$ and I_2 is the second order modified Bessel function. 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 is strongly influenced 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 value for the anomalous diffusivity of the particle is chosen $D_a = 10$ m²s⁻¹. This value is set to be constant spatially and temporally. It takes about twice as long as the typical confinement time to reach the stationary state. The typical confinement time is about 1 ms in the parameter region examined here.

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 and the interchange mode, both driven by the current diffusivity. The reduction of the anomalous transport

due to the inhomogeneous radial electric field was theoretically reported in the toroidal helical system [1]. (The validity of this model for heliotron/torsatron plasmas has not completely been investigated. This model predicted a trend of χ_a that χ_a can reduce as the magnetic axis is shifted inward. This has some relevance for the experimental observation [19].) The anomalous transport coefficient for the temperatures is given as $\chi_a = \chi_0/(1 + G\omega_{E1}^2)$, where $\chi_0 = F(s, \alpha)\alpha^{3/2}c^2v_A/(\omega_{pe}^2qR)$, where ω_{pe} is the electron plasma frequency. The factor $F(s, \alpha)$ is the function of the magnetic shear s and the normalized pressure gradient α , defined by $s = rq'/q$ and $\alpha = -q^2R\beta'$. For the ballooning mode turbulence for the system with a magnetic well, we employ the anomalous thermal conductivity $\chi_{a,BM}$ [18]: $F_{BM} = C/\sqrt{2(1-2s_1)(1-2s_1+3s_1^2)}$ ($s_1 < 0$) and $F_{BM} = C(1+9\sqrt{2}s_1^{5/2})/(\sqrt{2(1-2s_1+3s_1^2+2s_1^3)})$ ($s_1 > 0$), where $s_1 = s - \alpha$ for the negative pressure gradient and $s_1 = \alpha - s$ for the positive pressure gradient. The factors for the suppression due to the electric field shear are given by $\omega_{E1} = a\tau_{Ap}E_r'/(srB)$ and $G = 1/(2\alpha^2)$, where $\tau_{Ap} = a\sqrt{\mu_0 m_i n/B_p}$. In the case of the interchange mode turbulence [1], the factor F has been given by $F_{IM} = 3C(\Omega'/2)^{3/2}(R/a)^{3/2}/(qs^2)$, 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 $D_0 = \Omega'\beta'a^2R^2/(2r^2)$. For the standard parameters in CHS and LHD experiments, 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 is adopted, $\chi_a = \max(\chi_{a,BM}, \chi_{a,IM})$. The approximation $D_{Ea} = \chi_a$ is employed, where the validity of this approximation is discussed in ref. [20].

4. Results of Analysis by Use of CHS

Device Parameters

4.1 Typical solution of radial electric field

At first, we use the machine parameters of CHS. In order to set the line-averaged temperature of electrons to be around $\bar{T}_e = 250$ eV (T_e at the center, $T_e(0) = 900$ eV) and the line-averaged density to be around $\bar{n} = 1 \times 10^{19} \text{ m}^{-3}$, the absorbed power of electrons is 100 kW and the coefficient S_0 is $7 \times 10^{24} \text{ m}^{-3}\text{s}^{-1}$ for the choice of above values of the anomalous transport coefficients. The line-averaged ion temperature $\bar{T}_i$ is chosen to be about $\bar{T}_i = 150$ eV (T_i at the center, $T_i(0) = 500$ eV), where the absorbed power of ions is fixed at 50 kW.

The stationary solutions of the radial electric field are shown in Fig. 1(a) as a result analyzing equations

(6), (7), (8) and (9). At the point ($\rho = \rho_T(0.6)$), the transition of the radial electric field is found. Circles in Fig. 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 Fig. 1(b) and (c). Multiple solutions exist for the local ambipolar condition in the parameter region examined here. We call the hard transition when the transition occurs between the multiple solutions for the local ambipolar condition. In the case of Fig. 1(a), the electron root ($E_r > 0$) for $\rho < \rho_T$ is sharply connected to the ion root ($E_r < 0$)

Fig. 1 Radial profiles of (a) the radial electric field (full curve) (b) the density, (c) the electron temperature (solid line) and the ion temperature (dashed line). In figure 1(a), circles show the values of the ambipolar E_r . The absorbed power of electrons is 100 kW and that of ions is 50 kW, respectively. The coefficient S_0 of the particle source is $7 \times 10^{24} \text{ m}^{-3}\text{s}^{-1}$. The result in figure 1 is derived by use of the CHS typical parameters.

0) for $\rho > \rho_T$ with a thin layer between them. Transition points should be only determined by the Maxwell construction [13] when the constant D_{E_a} is adapted. However, the anomalous diffusivity for the electric field D_{E_a} has the radial dependence of E_r , n , T_e and T_i in this article. Therefore, the transition points should be determined by the effect (the second term in the right hand side of Eq. (9)) of the radial derivative of D_{E_a} and E_r in addition to the Maxwell's construction. The profile of the gradient of the radial electric field is observed in Fig. 2. The peak at the transition point $\rho = \rho_T$ is found. It is found that there is a difference between the half widths at the half maximum of the inner side ($\rho < \rho_T$) and the outer side ($\rho > \rho_T$) in the profile of the gradient of E_r . 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 gradient in this study is twice as that of the case for the constant D_{E_a} [14] which gives the same half width at the half maximum. The condition for the suppression due to the gradient of the electric field is satisfied where the ρ width in the profile of the gradient of the electric field is smaller than 0.35.

The transport barrier is obtained in the sum of the neoclassical transport and the anomalous transport, although it is not very clear in both the electron and ion temperature profiles in Fig. 1(c). The value of the anomalous diffusivity shown in Fig. 3(a) is that of χ_a . In Fig. 3(a), the reduction of χ_a is obtained due to the strong gradient of the electric field at the transition point. 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. In the case of the spatial

Fig. 2 Radial dependence of the gradient of the electric field. This result in figure 2 is obtained by use of the CHS typical parameters.

Fig. 3 Radial profiles of the diffusivities. The suppression of the anomalous diffusivity is obtained in figure 3(a) due to the strong gradient of E_r .

transition in Fig. 1(a), the electric field goes across zero at $\rho \approx \rho_T$. Therefore, the neoclassical diffusivities have a peak near the surface where the relation $E_r \approx 0$ satisfies, because they depend on the value of E_r itself. In Fig. 3(b), the sum of the anomalous and the 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 is found to exist but is small compared with that of the anomalous diffusivity. This is because the neoclassical diffusivity has a peak near the radius $\rho = \rho_T$. The model predicts the radial location of the internal transport barrier well compared with the experimental results of CHS. However, this model does not predict the profiles of the temperatures very well, especially the spatial structure of the internal transport barrier. The spatial width of the transport barrier is rather narrow compared with the experimental results. The further study including the anomalous transport to explain the experimental results is needed.

4.2 Phase diagram of bifurcation of E_r structure

When the value of the temperature or the density changes, the profile of the stationary electric field takes three types of roots. In this subsection, the typical

device parameters of the CHS are also used. At first, stationary electric fields in all radial points becomes the electron root in the region labelled 'e' in Fig. 4 ($\bar{n} - \bar{T}_e/\bar{T}_i$ plane). In the regime of the low density $\bar{n} \approx 10^{18} \text{ m}^{-3}$ and of the high temperature of electrons $\bar{T}_e/\bar{T}_i \approx 8$, the positive solutions of E_r are obtained. Secondly, when the density increases, the stationary electric field in the core plasma takes the electron root and the electric field in the outer plasma takes the ion root ($E_r < 0$) in the region labelled 'e-i'. Furthermore, in this case, the type of the transition is classified to the hard or soft one. The multiple solutions are obtained in the hatched region: $\bar{T}_e/\bar{T}_i \approx 2$ and $\bar{n} = (2 - 7) \times 10^{18} \text{ m}^{-3}$. In this region, the hard transition occurs between the multiple solutions and the reduction of the anomalous conductivity is found due to the strong gradient of the radial electric field. In the region labelled 'e-i' where the electron root and the ion root co-exist outside this hatched region, the spatial transition occurs without the multiple solutions. We call this the soft transition in the E_r profile. When the value of the density becomes much larger ($\bar{n} \approx 10^{20} \text{ m}^{-3}$), all radial stationary electric fields take the ion root in the parameter regime labelled 'i'. The parameter region of the three root patterns of the stationary electric field is shown in the $\bar{n} - \bar{T}_e/\bar{T}_i$ plane in Fig. 4 using the CHS device parameters.

Figure 4 is a phase diagram for the structural formation of plasmas. Changes of properties across the phase boundaries attract attentions. When the control parameters move across the boundary between the regions i and e - i, the domain of the positive electric field (electron root) appears ($i \rightarrow e - i$) or disappears (e

Fig. 4 Phase diagram in $\bar{T}_e/\bar{T}_i - \bar{n}$ plane. This result is obtained in the analysis by use of CHS typical parameters.

$-i \rightarrow i$) at the center of plasmas. At the boundary between the regions e - i and e, the domain of the negative electric field (ion root) disappears ($e - i \rightarrow e$) or appears ($e \rightarrow e - i$) at the plasma boundary. These two phase boundaries are related to the radial location of the domain interface of E_r .

5. Analysis Results by Use of Machine Parameters of LHD

5.1 Typical structure of radial electric field

We next study the case by use of the machine parameters of LHD. We choose the case that the absorbed power of ions is 500 kW. We set the electron heating is 1 MW and the particle source term $S_0 = 2 \times 10^{24} \text{ m}^{-3}\text{s}^{-1}$. Stationary solutions of the radial electric field are obtained for $\bar{n} = 4 \times 10^{18} \text{ m}^{-3}$, $\bar{T}_e = 1,600 \text{ eV}$ (T_e at the center: $T_e(0) = 4,200 \text{ eV}$) and $\bar{T}_i = 800 \text{ eV}$ (T_i at the center: $T_i(0) = 2,200 \text{ eV}$). The other parameters are same as those in Sec 4.1. The ratio of the electron temperature of the ion temperature takes the value $\bar{T}_e/\bar{T}_i \approx 2$.

The profile of the stationary radial electric field is shown in Fig. 5(a). The spatial transition of the radial electric field is found at the point $\rho = \rho_T(0.65)$. The values of the electric field which satisfy the local ambipolar condition for the profiles of the density and the temperatures of Fig. 5(b) and (c) by the circles in Fig. 5(a). Multiple solutions are also found for the ambipolar condition in the parameter region investigated here similar to the analysis by use of CHS device parameters. It is also confirmed that transition points are determined by the derivative of E_r and D_{Ea} in addition to Maxwell's construction in this case. The profile of the E_r gradient is shown in Fig. 6 and the gradient of the electric field is strong enough to suppress the turbulence: $|E'_r| = 9 \times 10^5 \text{ V/m}^2$ at $\rho = \rho_T$. Therefore, the reduction of the anomalous heat conductivity is found in the parameter region examined here in Fig. 7. The reduction of χ_a is smaller than that in the case by use of CHS device parameters. The value of the reduction depends on the choice of the model of the anomalous heat conductivity and also on the absolute power of electrons and ions. The test of the anomalous heat conductivity will be done by the ECRH experiments in LHD. The neoclassical diffusivities of electrons and ions has a peak in which the electric field goes across zero. Therefore, the total suppression of the transport becomes smaller and the transport barrier is not clear in both electron and ion temperature profiles in Fig. 5(c).

Fig. 5 Radial profiles of (a) the radial electric field (full curve) (b) the density, (c) the electron temperature (solid line) and the ion temperature (dashed line). In figure 5(a), circles shows the values of the ambipolar E_r . The absorbed power of electrons is 1 MW and that of ions is 500 kW, respectively. The coefficient S_0 of the particle source is 2×10^{24} m⁻³s⁻¹. The result in figure 5 is derived by use of the LHD typical parameters.

Fig. 6 Radial dependence of the gradient of the electric field. This result in figure 6 is obtained by use of LHD typical machine parameters.

Fig. 7 Radial profiles of the diffusivities. The suppression of the anomalous diffusivity is seen in figure 7 due to the strong gradient of E_r at $\rho = \rho_T$.

Fig. 8 Phase diagram in $\bar{T}_e/\bar{T}_i$ - $\bar{n}$ plane. This result is obtained in the analysis by use of LHD typical parameters.

5.2 Phase diagram of transition types of E_r structure

When the value of the temperature or the density changes, the profile of the stationary electric field takes different types of roots. In this subsection, the typical device parameters of the LHD are adapted. At first, all stationary electric fields in the radial points takes the electron root ($E_r > 0$) in the region labelled 'e' in Fig. 8 ($\bar{n}$ - $\bar{T}_e/\bar{T}_i$ plane). In the regime of the low density $\bar{n} \approx (1 - 2) \times 10^{18}$ m⁻³ and of the high temperature of electrons $\bar{T}_e/\bar{T}_i > 3$, the positive solutions of E_r are obtained. Secondly, if the value of the averaged density becomes larger, the stationary electric field in the core plasma takes the electron root and the electric field in the outer plasma takes the ion root ($E_r < 0$) in the region labelled 'e-i'. In the region labelled 'e-i', the type of the transition is classified to the hard or soft one. The

multiple solutions are obtained in the hatched region: $\bar{T}_e/\bar{T}_i \approx 2$ and $\bar{n} \approx (1 \times 10^{18} - 2 \times 10^{19})\text{m}^{-3}$. In this region, the hard transition occurs between the multiple solutions and the reduction of the anomalous conductivity is also shown due to the strong gradient of E_r . In the region labelled 'e-i' outside this hatched region, the slow transition takes place spatially since there are not multiple solutions of ambipolar E_r . When the value of the density becomes much larger ($\bar{n} \approx 10^{20}\text{m}^{-3}$, all radial stationary electric fields changes to the ion roots in the parameter regime labelled 'i'. The parameter region of the three root patterns of the stationary electric field is examined in the $\bar{T}_e/\bar{T}_i - \bar{n}$ plane in Fig. 8 by use of the LHD parameters. Compared with the phase diagram of the transition type using the CHS device parameters (Fig. 4), the ratio $\bar{T}_e/\bar{T}_i$ takes about 2 in the both hatched regions (using CHS and LHD parameters) in which the multiple solutions of the ambipolar E_r exist. However, the hatched region in the analysis by use of the LHD parameters becomes wider (to the value $\bar{n} \approx 2 \times 10^{19}\text{m}^{-3}$) in the axis of the averaged density $\bar{n}$ than that in the analysis by use of the CHS typical parameters.

6. Summary and Discussions

In this paper, the spatial structure of the radial electric field in helical plasmas is theoretically studied. Theoretical model of the ballooning mode or the interchange mode is adopted for the anomalous heat conductivity and the anomalous diffusion coefficient of the electric field. At first, the typical machine parameters of CHS are adapted. The hard transition of the E_r structure between the multiple ambipolar E_r is obtained in this study of $T_e/T_i \approx 2$. When $T_e/T_i \approx 3$ and the value of the density takes about $1 \times 10^{19}\text{m}^{-3}$, the transition type is found to become soft (without multiple ambipolar E_r). The condition for the suppression of the anomalous diffusivities is suggested to be rather high T_i in addition to the low density and high T_e . Next, the typical machine parameters of LHD are used. The hard transition (with the multiple solutions of E_r) is also shown in the E_r structure in the parameter region examined here. When $T_e/T_i \approx 3$ and the value of the averaged density takes about $2 \times 10^{19}\text{m}^{-3}$, the soft transition type is found in the E_r spatial structure (without multiple ambipolar E_r). The reduction of the anomalous transport is predicted due to the strong gradient of E_r at which the spatial transition of E_r between the multiple ambipolar E_r occurs in both devices of CHS and LHD. The transition types are classified in $\bar{T}_e/\bar{T}_i - \bar{n}$ plane by use of the CHS and LHD

typical machine parameters.

In this article, the diffusivity in an axisymmetric system is neglected. The value of the diffusivity in an axisymmetric system can be calculated according to the form in ref. [21]. In the core region ($\rho < 0.2$), this calculated value is about twice as large as the value in a nonaxisymmetric system in the parameter regime examined here. However, the anomalous diffusivity is dominant compared with both neoclassical (axisymmetric and nonaxisymmetric) transports in this region ($\rho < 0.2$). In other region ($\rho > 0.2$), the value of the diffusivity in an axisymmetric system is negligible compared with that in a nonaxisymmetric system in the parameter regime examined here. Therefore, the inclusion of the diffusivity in an axisymmetric system does not alter the essence of the analytic result in this article. The systematic analysis concerning the neoclassical transport in LHD was done in ref. [22].

In CHS device, the spatial transition from the larger positive E_r to the smaller positive E_r is observed [2]. Such a spatial transition does not induce a local peak of χ_j^{NEO} , and should be searched for in simulations. The discussion whether the reduction of the anomalous transport diffusivities predicted in this article is enough or not is needed when the transition of E_r is predicted from the larger positive value to the smaller positive value. The analysis of the dynamics of the electric field is needed to examine the electric pulsation observed in the CHS [23]. These are left for future studies.

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