IAEA
21st IAEA Fusion Energy Conference
Chengdu, China, 16 - 21 October, 2006

IAEA-CN-149/ PD/P6-4

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NIFS-869

Oct. 2006

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Abstract. The role of zonal flows in the formation of the transport barrier in the helical plasmas is analyzed using the transport code. A set of one-dimensional transport equations is analyzed, including the effect of zonal flows. The turbulent transport coefficient is shown to be suppressed when the plasma state changes from the weak negative radial electric field to the strong positive one. This bifurcation of the turbulent transport is newly caused by the change of the damping rate of zonal flows. It is theoretically demonstrated that the damping rate of zonal flows governs the global confinement in toroidal plasmas.

1. Introduction

The turbulence-driven transport and transport barriers are the key issues in fusion research. Main efforts have been focused on the understanding of improved confinement modes (such as the H-mode [1]). In these phenomena, the turbulent (anomalous) transport coefficient shows the steep gradient at a particular radius after the onset of the transition. One thread of thoughts to explain transport barriers is the structural transition of the profile of radial electric field E_r and the suppression of turbulence by its gradient [2]. The bifurcation of the radial electric field in helical plasmas is influenced by the neoclassical ripple transport, and the resultant electric field interface (by which the radial domains with positive E_r and negative E_r are separated) was predicted to induce the internal transport barrier due to the shear of the radial electric field in the helical plasmas. The E_r -interface was found on the Compact Helical System (CHS), and the improvement of the electron confinement was found inside of the interface for E_r [3] (hereafter called 'electron internal transport barrier', e-ITB). The appearance and the location of the E_r-interface were analyzed [4]. Observations on Wendelstein 7-AS [5], Large Helical Device (LHD) [6] and other confinement devices followed [7]. However, the essential issue of the e-ITB in helical devices has been unexplained; i.e., the turbulent transport coefficient was found to be suppressed not only near the interface (with the strong inhomogeneity of E_r) but also in the whole region of the strong positive E_r. Away from the transition radius, the gradient dE_r/dr is not strong enough to suppress the turbulent transport. Fundamental problems remain unresolved. (In LHD, an internal diffusion barrier (IDB) is recently observed with the high gradient of the density in a super dense core plasma. In a core region, the high density of $4.5 \times 10^{20}\,\mathrm{m}^{-3}$ and the temperature of 0.85keV are obtained. Physics of an IDB is beyond the scope of this article, and details of an IDB are discussed in [8].)

In this article, we study the role of zonal flows (ZFs) [9] in the formation of e-ITB. The turbulent transport coefficient, in which the screening influence of zonal flows is included, is shown to be reduced when the plasma state changes from the branch of weak negative E_r to the strong positive E_r. This new transition of the turbulent transport is induced by the change of the damping rate of zonal flows, which is strongly influenced by the neoclassical ripple transport. We show the clear transport barrier in the electron temperature profile. The analytic results by use of the transport code are shown.

2. One-dimensional model for transport equations

In this section, the model equations used here are shown. The one-dimensional transport model is employed. The cylindrical coordinate is used and r-axis is taken in the radial cylindrical plasma in this article. The region $0 < \rho < 1$ is considered, where a is the minor radius and $\rho = r/a$. The expression for the radial neoclassical flux associated with helical-ripple trapped particles is given in [10] which covers from the ν_j regime to the $1/\nu_j$ regime, where ν_j is the collision frequency for the species j. The total particle flux Γ^t is written as $\Gamma^t = \Gamma^{na} - D_T n'$, where Γ^{na} is the neoclassical flux associated with the helical-ripple trapped particles, and the prime denotes the radial derivative. Here, D_T is the turbulent (anomalous) particle diffusivity with the effect of the zonal flow. The effect of ZFs is discussed in the next section. The energy flux related with the neoclassical ripple transport, Q_j^{na}, is obtained like the neoclassical particle flux. The total heat flux Q_j^t for the species j is written as $Q_j^t = Q_j^{na} - n\chi_T T_j' - 3D_T n' T_j/2$, where χ_T is the anomalous heat diffusivity. A theoretical model for the anomalous heat conductivity is adopted and is explained later. The neoclassical diffusion coefficient for the electric field is expressed in [11]. The anomalous diffusion coefficient for the radial electric field is denoted by the parameter D_{ET}. The temporal equation for the density is

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

where 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 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. The temporal equation for the ion temperature is

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

The term P_{hi} represents the absorbed power of ions. The radial electric field equation in a nonaxisymmetric system is expressed by [11]

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

where $\varepsilon_\perp$ is the perpendicular dielectric coefficient which equals to $\varepsilon_0(1 + c^2/v_A{}^2)(1 + q^2/\sqrt{\varepsilon_t})$. Here, ε_0 is the dielectric constant in vacuum, v_A is the velocity of the Alfvén wave, ε_t is the toroidal ripple and q is a safety factor.

The source profiles are chosen here as follows. 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. This profile represents the peaking at the plasma edge of the particle source due to the ionization effect. The intensity, S_0, governs the average density, and is taken as a control parameter to specify the density in this article. The radial profiles of the electron and ion heating terms, P_{he} and P_{hi}, are assumed to be proportional to $\exp(-(r/(0.2a)^2)$ for the sake of the analytic insight. (Effect of the heating profile has been studied, and the assumption does not change the qualitative conclusion for the establishment of the internal transport barrier [4].)

The equations of density, temperature and electric field (1)-(4) are solved, with the prescribed source profiles, under the appropriate boundary conditions. We fix the boundary condition at the center of the plasma ($\rho = 0$) such that $n' = T_e' = T_i' = E_r = 0$. For the diffusion equation of the radial electric field, the boundary condition at the edge ($\rho = 1$) is chosen as $\sum_j Z_j \Gamma_j^{na} = 0$. 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 ($\rho = 1$), with respect to the density and temperature, are given by specifying the gradient scale lengths. We employ those expected in LHD: $-n/n' = 0.05\mathrm{m}$, $-T_e/T_e' = -T_i/T_i' = 0.02\mathrm{m}$ in this article. The machine parameters which are similar to those of LHD are set to be $R = 3.6\mathrm{m}$, $a=0.6\mathrm{m}$, $B = 3\mathrm{T}$, $\ell = 2$ and $m = 10$. In this case, we set the safety factor and the helical ripple coefficient as $q = 1/(0.4 + 1.2\rho^2)$ and $\varepsilon_h = 2\sqrt{1 - (2/(mq(0)) - 1)}\, I_2(mr/R)$, respectively. Here, $q(0)$ is the value of the safety factor at $\rho = 0$ and I_2 is the second-order modified Bessel function.

3. Model of turbulent transport coefficients

The system of Eqs. (1)-(4) has been known to predict the structural bifurcation such that the internal transport barrier is formed when the heating power at the core is high enough in a low density regime. The improvement of the confinement was predicted in two ways: the turbulent transport is suppressed by E_r' near the transition interface, and the neoclassical transport is strongly suppressed inside of the electric field interface. The suppression of the turbulent transport is limited near the interface, and its reduction in the entire core plasma ($\rho < \rho_T$) has not been explained, where the parameter ρ_T shows the location of the E_r -interface.

In the absence of the zonal flow, we adopt the model for the turbulent heat diffusivity χ_{T0} based on the theory of the self-sustained turbulence due to the ballooning mode and the interchange mode, both driven by the current diffusivity [12,13]. The reduction of the anomalous transport due to the inhomogeneous radial electric field was reported in the toroidal helical system. The anomalous transport coefficient for the temperatures is given as $\chi_{T0} = \chi_0/(1 + G\omega_{E1}^2)$, ($\chi_0 = F(s,\alpha)\alpha^{\frac{3}{2}} c^2 v_A^2/(\omega_{pe}^2 qR)$), 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 $\alpha = -q^2 R\beta'$. For the ballooning mode turbulence (in the system with a magnetic well), we employ the anomalous thermal conductivity $\chi_{T0,BM}$. The details about the coefficients $F(s,\alpha)$, G, and the factor ω_{E1}, which stands for the effect of the electric field shear, are given in [13] in the ballooning mode turbulence. In the case of the interchange mode turbulence for the system of the magnetic hill [12], we adopt the anomalous thermal conductivity $\chi_{T0,IM}$. The details about F, G, and the factor ω_{E1} in the case of the interchange mode were given in [12]. The greater one of these two diffusivities is adopted as $\chi_{T0} = \max(\chi_{T0,BM}, \chi_{T0,IM})$.

The zonal flows (at nearly zero frequency) are generated by the fluctuations and strongly influence the turbulent transport. The damping rate of zonal flows, ν_{damp}, controls the turbulent transport. The damping of zonal flows is caused by the collisional process and by the self-nonlinearity of zonal flows [9]. In the toroidal helical plasmas, the collisional process remains to be important even in the regime of $\nu_* < 1$ ($\nu_* = \nu_i qR/(\varepsilon v_{\mathrm{thi}})$). In the case that the collisional damping rate ν_{damp} is small, the heat diffusivity χ_{T} has been derived considering the screening by zonal flows [9]. Whether the zonal flows are excited or not is judged by comparing χ_{T0} (which is given in the absence of zonal flows) with the quantity

$$\chi_{\mathrm{damp}} \simeq k_\perp^2 q_r^{-2} k_\theta^{-2} \nu_{\mathrm{damp}}, \tag{5}$$

where q_r is the wave number of zonal flows, k_θ is the poloidal wavenumber and $k_\perp$ are the perpendicular wavenumber of the microscopic fluctuations, respectively. When the turbulence is weak and χ_{T0} is smaller than χ_{damp}, zonal flows are not excited and one has $\chi_{\mathrm{T}} = \chi_{\mathrm{T0}}$. If the condition $\chi_{\mathrm{damp}} < \chi_{\mathrm{T0}}$ is satisfied, zonal flows are excited and the fluctuation level of the electric field $\tilde{\mathrm{E}}$ is controlled as $|\tilde{\mathrm{E}}|^2 \propto \nu_{\mathrm{damp}}/\omega_*$, where ω_* is the drift frequency. Then the turbulent diffusivity χ_{T} is reduced as $\chi_{\mathrm{T}} = \sqrt{\chi_{\mathrm{T0}}\chi_{\mathrm{damp}}}$ [14]. A fitting formula is often employed as

$$\chi_{\mathrm{T}} = \sqrt{\chi_{\mathrm{T0}}}\,\min(\sqrt{\chi_{\mathrm{T0}}}, \sqrt{\chi_{\mathrm{damp}}}) \tag{6}$$

to include the effect of zonal flows in the transport codes.

This dependence of χ_{T} on the damping rate of zonal flows, in Eq. (6), explains the improved confinement in the e-ITB region of toroidal helical plasmas. The neoclassical part of the radial current J_r^{NEO} in helical plasmas is induced by the ripple transport and has a nonlinear dependence on E_r, where the superscript NEO stands for the neoclassical ripple transport. The damping rate of zonal flows due to the dependence of the radial current on the electric field is given by the neoclassical ripple transport as $\nu^{\mathrm{NEO}} = (\partial J_r^{\mathrm{NEO}}/\partial E_r)/\varepsilon_\perp$. We obtain the damping rate ν_{damp} as

$$\nu_{\mathrm{damp}} = \min(1, \nu_*)\frac{v_{\mathrm{thi}}}{qR} + \nu^{\mathrm{NEO}}, \tag{7}$$

where v_{thi} is the thermal velocity of ions. The first term $\min(1, \nu_*)$ takes the smaller value between the unity and ν_*, which represents the transports in the plateau and banana regimes, respectively. The second term comes form the ripple transport with the dependence of the radial electric field. Owing to the dependence of ν_{damp} on E_r, ν_{damp} of Eq. (7) is large in the ion root branch (i.e., the weak negative solution of E_r that satisfies $J_r^{\mathrm{NEO}}(E_r) = 0$), while it is small in the electron root branch of e-ITB (i.e., the strong positive E_r solution of $J_r^{\mathrm{NEO}}(E_r) = 0$). The turbulent transport coefficient becomes smaller when the strong positive radial electric field is established in e-ITB [15], when we consider the role of zonal flows in the e-ITB formation in helical plasmas. The bifurcation of E_r itself induces the transition of turbulent transport in the bulk of the plasma column as well as at the interface of the electric field.

For simplicity, the value for the anomalous diffusivities of the particle is set as $D_T = 10 m^2/s$. The essence of the results shown later does not change due to the value of D_T. Therefore, the value of D_T is set to be constant spatially and temporally. We also set $D_{ET} = \chi_T$ in order to examine the variation of the typical length for the electric field shear at the transition point.

4. Results of the Analysis

The reduction of the turbulent transport in the entire region of the strong positive E_r is quantitatively demonstrated by use of the transport code analysis. The one-dimensional transport analysis for LHD-like plasma has been performed and the mean profiles of E_r, T_e, T_i and n are solved using the Eqs. (1), (2), (3) and (4) and adapting Eqs. (5) and (6) as the heat diffusivities. In this analysis, the thermal diffusivity is given as the sum of χ_T and neoclassical transport. (In this calculation, χ_{T0} is given based on the nonlinear current-diffusive interchange mode which was found relevant in preceding analysis [4]. Here, the screening of χ_T near the edge is not taken into account, because the study is focused in the core.) An example is taken from the plasma which is sustained by electron cyclotron resonance (ECR) heating. In order to set the line-averaged temperature of electrons to be around $\overline{T}_e = 1.6 keV$ (T_e at the center, $T_e(0) = 4.4 keV$) and the line-averaged density to be around $\overline{n} = 2 \times 10^{19} m^{-3}$, the absorbed power of electrons is set to be 1MW and the coefficient S_0 is taken as 7×10^{22} m^{-3} s^{-1}, for the choice of the above mentioned anomalous transport coefficients. The line-averaged ion temperature $\overline{T}_i$ is chosen to be about $\overline{T}_i$=0.9keV (T_i at the center, $T_i(0) = 2.5 keV$), where the absorbed power of ions is taken as $500 kW$. When we evaluate χ_{damp}, we employ an estimate $k_\perp^2 q_r^{-2} k_\theta^{-2} \rho_i^{-2} \sim 50$. [14]

The profile of the stationary radial electric field is demonstrated in FIG. 1 by the solid line, including the effect of zonal flows (ZFs). To show the reference, the radial profile of E_r without the effect of the zonal flow is also shown in FIG. 1 by the dashed line. The parameter

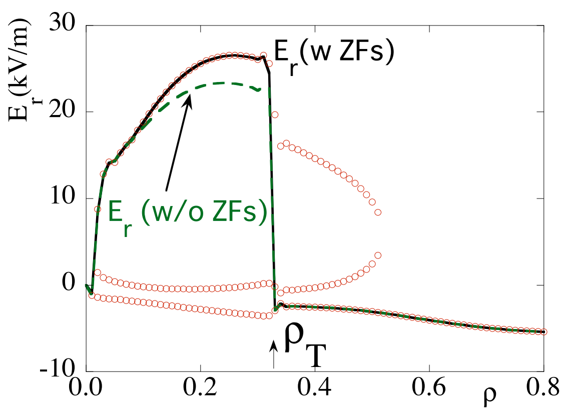

FIG. 1. *Stationary profiles of the radial electric field as the result of the transport code. The solid line shows the case with the effect of zonal flows and the dashed line indicates the case without the effect of zonal flows.*

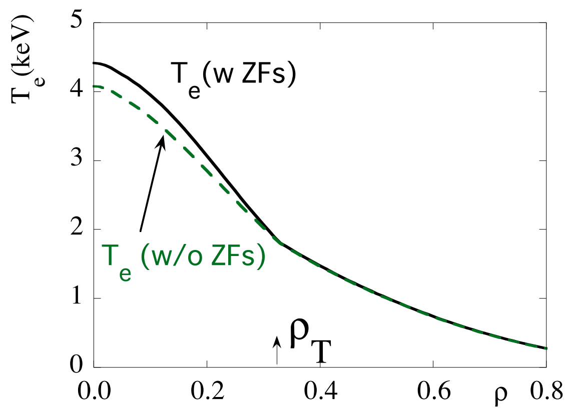

FIG. 2. *Profiles of the electron temperature. Cases with the effect of zonal flows (the solid line) and without the effect of zonal flows are shown (the dashed line), respectively. The transport barrier can be obtained.*

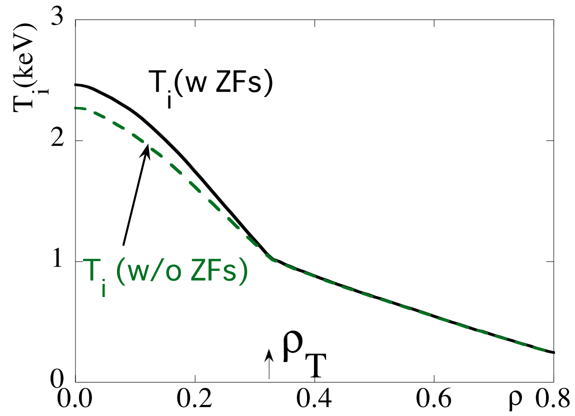

FIG. 3. *Profiles of the ion temperature. The case with the effect of zonal flows is obtained (the solid line) and the case without the effect of zonal flows is shown (the dashed line), respectively.*

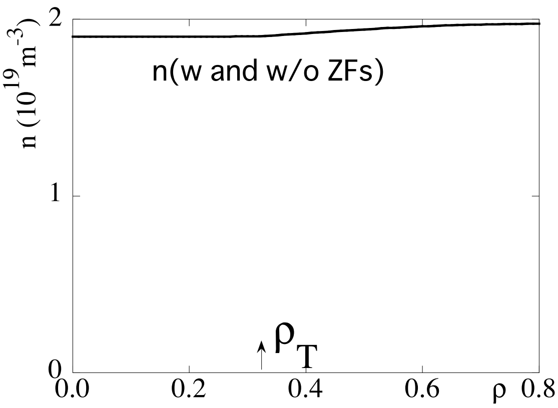

FIG. 4. *The density profile as the results. Both cases with and without the effect of zonal flows qualitatively show the similar profile.*

ρ_T represents the location of the transition for the strong positive E_r to the negative E_r. In both cases, the E_r-interface is established at $\rho_T = 0.3$ and the steep gradient of E_r can be obtained. Therefore, the improvement near the transition point can be obtained in a narrow region even in the case without the effect of the zonal flows. Maxwell's construction chooses the consistent solution for E_r from the multiple local solutions (circle marks in FIG. 1 with the effect of zonal flows) for a radial point. The local solution for E_r satisfies the ambipolar condition which is derived from the obtained density and the temperature profiles. It is found that E_r is strongly positive for $\rho < \rho_T$. Including the effect of zonal flows, the stronger positive E_r (owing to the increment of the temperature gradient) is shown in the region $\rho < \rho_T$ in FIG. 1. Profiles of the electron temperature with and without the zonal flow effects are shown in FIG. 2. We obtain the steeper gradient in the T_e profile in the case with the effect of zonal flows, in comparison with the case without the effect of zonal flows. We also show the profiles of the ion temperature and the density with and without the effect of zonal flows in FIG. 3 and FIG.4, respectively. The clear change of the gradient for the ion temperature can be obtained in the case with the effect of zonal flows. In the density profile, the significant effect of zonal flows cannot be found, because the particle diffusivity is set to be constant as $D_T = 10\mathrm{m}^2/\mathrm{s}$ in both cases with and without the effect of zonal flows. A weak hollowness of the density (dn/dr >0) is generated. This is due to the outward neoclassical particle flux, which is driven by temperature gradient and radial electric field.

A profile of the total diffusivity with the zonal flow effect (solid line) is shown in FIG. 5. The clear reduction of the total diffusivity is shown in the region $\rho < \rho_T$ compared with that in the region $\rho > \rho_T$. The total thermal diffusivity of electrons χ_e^{total} represents the sum of the turbulent part and neoclassical part. Therefore, we can obtain the clear transport barrier in FIG.2 (T_e profile). It is found that the condition and χ_T is reduced there (thin broken line), due to the smaller damping of zonal flows. [In the reference simulation using bare fluctuations (without the effects of zonal flows), the thermal diffusivity χ_{T0} has a dip near the interface, but does not show the noticeable reduction for $\rho < \rho_T$ (dashed line); χ_{T0} increases in the core owing to the higher temperature (thin dotted line) in FIG. 6.] The screened transport coefficient is close to what has been reported from LHD experiments [16]. Outside the transition point ρ_T, where the ion root branch appears, ν_{damp} becomes large and the strong

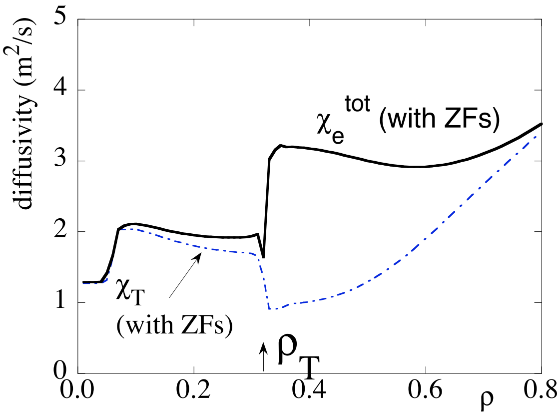

FIG. 5. Profiles of the heat diffusivity by use of the transport code analysis of LHD-like plasma with the effect of the zonal flow.

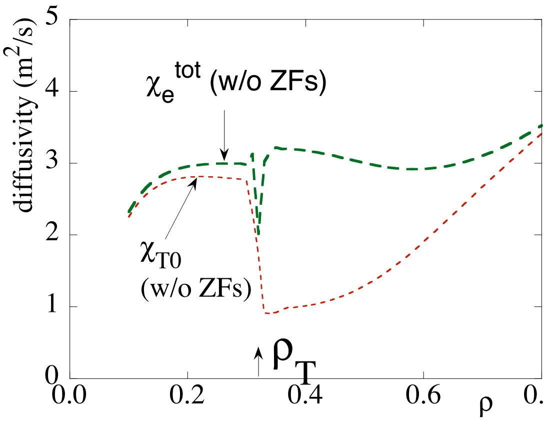

FIG. 6. Profiles of the heat diffusivity without the effect of the zonal flow

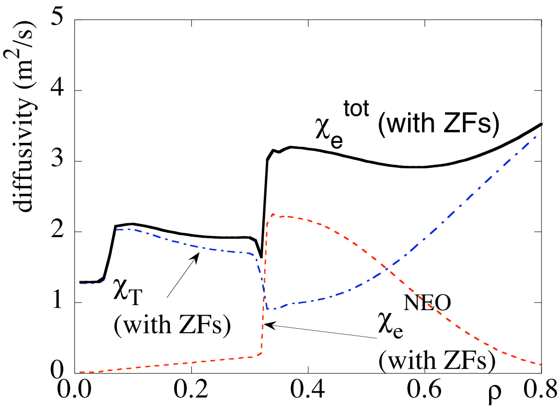

FIG. 7. Profile for the neoclassical heat diffusivity of electrons with dashed line as the result of the transport code analysis.

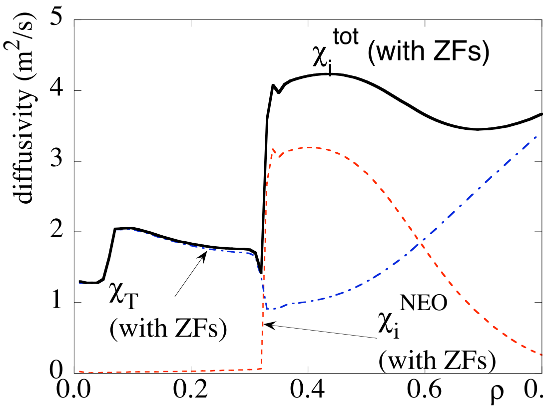

FIG. 8. Profile for the neoclassical heat diffusivity of ions with dashed line. The reduction of the neoclassical transport of ions is obtained in the region $\rho < \rho_T$ due to the strong positive E_r.

zonal flows are not excited. Thus, the reduction is not expected for the region $\rho > \rho_T$ in this example. We also show that the neoclassical parts for the heat diffusivities of electrons χ_e^{NEO} and ions χ_i^{NEO} in FIGS. 7 and 8, respectively (with the dashed line) in the case with the effect of zonal flows. In the inner region ($\rho < \rho_T$), the turbulent transport is found to be dominant compared to the neoclassical transport in both electron and ion cases. Specially, the neoclassical transport of ions in the inner region ($\rho < \rho_T$) is suppressed due to the strong E_r.

5. Summary

We have studied the role of zonal flows in the e-ITB formation of toroidal helical plasmas. It was found that the neoclassical ripple transport can enhance the turbulent transport, through its impact on the damping of the zonal flows. The bifurcation of the radial electric field (from the state with weak and negative E_r to that with strong and positive E_r) was found to induce the transition of the turbulent transport coefficient. The electron ITB is established by the mechanisms of (i) the bifurcation of the radial electric field via the neoclassical process and the reduction of neoclassical energy transport, (ii) the establishment of the electric field interface that quenches the turbulence, and (iii) the reduced damping of zonal flows which causes the suppression of the turbulent transport. When the electron internal transport barrier of LHD appears, the results of the transport code analysis show that the total heat diffusivity χ_T in the entire inner region ($\rho < \rho_T$) is reduced. The effect of zonal flows on the anomalous transport is investigated. The transport reduction is obtained in the wide region for E_r>0

($\rho<\rho_T$) in conjunction with the internal transport barrier. This is demonstration that the change of the collisional damping of zonal flows can cause the transition in the turbulent transport. The experimental confirmation is given on CHS. It is reported that the fluctuation energy is transferred into zonal flows when the damping rate ν_{damp} becomes weak. Details will be discussed in [17].

The result of this article provides further understanding of confinement in toroidal helical plasmas. The important finding is that the reduction of the effective helical ripple ratio ε_h causes the reduction of χ_{damp} (thus, of χ_T) even in the branch of the ion root. This finding can explain the observations on LHD. In the collisionless plasmas of LHD (ion root branch), if the smaller the helical ripple, the lower the anomalous transport. The study of this article is not limited to toroidal helical plasmas. The control of the damping rate of zonal flows for further improvement of plasma confinement has been investigated [18]. The wide extension of the present work is possible, and is left for the future work.

Authors wish to acknowledge Dr. K. Hallatschek for useful discussions and Prof. O. Motojima for the encouragement. This work was partly supported by the Grant-in-Aid for Specially-Promoted Research (16002005) and the Grant-in-Aid for Scientific Research (15360495). This work is also partly performed with the support and the auspices of the NIFS Collaborative Research Programs, Nos. NIFS06KLDD008 and NIFS06KNXN062 and of the Research Institute for Applied Mechanics of Kyushu University.

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