Physics of internal transport barrier of toroidal helical plasmas

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The role of zonal flows (ZFs) in the formation of an internal transport barrier in a toroidal helical plasma is analyzed. The turbulent transport coefficient is shown to be suppressed when the plasma state changes from the branch of a weak negative radial electric field to the strong positive one. This new transition of turbulent transport is caused by the change of the damping rate of the ZFs. It is clearly demonstrated, theoretically and experimentally, that the damping rate of the ZFs governs the global confinement of toroidal plasmas. © *2007 American Institute of Physics*.
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The turbulence-driven transport and the structural formation in confined plasmas are one of the principal issues of modern plasma physics.[1] In particular, the transport barriers in toroidal plasmas[2] have attracted attention, in which the turbulent transport coefficient shows a steep gradient at a particular radius after the onset of the transition.[3–5] One thread of thought to explain transport barriers is the structural transition in the profile of the radial electric field, E_r, and suppression of turbulence by its gradient through the sheared advection of fluctuations.[3,6–9] For the study of turbulent structural transitions, toroidal helical plasmas provide unique opportunities: That is, the bifurcation of the radial electric field is influenced by the neoclassical ripple transport,[10] 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. The E_r interface was found on the compact helical system (CHS),[11] and the improvement of the electron confinement was found inside of the E_r interface[12] [hereafter called the electron internal transport barrier (e-ITB)]. Observations on Wendelstein 7AS (W7AS),[13] LHD,[14] and other experiments followed.[5,15] The appearance and location of the E_r interface were analyzed.[16–18] However, the essential issue of e-ITB formation has been unexplained, i.e., the turbulent transport coefficient was found to be suppressed not only near the interface but also in the whole region of strong positive E_r (where the gradient $\mathrm{d}E_r/\mathrm{d}r$ is not strong enough to suppress turbulent transport). Therefore the fundamental problem remains unresolved.

In this article, we study the role of zonal flows (ZFs) (Ref. 19) in the formation of an e-ITB. The turbulent transport coefficient, in which the screening influence of ZFs is included, is shown to be suppressed when the plasma state changes from the branch of weak negative E_r to that of strong positive E_r. This new transition of turbulent transport is induced by the change of the damping rate of the ZFs, which is strongly influenced by the neoclassical ripple transport. The analytic theory is explained first. Then the transport analysis is shown. Finally, the experimental verification based on the CHS plasmas is demonstrated. This is the first report to clarify that the collisional damping rate of the ZFs governs the transition of global confinement of toroidal plasmas including the experimental test. This gives an answer to the basic question, in the laboratory plasma turbulence and in the planetary zonal flows,[19] of how turbulent transport and frictional damping couple to each other in generating zonal flows.

We first discuss the system of global transport equations for mean plasma parameters and the mean radial electric field

$$\frac{d}{dt}\frac{3}{2}nT = -\nabla q_r + S, \tag{1}$$

$$\frac{d}{dt}E_r = \nabla_\perp \mu_\nu \nabla_\perp E_r - \frac{J_r}{\varepsilon_0 \varepsilon_\perp}, \tag{2}$$

where the energy transport, q_r, is a combination of the turbulent transport, $q_r^T = -n\chi_T \nabla T$, and neoclassical transport, q_r^{nc}, S is the local source, ε_0 is the dielectric constant in vacuum, $\varepsilon_\perp$ is the perpendicular dielectric constant of a magnetized plasma $\sim(1+Cq^2\varepsilon^{-1/2})c^2\nu_A^{-2}$ (ν_A is Alfvén velocity, q is the safety factor, $\varepsilon = r/R$, r and R are minor and major radii, respectively, and a coefficient C, with a dependence on plasma parameter and electric field, is taken as unity for analytic transparency), and μ_ν is the shear viscosity.[1] The radial current J_r in helical systems is induced by ripple transport and has a nonlinear dependence on E_r. In conventional analyses, the suppression of q_r^T by the mean $d\bar{E}_r/dr$ is taken into account, $\chi_{T0}=\chi_{T0}^{(L)}/(1+\tau_c^2\omega_E^2)$, where $\chi_{T0}^{(L)}$ is the transport coefficient by "bare" turbulence in L-mode plasmas, τ_c is the correlation time of microfluctuations and $\omega_E = r d(\bar{E}_r B^{-1} r^{-1})/dr$.[1]

This system of mean variables is known to have a structural transition, by which the internal transport barrier is realized. The transport barrier is associated with the interface of E_r, e.g., E_r is strongly positive for $r<r_{\text{int}}$ and negative (or weakly positive) for $r>r_{\text{int}}$ (r_{int}: the radius of the interface). The origin of the transition is due to the nonlinear dependence of J_r (the component which is carried by helically trapped particles) on E_r. The deviation of the orbit of helically trapped particle from the magnetic surface, which contributes to J_r, is suppressed when $|E_r|$ becomes stronger. This dependence on $|E_r|$ is stronger for ions than electrons, because the effective collision frequency is greater for the trapped electrons under consideration, so that the function $J_r[E_r]$ is no longer monotonous. Thus the charge neutral condition, $J_r[E_r]=0$, allows multiple solutions of E_r (a strong positive one or a weak negative one for fixed plasma parameters). This mechanism has been investigated in detail, and confirmation by experiments has been shown (see, e.g., a review in Ref. 5). The improvement of the confinement was predicted in two ways: χ_T is suppressed by dE_r/dr near the interface, and q_{nc} is strongly suppressed inside of the electric field interface, $r<r_{\text{int}}$.[16] The suppression of χ_T is limited to the region near the interface, and its reduction in the entire core plasma ($r<r_{\text{int}}$) has not been explained.

The zonal flows (with nearly zero frequency) are generated by microscopic fluctuations and influence the turbulent transport strongly. The damping rate of ZFs, ν_{damp}, controls the turbulent transport. The damping of ZFs is caused by the collisional process as well as by the self-nonlinearity of ZFs.[19] In toroidal helical plasmas, as is explained in the following, the collisional process remains important even in the regime of $\nu_* < 1$ ($\nu_* = \nu_{ii} qR/\varepsilon v_{\text{th},i}$). When collisional damping dominates ν_{damp}, χ_T has been derived considering the screening by ZFs.[19] Whether the ZFs are excited or not is judged by comparing χ_{T0} (which is given in the absence of ZFs) with the quantity

$$\chi_{\text{damp}} \simeq k_\perp^2 q_r^{-2} k_\theta^{-2} \nu_{\text{damp}}, \tag{3}$$

where k_θ and $k_\perp$ are the poloidal and perpendicular wave numbers of the microscopic fluctuations, respectively, and q_r is the radial wave number of the ZFs. When the turbulence is weak and χ_{T0} is smaller than χ_{damp}, ZFs are not excited and one has $\chi_T=\chi_{T0}$. If the condition $\chi_{\text{damp}}<\chi_{T0}$ is satisfied, ZFs are excited and the fluctuation level is controlled as $|\tilde{E}|^2 \propto \nu_{\text{damp}}/\omega_*$. Then χ_T is reduced as $\chi_T=\sqrt{\chi_{T0}\chi_{\text{damp}}}$.[20] (Such theoretical model is backed-up by simulations.[21]) A fitting formula is often employed as

$$\chi_T = \sqrt{\chi_{T0}} \min(\sqrt{\chi_{T0}}, \sqrt{\chi_{\text{damp}}}). \tag{4}$$

This sensitivity of χ_T to the damping rate of ZFs explains the improved confinement in the e-ITB region of toroidal helical plasmas. The neoclassical ripple transport contributes to the radial current J_r. From Eq. (2), one obtains the damping rate of ZFs by the neoclassical ripple transport as

$$\nu^{\text{ncr}} = \varepsilon_0^{-1}\varepsilon_\perp^{-1}(\partial J_r^{\text{ncr}}/\partial E_r)$$

where the superscript ncr stands for the neoclassical ripple transport. For physical insight, we employ an analytic formula for J_r^{ncr} from Ref. 22 to obtain

$$\nu_{\text{damp}} = \left(\min(1,\nu_*) + \frac{\varepsilon_h^{3/2}}{\sqrt{\varepsilon}}\frac{1}{\nu_*}F(E_r)\right)\frac{v_{\text{th},i}}{qR}. \tag{5}$$

The term $\min(1,\nu_*)$ represents the plateau and banana transport,[19] and the second term comes from the ripple transport with the effect of the mean E_r

$$\begin{aligned} F(E_r) = {} & 24.7(1+s_iX^{1.5})^{-2}(1-0.5s_iX^{1.5}-1.5\sigma s_iX^{0.5}Y_i) \\ & + 11.5(T_e/T_i)^2\nu_i\nu_e^{-1}(1+s_eX^{1.5})^{-2}(1-0.5s_eX^{1.5} \\ & + 1.5\sigma s_eX^{0.5}Y_e), \end{aligned} \tag{6}$$

where ε_h is the helical ripple of the magnetic field, $X = |e\bar{E}_r r/T_i|$, $\sigma=\text{sign}(E_r)$, $s_i=69.5\varepsilon^{-3}(\varepsilon_h q\rho_i/r\nu_*)^{1.5}$, $s_e = 21.5\,\varepsilon^{-3}(\nu_i\varepsilon_h q\rho_i/r\nu_*\nu_e)^{1.5}$, $Y_i=-r\nabla n/n - c_1 r\nabla T_i/T_i$, $Y_e = T_eT_i^{-1}(-r\nabla n/n - c_2 r\nabla T_e/T_e)$. (Coefficients c_1 and c_2 depend on plasma parameters etc. However, they remain of order unity. We use an approximation of $c_1=c_2=1$ for the transparency of the analysis in the following.) Equations (5) and (6) explicitly show that the damping of ZFs is influenced by E_r. When E_r is evaluated by the condition $J_r^{\text{ncr}}(E_r)=0$, which is a good approximation away from the interface, the relation $X \propto Y$ approximately holds. Under this circumstance, the factor $F(E_r)$ satisfies the relation $F(E_r) \propto |X|^{-1.5}$ (i.e., it is a decreasing function of $|E_r|$), at large values of $|E_r|$. Owing to this dependence of ν_{damp} on E_r, ν_{damp} of Eq. (5) is large when E_r takes small values, while it is small when E_r takes large and positive values. Thus, the turbulent transport coefficient, Eq. (4), becomes smaller when the strong positive radial electric field is established in the e-ITB, $r<r_{\text{int}}$. This role of the ripple transport in the turbulence causes a new bifurcation of the turbulent transport in toroidal helical plasmas. That is, the bifurcation of E_r itself induces the transition of turbulent transport in the bulk of the plasma column ($r<r_{\text{int}}$) as well as at the interface of the electric field.

The reduction of turbulent transport in the entire region of strong positive E_r is quantitatively demonstrated by use of transport code analysis. The one-dimensional transport analysis [Eqs. (1) and (2) and that for density n] for LHD-like plasma has been performed and the mean profiles of E_r, T_e, T_i, and n are solved for.[16] In the analysis of Ref. 16, $\chi_T = \chi_{T0}$ (based on the nonlinear current-diffusive interchange mode[1] which was found relevant in the system with an average magnetic hill) was used. An example is taken from a low density plasma which is sustained by electron cyclotron resonance (ECR) heating.[14] [Parameters are: major and minor radii, $R=3.6$ m, $a=0.6$ m, respectively, $B=3$ T, $\bar{n}=4.1\times10^{18}$ m^{-3}, $T_e(0)=4$ keV, $T_i(0)=2$ keV.] Figure 1(a) illustrates the profile of E_r for e-ITB plasmas, in which the interface is established at $r_{\text{int}}\simeq 0.6a$. Profiles of χ_{T0} and χ_{nc} are demonstrated in Fig. 1(b). Multiple solutions of E_r are allowed in the core, and r_{int} is determined by Maxwell's con-

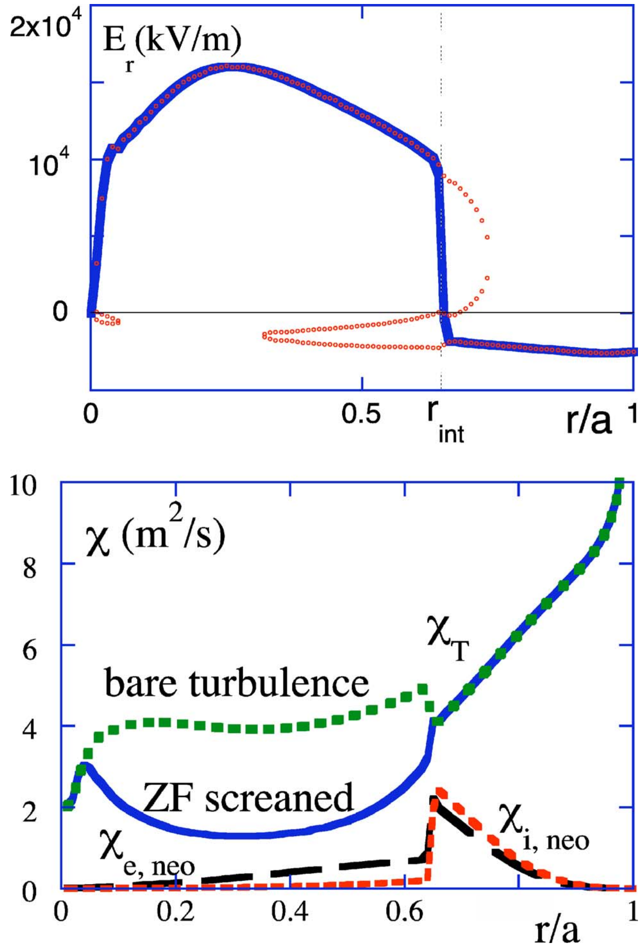

FIG. 1. Transport code analysis of LHD plasma with e-ITB. Radial electric field profile (solid line) is shown with solutions of local charge neutrality condition (dots) in (a). Profiles of neoclassical thermal conductivity and turbulent conductivity (b). Prediction based on the bare microturbulence (dotted line) and the one with screening by ZFs (solid line) are shown.

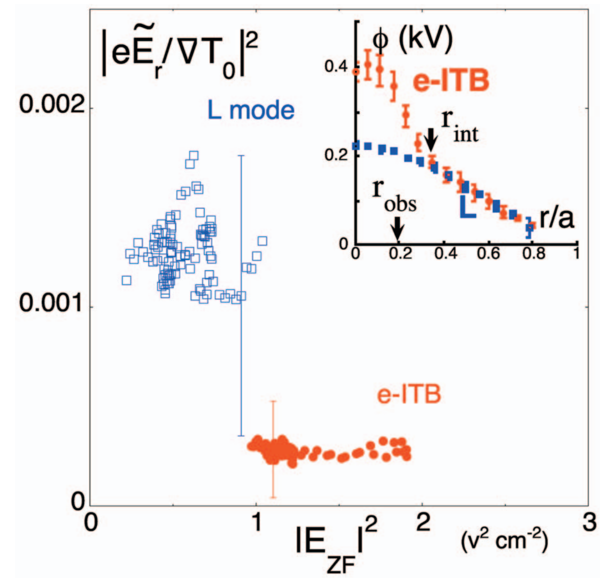

FIG. 2. (Color) Simultaneously observed ZFs and microturbulence intensities during the e-ITB phase (solid circle, red) and the L-phase (open circle, blue). Vertical and horizontal axes indicate normalized fluctuation amplitude $|e\tilde{E}_r/\nabla T_0|^2$ and ZFs amplitude $|E_{\mathrm{ZF}}|^2$, respectively. The insert shows the profile of the mean potential for e-ITB and L plasmas. Locations of interface and observation, r_{int} and r_{obs}, are also indicated.

struction rule. The transport coefficient by bare fluctuations (without ZFs effects), χ_{T0}, shows a sharp dip near the interface, but does not show a noticeable reduction for $r<r_{\mathrm{int}}$, owing to the increased temperature. The value of χ_{damp} for three branches of the electric field is also illustrated in Fig. 1. By use of the consistent solutions of E_r, T_e, T_i, and n, the damping rate of ZFs, ν_{damp}, is calculated after Eqs. (5) and (6). χ_{damp} is evaluated by employing an estimate of $k_\perp^2 q_r^{-2} k_\theta^{-2} \rho_i^{-2} \sim 50$ (i.e., $k_\perp^2 q_r^{-2} \sim 6$ and $k_\theta \rho_i \sim 1/3$).[20] The value of χ_{damp} is reduced much in the e-ITB domain, owing to the reduced damping of ZFs, ν_{damp}. The screened turbulent transport coefficient is calculated from Eq. (4). Owing to the screening by ZFs, χ_T is predicted to be quenched in the core of e-ITB plasmas as is shown in Fig. 1(b). The screened transport coefficient is close to the experimental observation, where the reduction of χ to $\sim 2\ \mathrm{m^2/s}$ was reported in the core of the e-ITB plasma.[23] Outside the interface, where E_r is weak and negative, ν_{damp} is large and strong ZFs are not excited. Thus the screening is not expected to occur for $r > r_{\mathrm{int}}$ in this example.

The reduction of the turbulent transport in the core of e-ITB plasma, via the enhanced ZFs, has been experimentally confirmed on CHS plasma. The ZFs have been identified in the CHS plasma,[24] and the temporal evolution of the intensities of the microfluctuations and the ZFs have been measured simultaneously.[25] Figure 2 shows the intensity of the ZFs, $|E_{\mathrm{ZF}}|^2$, and the normalized fluctuation amplitude, $|e\tilde{E}_r/\nabla T_0|^2$, during the period of the e-ITB and in the case without the barrier. (∇T_0 is the gradient of the mean electron temperature.) Data in the time window of 10 ms before the ITB-to-L transition (e-ITB) and those after the transition (L) are shown. This example is a low density plasma which is heated by ECR. [$R=1$ m, $a=0.2$ m, $B=0.88$ T, $\bar{n}=5\times 10^{18}\ \mathrm{m^{-3}}$, $T_e(0)\simeq 1$ keV and details of the discharges are given in Ref. 25.] The ZFs intensity is given by the integral of the power spectrum of the fluctuating electric field in the interval of $0.25\ \mathrm{kHz} < \omega/2\pi < 2.5\ \mathrm{kHz}$, and those in the interval of $25\ \mathrm{kHz} < \omega/2\pi < 250\ \mathrm{kHz}$ are integrated for $|e\tilde{E}_r/\nabla T_0|^2$. The error in the estimate of $|e\tilde{E}_r/\nabla T_0|^2$ (shown by an error bar) is mainly due to the uncertainty in ∇T_0. The data in Fig. 2 are measured at $r\simeq 5$ cm, i.e., for $r<r_{\mathrm{int}}$ where $d\bar{E}_r/dr$ is too weak to suppress turbulence even in the ITB. The difference in the fluctuation amplitudes $|e\tilde{E}_r/\nabla T_0|^2$ (between the e-ITB and L-mode plasmas) is distinctive.

This experimental result clearly demonstrates that the energy of the fluctuations is preferentially transferred into ZFs when ν_{damp} becomes weak in the e-ITB. The normalized fluctuation amplitude $|e\tilde{E}_r/\nabla T_0|^2$ is, as an average, about 5 times smaller in the case with an e-ITB compared to that without it. This difference is understood from the dependence of ν_{damp} on $\bar{E}_r$. The damping rate was also measured on CHS, and ν_{damp} is smaller by the factor 6 in the case of an e-ITB compared to the L-mode plasma.[11] It was theoretically predicted that $|e\tilde{E}_r/\nabla T_0|^2$ is proportional to the damping rate of ZFs when ZFs are excited.[19] The observed difference of

$|e\tilde{E}_r/\nabla T_0|^2$ between the e-ITB and L-mode plasmas does not contradict the theoretical prediction, in which the difference of ν_{damp} causes the change of χ_T. It should be noted that the pressure gradient at the observation radius is weaker in the L-mode plasma compared to the e-ITB plasma. (Other parameters such as geometrical factors and magnetic field, etc. are unchanged between the two states.) Thus, the enhanced normalized fluctuation level in the L-mode is opposite to the reduction of mean pressure gradient and cannot be simply explained by linear instability. When E_r jumps to a strongly positive value, ν_{damp} is reduced, and microfluctuations (which are responsible for turbulent transport) become smaller. Thus, the increased ZFs cause the further reduction of the turbulent transport in the entire region of the e-ITB, in addition to the strong $\mathrm{d}\bar{E}_r/\mathrm{d}r$ at the interface.

In summary, we have studied the role of zonal flows in the e-ITB formation of toroidal helical plasmas. It was found that neoclassical ripple transport can enhance the turbulent transport, through its impact on the damping of the zonal flows. The bifurcation of E_r (from the negative value to the strong and positive value) 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 ZFs which causes the suppression of turbulent transport. The test by transport modeling was shown, and the experimental evidence for the energy accumulation in ZFs in e-ITB plasma was demonstrated. This is the first demonstration, including an experimental test, that a change in the collisional damping of ZFs can cause a transition in the turbulent transport.

Note that the reduction of ν_{damp} at large values of E_r is a robust result. The result here emphasizes analytic transparency, and is backed up by a more detailed form for the collisional damping given in Ref. 26. The self-consistent solution of Eqs. (1)–(4) was obtained, and the result in this letter was confirmed (which will be published in a forthcoming article). The other 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 if E_r is negative. This finding can explain the observations on LHD: In the collisionless plasmas of LHD, the smaller the helical ripple, the lower the anomalous transport.[23] The control of the damping rate of ZFs for further improvement of the plasma confinement has been investigated.[27] Wide extension of the present work is possible, and is left for future work.

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