Inter-linkage of transports and its bridging mechanism

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The physical mechanisms determining the diffusive and non-diffusive terms of particle, momentum and heat transport are described. The non-diffusive term in the particle transport, which causes inward pinch or outward flow is driven by the temperature gradient and the magnetic field curvature. The non-diffusive term in the momentum transport, which drives spontaneous toroidal rotation, is found to be sensitive to the sign of the electric field. In heat transport, there is no clear non-diffusive term observed. The temperature and temperature gradient dependences of the diffusive terms are discussed.

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The existence of the non-diffusive term of transport has been recognized in particle transport (and impurity transport) as the Ware pinch by the toroidal electric field[1] or convection by ion temperature gradient driven turbulence[2] . The peaked profile of the electron density observed in the steady-state with gas puff fueling clearly shows the significant contribution of the non-diffusive inward particle flux, because the particle source is localized near the plasma periphery. The inward pinch observed in a stellarator where there is no toroidal electric field, suggests that turbulence driven convection can easily overcome the thermodiffusion[3]. The Non-diffusive term in the momentum transport was found experimentally[4] and it appears as an spontaneous toroidal rotation[5]. The significant contribution of the non-diffusive term to the transport shows a strong inter-linkage of the transport between particle, (poloidal and toroidal) momentum and (ion and electron) heat transport. In the plasmas with a transport barrier, where a strong gradient is produce, the inter-linkage of the transport becomes more significant. (A good example is a large spontaneous toroidal rotation at the internal transport barrier[6, 7]). This is because these non-diffusive terms are correlated to the gradients of other plasma parameters (ion temperature gradient for particle transport or potential gradient for momentum transport). Therefore these non-diffusive term are considered to be off-diagonal terms of the so-called transport matrix. Recent turbulence transport theory explores the physics bridging mechanism for the off-diagonal terms of the transport matrix[8]. For example, the theoretical model of symmetry breaking of turbulence by radial electric field shear[9] could explain the strong correlation between non-diffusive momentum flux and ion pressure gradients (and also radial electric field) observed in experiments. In this paper, non-diffusive terms of particle and momentum transport and diffusive terms of heat transport are discussed based on experiments in stellarators and tokamaks.

It is well known that the non-diffusive term has a significant contribution to the radial flux of particles and it causes the inward flux which is necessary to achieve a peaked density profile with a particle source localized near the plasma edge. Due to the role of spontaneous toroidal rotation in MHD stability, the non-diffusive term of momentum transport has become highlighted in recent momentum transport studies. On the other hand, the non-diffusive term of heat transport has not been clearly identified, although there were experimental results that suggest the heat pinch. Figure 1 shows the physics mechanism determining the diffusive term and non-diffusive terms of the radial flux of a particle, momentum and energy transport. There are various physics mechanisms contributing to the non-diffusive term in the particle transport. The inward pinch driven by the toroidal electric field is well known as the Ware pinch in tokamaks. However, the inward pinch observed in steady state plasmas in tokamaks and in stellarators can not be explained by the Ware pinch, because there is no toroidal electric field in these experiments. In stellarator plasmas, the thermodynamic force driven by the electron temperature gradient contributes to significant outward flux. This term has been confirmed experimentally in stellarators. It is well known that momentum and energy transport have convection terms due to the radial flux of particles. In general, these convective terms are relatively small. It is interesting that the radial electric field and the magnetic field curvature affects both the non-diffusive terms of particle transport and momentum transport, while the radial electric field and its shear affect both the diffusive

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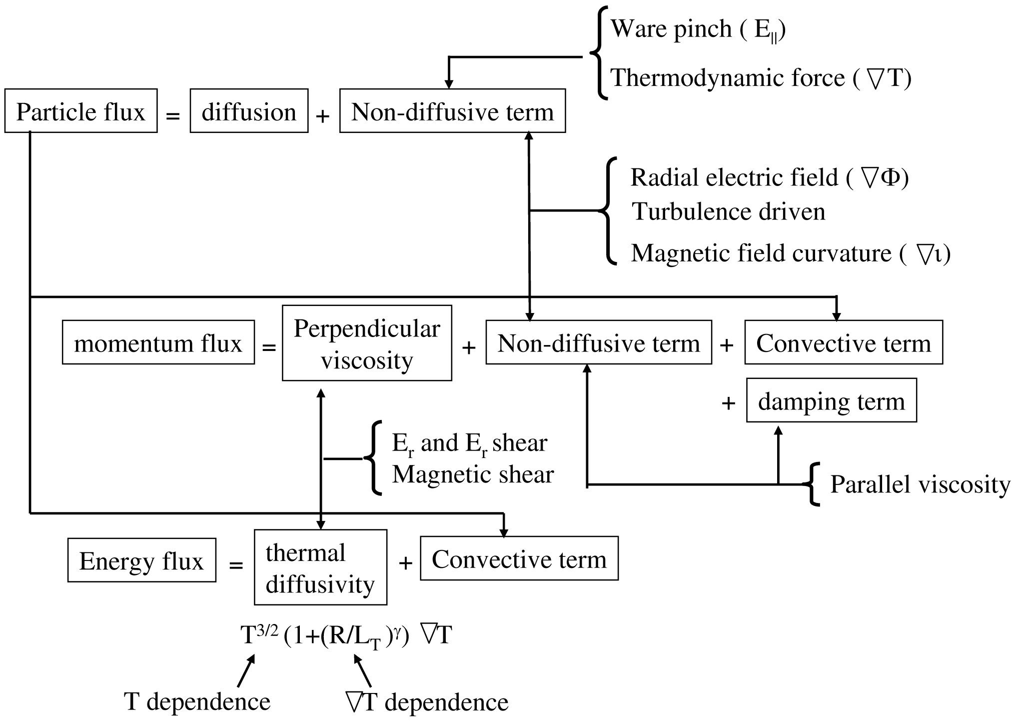

Fig. 1 Physics mechanism determining the diffusive term and non-diffusive terms of the radial flux of particle, momentum and energy transport.

term of momentum transport and energy transport. Therefore particle, momentum and heat transport are coupled to each other through these physics elements.

The diffusive term of particle transport has been derived from the time dependent transport analysis of a discharge with gas puff modulation. Figure 2 (a) shows the temperature dependence of the diffusion coefficient evaluated in LHD. The diffusion coefficient measured is larger than the prediction by neoclassical theory by one order of magnitude. Both in the core and edge, the diffusion coefficient has the electron temperature dependence of $\alpha \approx 1$, where $D \propto T_e^{\alpha}$, which is weaker than that of the neoclassical prediction ($\alpha \approx 2.6$). Figure 2(b) shows the relation between the normalized temperature and density gradients experimentally obtained in Wendelstein 7AS and LHD. Since both the density gradient and temperature gradient contribute to the outward flux, there should be an inward flux to sustain the steady state density profile where $\Gamma \approx 0$. The particle flux can be written as $\Gamma = -n_e(D_{11}\nabla n_e/ne_e + D_{12}\nabla T_e/Te - u)$. Where D_{11} and D_{12} are the on- and off-diagonal elements of the transport matrix and the velocity u is a convective contribution. The ratio of these coefficient derived from the slope of the data plotted in Fig2(a) are $D_{12}/D_{11} \approx 1.4$ and $u/D_{11} \approx -12.5$ m^{-1}, respectively. The significant contribution of the inward term of u/D_{11} overcomes the outward term of D_{12}/D_{11} of the non-diffusive term as well as the diffusive term and sustains the peaked density profile in steady state. Because various physics mechanisms contribute to the non-diffusive term of particle transport, it is still open to question which physics mechanisms become dominant. A more comprehensive understanding should be sought from the comparison of density profiles in stellarators (typically flat or hollow) with these in tokamaks (typically peaked).

Similar experiments have been done in steady state fully noninductive current plasmas in tokamaks to eliminate the contribution of the Ware pinch due to toroidal electric field to drive ohmic current. Figure 3 shows the relations between $\nabla n_e/n_e$, $\nabla T_e/T_e$ and $\nabla q/q$ in the Tore Supra tokamak. As seen in Fig.3(a) and Fig.3(b), there are two distinguished regions ($\rho < 0.3$ and $0.35 < \rho < 0.6$) that show different slopes. The direction of the thermodiffusion flux is found to change when moving from the outer to the inner plasma. The sign of the thermodiffusion pinch is determined by the slope. This experiment shows that thermo-diffusion can be inward ($\rho < 0.3$) or outward ($0.35 < \rho < 0.6$) depending on the plasma radius, where the unstable mode (ITG or ETG) is expected to be different because of the change in the ratio of $\nabla T_e/\nabla T_i$. In the region of $\rho = 0.35 - 0.6$, where the thermo-diffusion flux is outward, a physics mechanism driving the inward pinch is necessary in

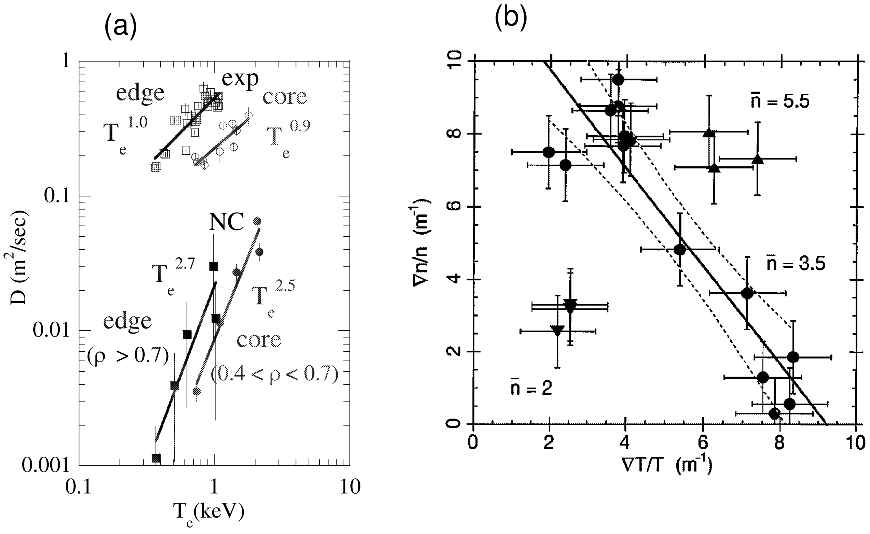

Fig. 2 (a) Temperature dependence of the diffusion coefficient in the core ($0.4 < \rho < 0.7$) and edge ($\rho > 0.7$) experimentally evaluated and neoclassically predicted in LHD[10] and (b) average density versus temperature gradient scale length estimated between r = 2 and 8 cm for three densities. For $\Gamma \approx 0$ it follows that $D_{12}/D_{11} \approx 1.4$ and $u/D_{11} \approx -12.5$ m^{-1} [3] and (b) the relation of normalized temperature and density gradient. The core and edge values are estimated from the average value in the core ($0.4 < \rho < 0.7$) and edge ($0.7 < \rho < 1.0$) at $R_{ax} = 3.6$m, $B_t = 2.75$, 2.8T.

order to sustain the sharp density gradient in steady state. A clear relation between $\nabla n_e/n_e$ and $\nabla q/q$ in Fig.3(c) strongly suggests that the magnetic field curvature drives the inward pinch. It is interesting that the sign of the magnetic field curvature driven flux in stellarators is opposite to that in tokamak and outward flux is expected. It is still open to question what the physics mechanism is causing the inward flux near the plasma edge in sterllarators, where there is no Ware pinch and both the thermo-diffusion flux and the flux driven by the magnetic field curvature are expected to be outward because of $\nabla T_e/T_e < 0$ and $\nabla q/q < 0$. Because the impurity has a higher ion charge, Z, impurity transport is more sensitive to the radial electric field than bulk particle transport. The positive radial electric field in the electron root tends to drive outward flux and suppress the accumulation of impurities and radiation collapse[15, 16]. It is a crucial issue to achieve poor impurity confinement (impurity exhaust) and good energy confinement, simultaneously. In stellarators, poor impurity confinement is observed in plasmas with good energy transport, for example the HDH mode in Wendelstein 7-AS[17] and the electron ITB and high ion temperature mode in LHD.

Since the damping of the plasma toroidal velocity owing to parallel viscosity is significant near the plasma periphery in stellarators[12], toroidal rotation near the plasma edge is determined by the radial electric field, while the core toroidal rotation is determined by the momentum from the tangential NBI. The momentum flux including the non-diffusive term due to the radial electric field can be expressed as $P_\phi = -mn(\mu_\perp \nabla V_\phi - \xi E_r/B_\theta)$[13]. In order to investigate the effect of the radial electric field on the toroidal rotation, a density scan is made near the threshold of the transition from the ion root (negative E_r) to electron root (positive E_r). In LHD, the transition from the ion root to the electron root takes place at the low density where the plasma is well into the collisionless regime $\mu_e^* < 0.1$, because of the non-ambipolar particle flux as predicted by neoclassical theory. As seen in Fig.4, the plasma rotates more in the counter direction (anti parallel to equivalent plasma current) for positive E_r, while it rotates more in the co direction for negative E_r. The relation between the toroidal rotation and the radial electric field is plotted in Fig4(c). This result shows that the positive radial electric field drives the toroidal rotation in the counter direction, where the toroidal rotation contributes to the negative radial electric field. It should be emphasized that the direction of the toroidal flow is anti-parallel to the direction of the $< E_r \times B_\theta >$ drift. This is in contrast to the spontaneous flow in a tokamak, where the direction of the toroidal flow is parallel to the direction of the $< E_r \times B_\theta >$ drift, because the toroidal viscosity is nearly zero due to the toroidal symmetry. The spontaneous toroidal flow becomes more significant in the plasma with an internal transport barrier, where large electric fields are observed. In CHS the sponta-

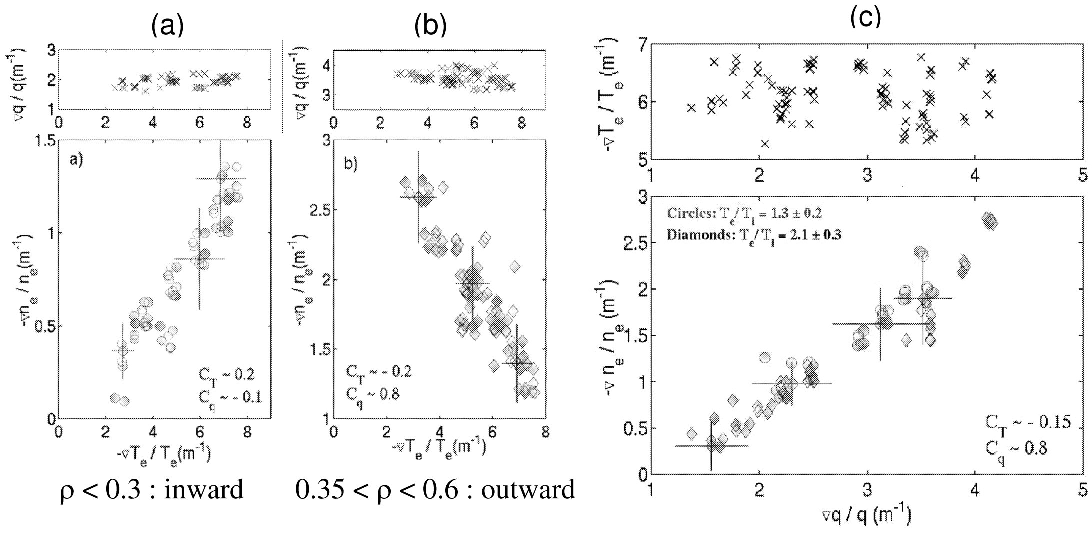

Fig. 3 $\nabla n_e/n_e$ $\nabla T_e/T_e$ from a set of seven discharges: (a) for $r/a \leq 0.3$, $T_e/T_i = 2 \pm 0.4$, $\nabla T_e/T_e$ = 3.8-4.8; (b) for $0.35 \leq r/a \leq 0.6$, $T_e/T_i = 1.2 \pm 0.4$, $\nabla T_e/T_e$ = 0.7-3.5. Corresponding variation of $\nabla q/q$ is displayed at the top. (c) $\nabla n_e/n_e$ versus $\nabla q/q$ within $0.3 \leq r/a \leq 0.6$ from a set of seven discharges, keeping $|\nabla T_e/T_e|$ at the values of $6m^{-1} \pm 10$ % and $\nabla T_e/T_e = 0.6 \pm 0.3$ [11].

neous toroidal flow overcomes the toroidal flow driven by co-NBI and the plasma rotates in the counter direction associated with the formation of a large positive E_r. In contrast, in JT-60U, the plasma rotates in the counter direction at the ITB region where a strong negative radial electric field is produced. The significant difference between tokamaks and heliotron devices is the relationship between the poloidal field direction and the direction of the dominant symmetry. The pitch angle of the dominant symmetry is even larger than that of the averaged poloidal field in a Heliotron device, while it is zero due to the toroidal symmetry in a tokamaks.

In a stellarator turbulence in the plasma as well as non-ambipolar flux can drive flows perpendicular ($E \times B$) and parallel (spontaneous toroidal flow) to the magnetic field though Reynolds stress. The experiments to investigate the turbulence driven $E \times B$ flow and the spontaneous toroidal flow have been done in the vicinity of the last closed flux surface (LCFS) in JET and in TJ-II. The radial-perpendicular component of the production term has been investigated in the LCFS vicinity in the JET tokamak as seen in Fig.5(a). Figure 5(b) shows the radial structure of the cross correlation between parallel and radial fluctuating velocities in the proximity of the LCFS in the TJ-II stellarator. The level of cross correlation $< vM_{||} >$ increases for plasma densities above the threshold value to generate $E \times B$ sheared flows. The appearance of gradients on $< vM_{||} >$ is due to both radial variations in the level of fluctuations and in the cross-phase coherence between fluctuating radial and parallel velocities. It has been found that the energy transfered from dc flows to turbulence, directly related to the momentum flux and the radial gradient in the perpendicular flow, can be both positive and negative in the proximity of sheared flows. Furthermore, the energy transfer rate is comparable with the mean flow of kinetic energy normalized to the correlation time of the turbulence, implying that this energy transfer is significant. These results show that turbulence can act as an energy sink and energy source for the mean flow near the shear layer.

There is no clear evidence of a non-diffusive term of the energy transport except for a few experiments in plasmas with ECH[21]. In most cases the diffusive term only can explain the energy transport observed in experiments. The diffusive term of the energy transport is evaluated as thermal diffusivity (the ratio of heat flux normalized by density to the temperature gradient). In general, the heat flux depends on the temperature and the temperature gradient and it is non-linear. Therefore the thermal diffusivity has a temperature dependence and also a temperature gradient dependence in the non-linear regime. Figure 6 shows the ∇T_e dependence of χ_e (obtained from the static analysis i.e. the power balance analysis) in JT-60U, Wendelstein 7-AS and LHD. In Fig.6, the thermal diffusivity is normalized by $T_e^{3/2}$, which is predicted by Gyro-Bohm transport, in order to eliminate the T_e dependence of χ_e and make the ∇T_e dependence clear. The ∇T_e is normalized by R/T_e, Because the ratio of the major radius to the scale length of the temperature is expected to give the threshold of turbulence in the critical temperature gradient transport model. As seen in Fig.6, there is no clear critical gra-

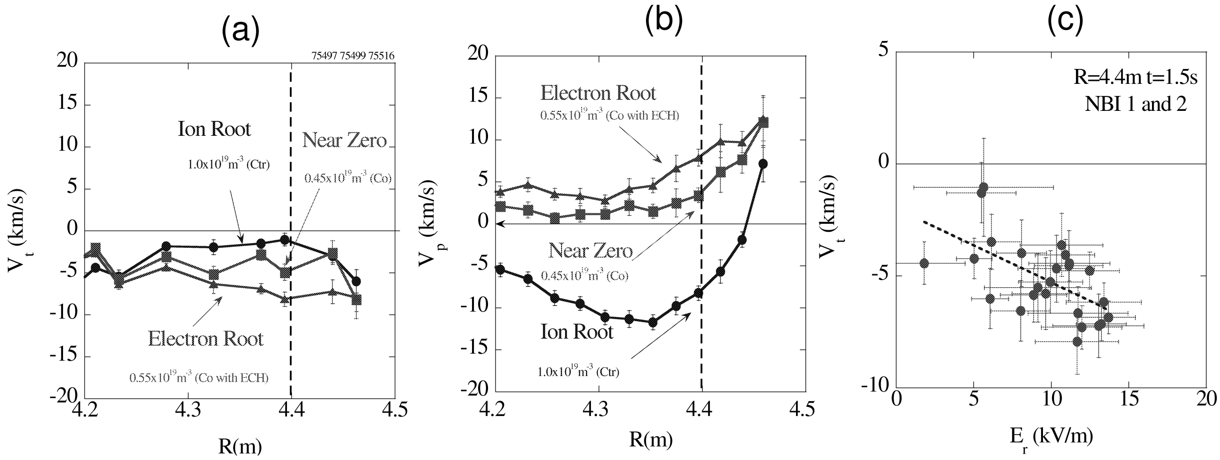

Fig. 4 Radial profiles of (a) toroidal and (b) poloidal rotation velocities and (c) relation between toroidal and poloidal rotation velocities in LHD.

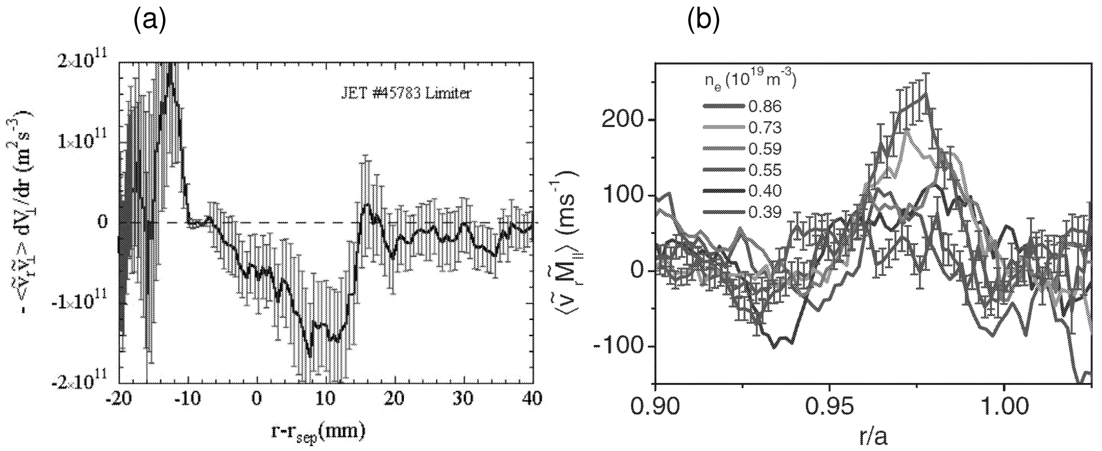

Fig. 5 Radial profile of the (a) radial-perpendicular Reynolds stress component in the plasma boundary region in the JET tokamak and the (b) radial-parallel Reynolds stress component in the TJ-II plasma boundary region at different plasma densities. Parallel velocity is quantified by the parallel Mach number [14, 18].

dient scale length observed in LHD, although the existence of a critical gradient scale length is suggested in Wendelstein 7-AS and JT-60U. The thermal diffusivity χ_e shows a Gyro-Bohm type T_e dependence when the temperature gradient is small enough, while it depends mostly on the scale length above a critical value of the temperature gradient. This implies that there is a strong nonlinear mechanism in transport. One of the candidates for the mechanism causing strong nonlinearity is non-linear flow damping of the zonal flow in a tokamak plasma. In the LHD heliotron, there is no critical value of the temperature gradient, because the transition from L-mode to an electron ITB take place at a lower temperature gradient[22]. The transition from L-mode to the electron ITB is due to the change in the temperature dependence of α from positive values ($\sim 3/2$ as predicted by gyro-Bohm scaling) to negative values ($\sim -3/2$), where α is defined as $Q/n_e \propto T_e^{\alpha} \nabla T_e$[23]. The temperature dependence tends to decrease (weak temperature dependence) as the electron density is increased. This change in the temperature dependence of the thermal diffusivity is consistent with the change in the power degradation of the energy confinement time. It should be noted that the L-mode scaling of the global energy confinement time expressed by $t_E \propto (n_e/P)^{3/5}$ is equivalent to the temperature dependence of the thermal diffusivity expressed by $\chi \propto T_e^{3/2}$. Therefore the weak temperature dependence ($\alpha = 1/2$) appears as a tendency of the saturation of the energy confinement time at higher density as $n_e^{1/3}$. The temperature dependence factor α becomes ~ 0.5 at lower temperatures below the critical value (in the more collisional regime[24]) or in the plasma with pellet injection[25]

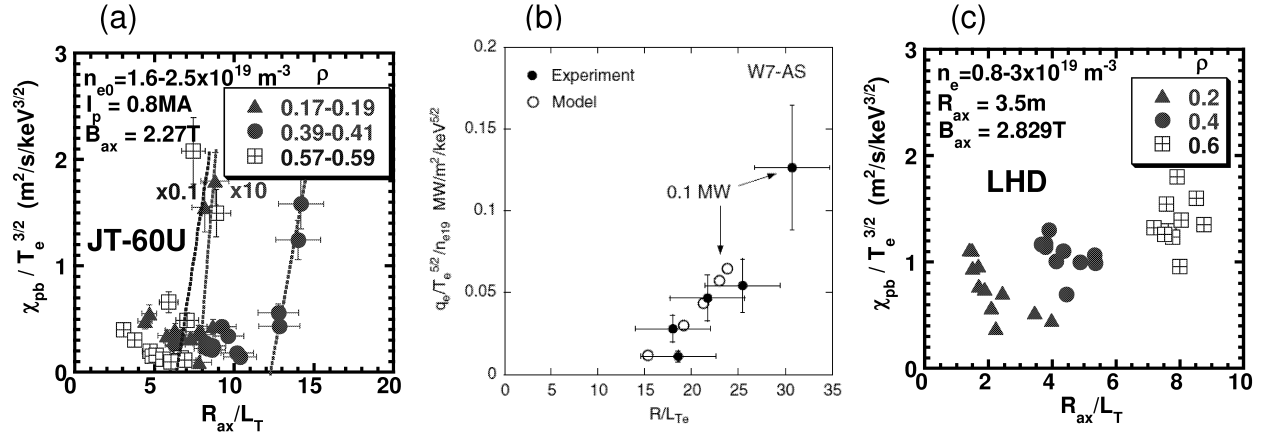

Fig. 6 ∇T_e and T_e dependence of χ_e at different normalized radii in (a)JT-60U, (b) Wendelstein 7AS and (c) LHD NBI plasmas. χ_e is normalized by the gyro-Bohm T_e dependence and ∇T_e is normalized by (R/T_e), where R is the major radius and $L_T = \nabla T_e/T_e$ in (a) and (c)[19, 20].

In summary, the non-diffusive term driven by the thermo-diffusion due to the temperature gradient is experimentally identified in stellarators and tokamaks. In stellarators, thermo-diffusion always drives outward flow, while that in tokamak drives inward or outward flow depending on the unstable mode of the turbulence. The inward pinch due to the magnetic field curvature is found in steady state fully non-inductive current plasmas in tokamaks. However, this does not explain the inward pinch observed in the heliotron plasma, where the non-diffusive term due to the magnetic field curvature is expected to be outward. In momentum transport, the significant contribution of the non-diffusive term is experimentally observed and is identified as spontaneous flow. The physics mechanisms driving the spontaneous flow, which is parallel to the magnetic field, are investigated. Both the mean flow perpendicular and parallel to the magnetic field are driven by turbulence as well as by non-ambipolar flux. The mean flow parallel to the magnetic field (spontaneous toroidal flow) is in the direction of the toroidal flow anti-parallel to the $< E_r \times B_\theta >$ drift, which is in contrast to the spontaneous flow in a tokamak, where the direction of the toroidal flow is parallel to the direction of the $< E_r \times B_\theta >$ drift. Finally the parameter dependence of the diffusive term of the energy transport is discussed. The thermal diffusivity shows a Gyro-Bohm type T_e dependence when the temperature gradient is small. When the temperature gradient exceeds the threshold of the scale length, the thermal diffusivity increases rapidly if the plasma stays in L-mode. The threshold of the scale length is observed in tokamaks and Wendelstein 7-AS plasmas, but not in the LHD plasma, where the transition from L-mode to the electron ITB mode take place before the threshold.

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