§10. Theoretical Study towards the Extension of High Ion Temperature Regime in LHD

Yokoyama, M., Matsuoka, S. (Grad. Univ. Advanced Studies), Funaba, H., Ida, K., Nagaoka, K., Yoshinuma, M., Takeiri, Y., Kaneko, O., LHD Experiment Group

Experiments have been conducted in LHD to extend ion-temperature ($T_i$) regime, to achieve 5.6 keV\textsuperscript{10}. In such plasmas, typically $T_i$ is higher than the electron temperature ($T_e$) in the core region. The negative radial electric field ($E_r$) (ion root) has been predicted there, based on the neoclassical (NC) ambipolarity, and it has been verified with the potential measurement by utilizing the heavy ion beam probe (HIBP)\textsuperscript{3}. The $E_r$ can reduce NC transport in low-collisional high-$T_i$ LHD plasmas\textsuperscript{3}. However, it is increasing as $T_i$ is increased even with the presence of $E_r$, although the degree of the increase is much smaller than that predicted from the “pure” ($E_r=0$) $1/\nu$ ripple transport. Thus, it is important to consider plausible approaches to reduce (at least) the NC ion diffusion for the further extension of $T_i$-parameters. For this purpose, NC calculations have been performed with the GSRAKE code\textsuperscript{10}, which is based on the bounce-average approach.

Another low-energy (60 keV) neutral beam will be installed in FY2010 to increase the ion heating power. It may be concerned that the ripple transport gets worse as $T_i$ is increased in near-term LHD experiments. Figure 1 predicts that this concern is not the case. It shows the dependence of NC ion and electron fluxes, $\Gamma_{i,NC}$ and $\Gamma_{e,NC}$, on $E_r$. The open symbols represent those at $\rho=0.2$ in a particular example of high-$T_i$ plasmas so far obtained (“base case”), and solid ones those in an artificial case with only $T_i$ is doubled (“double-$T_i$ case”). Since $T_e$ is fixed, $\Gamma_{e,NC}$ does not change. The equilibrium is fixed as it is for the “base case”. An artificial case is considered to be corresponding to the expected selective ion heating. The point of intersection of $\Gamma_{i,NC}$ and $\Gamma_{e,NC}$ corresponds to the NC ambipolar $E_r$ for each case. The $\Gamma_{i,NC}$ at $E_r=0$ for “double-$T_i$” case is almost one-order larger than that for the “base case”, which is understood from the $T_i^{1/2}$-dependence of “pure” ripple transport. However, as seen in Fig. 1, the ambipolar flux given at the ambipolar $E_r$ is almost unchanged due to the enhancement of ion-root $E_r$. Therefore, in the near-term LHD experiment with selective ion heating, ion-root enhancement is predicted to avoid the appearance of deteriorate level of NC ripple transport. This scenario can be called as “ion-root” scenario.

On the other hand, when it is aimed to achieve high-$T_i$ plasmas in a higher density than the current level ($\sim 1.4 \times 10^{19} \text{ m}^{-3}$), $T_i/T_e$ ratio becomes closer to 1 with the equipartition of the energy. It is then required to draw appropriate scenario to avoid the ripple transport in such a condition. Since $T_i$ and $T_e$ are almost the same at $\rho=0.4$ in a “base case”, both $T_i$ and $T_e$ is simultaneously varied based on it. Here, the equilibrium is unchanged regardless the varied temperature. The density is also unchanged. Figure 2 shows the dependence of the NC ion heat diffusivity ($\chi_{i,NC}$) on temperature. The case with about 3 keV corresponds to the “base case”, and the indicated numbers denote the multiplication factor of temperature (from 0.5 to 4). The ion-root $E_r$ becomes smaller in the magnitude as the temperature is increased, which is due to the increase of $\Gamma_{e,NC}$ as a result of the increase of $T_e$. The decrease of the magnitude of ion-root $E_r$ results in the significant increase of $\Gamma_{i,NC}$ and then $\chi_{i,NC}$ as seen in Fig. 2. It is considered from this tendency that the “ion-root” scenario is not appropriate for plasmas with $T_i/T_e$. However, once the temperature reaches a certain value (1.5 times, in this particular case), the electron-root $E_r$ can appear with the significant reduction of $\chi_{i,NC}$ with the favorable nature of its decrease as the temperature is increased. It should be also pointed out that since Fig. 2 is obtained for the current level of the density, further 50 % increase of temperatures will provide the opportunity of the experimental verification of the electron-root $E_r$ in core of high-$T_i$ plasma. This amount of temperature increase might not be so unrealistic in the coming experiments. This approach utilizing the electron-root $E_r$ can be called as “electron-root” scenario.

Fig.1: $\Gamma_{i,NC}$ and $\Gamma_{e,NC}$ on $E_r$. The open symbols represent those at $\rho=0.2$ in an example of high-$T_i$ plasmas (“base case”), and solid ones those in an artificial case with only $T_i$ is doubled (“double-$T_i$ case”).

Fig.2: Dependence of $\chi_{i,NC}$ on temperature. The case with about 3 keV corresponds to the “base case”, and the indicated numbers denote the multiplication factor of temperature (from 0.5 to 4).

2) Ido, T. et al., to be presented at the 37\textsuperscript{th} EPS Conf. on Plasma Phys., Dublin Ireland, (Jun. 2010).