§7. Impact of Ion Species on Ambipolar Radial Electric Field in LHD

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High ion temperatures have been achieved in LHD experiments in high Z plasmas (such as Ne and Ar) 1,2). The radial electric field, \( E_r \), deduced from CXRS measurements 3) and the corresponding neoclassical calculations for such high-Z experiments have been reported 2,4). The systematic theoretical study is presented to clarify the impact of ion species on \( E_r \) in such discharges.

The GSRAKE 5) code has been employed to calculate the neoclassical radial particle flux, \( \Gamma_j \) (\( j \) is the particle species index), to determine \( E_r \) based on the ambipolarity condition \( \Sigma Z_i \Gamma_i = 0 \) where \( Z_i = \pm 1 \) is taken for electrons. The results presented below are for the \( \rho = 0.8 \) flux surface of the LHD with \( R_{\text{in}} = 3.75 \text{m} \) and \( B_{\phi} = 1.5 \text{T} \), for which GSRAKE calculations have been thoroughly benchmarked with other numerical approaches 6). Density and temperature profiles of \( n_i(0)(1- \rho^2) \) and \( T_i(0)(1- \rho^2) \) are assumed with fixed \( n_i(0) = 0.5 \times 10^{19} \text{ m}^{-3} \). The central temperatures, \( T_i(0) \) and \( T_e(0) \), are taken to be free parameters.

Figure 1 shows \( E_r \) diagrams in the \( T_i, T_e \) plane for pure H (\( Z_{\text{in}}=1 \)), He (\( Z_{\text{He}}=2 \)) and Ne (\( Z_{\text{Ne}}=10 \), \( T_0=1.36 \text{keV} \) for full ionization) plasmas. For H and He cases, two curves are indicated which separate the diagram into three regions. Above the upper curve, only one solution for \( E_r \), the so-called “electron” root, is found. A single solution also exists below the lower curve, referred to as the “ion” root. In the region bounded by the two curves multiple solutions exist. Previous experiments have shown that the electron root is generally realized in LHD when multiple solutions exist 7). It will be noted that for a given \( T_e \), the upper curve is shifted to lower \( T_i \) in the He case. For Ne plasma, only a single solution of the ambipolarity condition for \( E_r \) exists. The dotted curve in Fig. 1 indicates the temperatures for which the ambipolarity condition is satisfied by \( E_r = 0 \); above (below) the curve \( E_r > 0 \) (\( E_r < 0 \)) holds. This contrast to H, He results is due to the increase in charge; large \( Z \) magnifies the importance of the so-called mobility term in \( \Gamma \) (the term in which \( E_r \) appears as a thermodynamic force) for ions, while at the same time shifting them to higher collisionality where ripple transport plays a reduced role in determining the transport coefficients.

The effect of a gas mixture is examined below. The case of \( n_{\text{He}}=0.5n_i \) and \( n_{\text{Ne}}=0.05n_i \), (assuming \( T_{\text{He}}=T_{\text{Ne}} \)) is considered. The boundary separating the regions with only the ion root and with multiple solutions is shifted towards higher \( T_e \) for a case of a gas mixture. This can be explained by plotting the neoclassical particle fluxes as a function of \( E_r \) for the two cases, as in Fig. 2. The temperatures are \( (T_i, T_e) = (1.48, 0.76) \text{keV} \), corresponding on the boundary curve for pure H but below the boundary curve for the H+Ne mixture. In Fig. 2 it will be noted that the monotonic increase of the Ne flux with increasing \( E_r \) enhances the total ion flux at large positive \( E_r \). As a further hindrance to the appearance of the electron root, the higher \( Z_{\text{ion}} \) of the H+Ne plasma increases electron collisionality and thereby reduces electron ripple transport at moderate \( E_r \) values.

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References
1) S.Morita et al., Nucl. Fusion 43, 899(2003).

Fig. 1. \( E_r \) diagrams in the \( T_i, T_e \) plane for pure H, He and Ne cases at \( \rho = 0.8 \) of the LHD (\( R_{\text{in}}=3.75 \text{m}, B_{\phi} = 1.5 \text{T} \)).

Fig. 2. Charge-weighted particle fluxes for (a) pure H and (b) H+Ne mixture cases are shown as a function of \( E_r \) for the temperatures (\( T_i, T_e) = (1.48, 0.76) \text{keV} \).