§57. Analysis of Detachment Transition in LHD

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The divertor detachment is an attractive method to mitigate power load on the divertor plates via radiation energy loss. The scenario to the detachment has been extensively investigated in tokamaks. By increasing the density of core plasma, i.e. upstream density (n_u), the downstream temperature (T_d) and density (n_d) evolves as,

$$T_d \propto n_u^{-2}, \quad n_d \propto n_u^3, \qquad (1)$$

due to the pressure conservation along the flux tubes and to the dominant energy conduction flux over convection one. This relation then gives evolution of divertor recycling flux (Γ_{div}) as,

$$\Gamma_{div} \propto n_u^2. \qquad (2)$$

When Γ_{div} exhibits such dependence, it is called high recycling regime, which is often observed in tokamaks. As T_d decreases further according to eq.(1), the radiation energy loss significantly increases especially at $T_d < 10$ eV. When T_d becomes below 5 eV, the interaction between plasma and recycling neutrals is enhanced and the momentum removal by charge exchange process becomes large, leading to the breakdown of pressure conservation along flux tubes, and thus eq.(2). Furthermore, when T_d reaches ~ 1.5eV, the volume recombination sets in. It finally reduces divertor flux significantly, resulting in role over of Γ_{div}. It is also noted that the ionization activity at the divertor region is weakened due to the small T_d (< 10 eV), and thus the ionization front shifts upstream. It is considered that all these process are the cause of the divertor detachment in tokamak SOL's.

In order to investigate the SOL transport characteristics of LHD divertor, we have analyzed the evolution of ion saturation current (I_{sat}) measured by the divertor probe together with the 3D modelling results. Figure 1 shows I_{sat} obtained at density ramp up discharge as a function of the line averaged density ($\bar{n}$). From the density measurements of Thomson scattering system and the microwave interferometer, we found that n_u scales linearly with $\bar{n}$. At the lower density, I_{sat} increases with increasing $\bar{n}$ but linear dependence, which is different from eq.(2). This means that already at the low density regime, the pressure conservation is broken in the SOL of LHD, and leads to the absence of the high recycling regime. In Fig. 1, the total recycling flux obtained by the 3D modelling of EMC3-EIRENE is plotted. One sees that the modelling result reproduces the experimental observation very well. In ref. 1, it was found that the friction between counter flows along island structure gives rise to the momentum loss and it breaks the relation of eq.(2). The momentum loss factor, which is defined as $n_uT_u = 2n_dT_d(1+f_m)$, is given by

$$f_m = \frac{D_\perp}{\beta c_{sd}}\left(\frac{1}{c_{sd}n_d}\int\frac{n\Delta V_{//}}{\Delta^2}dr\right), \qquad (3)$$

where $D_\perp, \beta, c_s, \Delta V_{//}, \Delta$ are the cross-field transport coefficient, relative pitch of magnetic field inside of islands, sound speed, relative velocity between the counter flows and representative distance between counter flows, respectively. r is radial coordinate. The finite f_m breaks the momentum conservation, and thus the dependence of divertor flux on n_u deviates from eq.(2). The modelling result is also in good agreement with experiments in terms of role over of the divertor flux. It should be noted that the model does not includes the volume recombination process, so that there must be a process that compensates the volume recombination for reducing the divertor flux.

Figure 2 shows the radial profiles of ionization source of hydrogen obtained by the 3D modelling around the role over point for different densities. At the low density case, the peak of the ionization is located at the edge surface layer, where short and long flux tubes coexist together and is surrounding the stochastic region as indicated in the figure. As the density increases, the ionization region starts to shift gradually due to the reduction of ionization cross section at the low T_d, as mentioned above. It then finally enters the stochastic region. This means that the flow acceleration starts upstream of the edge surface layers, and it thus has long path along the flux tubes until the divertor plates. The integration by r in Eq.(3) indicates that the longer path increases momentum loss factor, which then leads to further reduction of divertor recycling flux, as observed in Fig. 1.

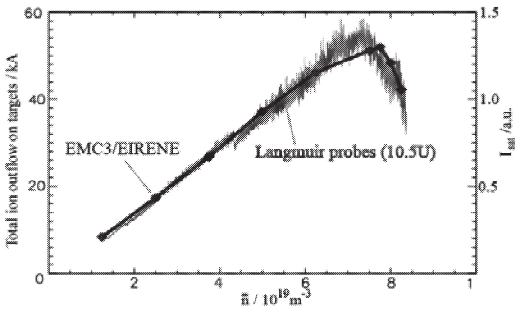

Fig. 1 Evolution of divertor flux as a function of $\bar{n}$ for both experiment and the 3D modelling.

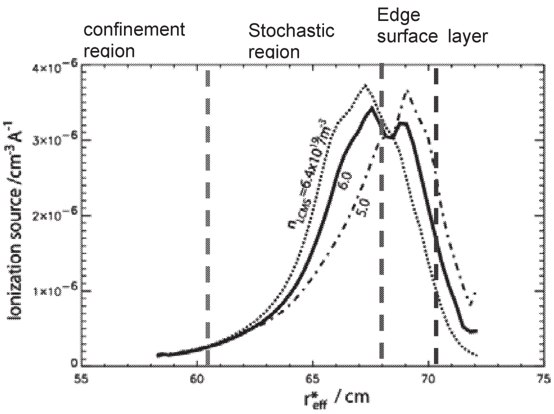

Fig. 2 Radial profiles of ionization source obtained by the 3D codes for different densities around the role over of I_{sat}.

Reference
1) M. Kobayashi, M. et al., J. Nucl. Mater. **363-365**, (2007) 294.