Progress of Superdense Plasma Research in LHD: Sustainment and Transport Study

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Abstract. The superdense core (SDC) plasma with the formation of the internal diffusion barrier (IDB) has been obtained in the Large Helical Device (LHD). Recently the IDB-SDC plasma with central electron density of ~ 2 × 10^{20} m^{-3} could successfully be sustained for more than 3 seconds. The IDB was robustly maintained against the strong perturbation of fuelling pellets. No serious increase in radiation power or impurity accumulation was seen during the discharge. In such a high density regime, a large Shafranov shift takes place which strongly modifies the edge magnetic topology. Therefore it is interesting to investigate the transport properties in the modified edge region which surrounds the SDC plasma. The active experiments with resonant magnetic perturbation (RMP) were performed to further modify the edge magnetic topology. The pump-out effect for particles was clearly observed in the edge region with RMP.

1. Introduction

The high density operation is favourable for the fusion reactors since the fusion reaction rate is proportional to the density squared. In addition, the energy confinement is also expected to improve with density in helical and tokamak devices. In tokamaks, however, the density is limited by the well-known Greenwald density [1]. On the other hand, in net current free helical systems, there is no essential density limit like tokamaks. If anything, it is only limited by the power balance with edge radiation [2]. Thus high density operation research is intensively conducted in helical systems. In 2005, an SDC mode with central electron density of more than ~ 1 × 10^{21} m^{-3} was discovered in LHD with the formation of IDB when a series of pellets was injected into the neutral beam heated plasma under the condition of low edge neutral pressure [3,4]. In order to develop the IDB-SDC mode to the reactor plasma, it is essential to sustain it in the steady-state operation. So far, however, the IDB-SDC plasmas have only been obtained transiently [3,4]. Therefore the most important and urgent issue is to verify if the continuous pellet fuelling is valid or not for the sustainment of SDC in the long pulse discharge. Recently a repetitive pellet injector which can launch a series of 20 barrels has newly been developed and experiments to demonstrate the quasi-steady-state sustainment of the IDB-SDC plasma have started.

For the IDB-SDC discharge to be sustained for a long time, particle transport including recycling process in the edge region plays an important role. In such a high pressure regime, a large Shafranov shift due to the high pressure at the central region modifies the magnetic topology. Especially the edge magnetic structure becomes stochastic, where heat and particle transports are predicted to have different properties from those in the closed flux surface region [5].

In this paper recent progress of superdense plasma research is presented, especially focused on the quasi-steady-state sustainment of the IDB-SDC plasma and particle transport in the edge region. In section 2, experimental setup and short introduction to the IDB-SDC plasma are presented. After describing experimental results of the quasi-steady-state sustainment of the IDB-SDC plasma in section 3, particle transport and its relation to the edge magnetic structure are discussed in section 4. Finally summary and discussions are given in section 5.

2. Experimental setup and IDB-SDC plasma formation

The LHD is the largest superconducting heliotron device, with poloidal/toroidal period numbers of 2/10, major and minor plasma radii of 3.5 – 4.1 m and 0.6 m, respectively, and toroidal magnetic field of 3.0 T [6]. The plasma is produced and heated by neutral beams (NBs) with total power of ~ 18 MW.

The IDB-SDC mode is obtained with a core fuelled condition by the repetitive pellet injection [7]. Each pellet barrel can supply (2 to 3) × 10^{21} m^{-3} atoms of hydrogen. After several pellets are injected to the NB-heated plasma, the density profile takes on a peaked shape. Since NBs are still heating the plasma after the final pellet injection, electron temperature at the central region rises according to the decrease of the electron density. In this way, the IDB-SDC plasma is established. No gas puff is injected during the discharge.

Typical electron density and temperature profiles measured with the Thomson scattering diagnostics are shown in FIG. 1. It can be seen that a core region with electron density ~ 5 × 10^{20} m^{-3} and temperature ~ 0.8 keV are maintained by an IDB. The extremely steep density gradient is formed on the IDB foot which is depicted with thick solid line(s) in FIG. 1, while temperature profile shows a shoulder or pedestal shape. Outside the IDB, the density gradient is relatively moderate, which we call the "mantle" region. As shown in FIG. 1, the IDB-SDC plasma can be obtained both Local Island Divertor (LID) [8] and Helical Divertor (HD) [9] configurations, if only with sufficient pumping capability, which will be discussed again in section 3. Due to the high central pressure, the magnetic axis moves from 3.75 m to 4.05m (Shafranov shift), which causes strong modification to the edge magnetic topology (see section 4). In the IDB-SDC plasma, the typical central pressure and beta value are more than 0.15M Pa and 4.4 %, respectively.

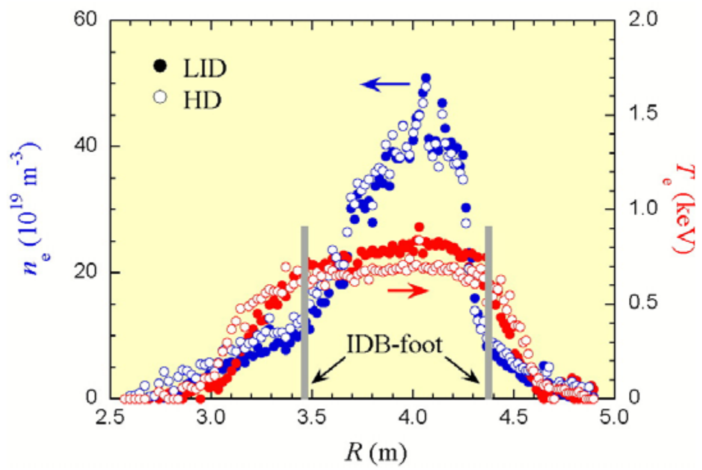

FIG. 1. Density (blue) and temperature (red) profiles of IDB-SDC plasma. Closed and open symbols represent data obtained in Local Island Divertor (LID) and Helical Divertor (HD) configurations.

3. Quasi-steady-state sustainment of IDB-SDC plasma

As described in previous section, the ordinary IDB-SDC mode is achieved in the density decay phase after stopping the pellet injection, therefore it is essentially transient. In order to sustain the IDB-SDC mode, continuous fuelling at the core region is necessary. For the experiment of the IDB-SDC sustainment, a new repetitive pellet injector which can launch a series of 20 barrels is employed.

FIG. 2 shows the time evolution of principal parameters of the discharge. In the initial phase of the discharge from 3.75 s to 3.90 s, four pellets are injected to the plasma every 50 ms to rapidly increase the core density. After stopping the initial injection, the core density $n_e(0)$ begins to decrease, while central electron temperature $T_e(0)$ starts to rise. Then the stored energy W_p comes to its peak value due to the "reheat" effect, and the IDB-SDC plasma is established at this moment. The SDC will decay with the time constant of particle confinement time if no active control is applied. In this discharge, the fifth and following pellets are injected to sustain the SDC, which is controlled by the feedback signal of the line integrated density $n_e l$. It can be seen that $n_e(0)$ and $T_e(0)$ are well controlled, and oscillation of W_p is kept within 20 %. This quasi-steady-state phase lasts for more than 3 s by the repetitive pellet injection of 13 pellets. The discharge is terminated by switching off the NBs, not by the radiation collapse. During the discharge, no serious increase of impurities is observed.

From the n_e and T_e profiles at t = 4.6 s and 7.2 s, as shown in FIG. 3, it is also demonstrated that highly peaked n_e profile with IDB is sustained during the steady-state phase, except for a little increase in the edge n_e outside the IDB at t = 7.2 s. This is considered to be an increase of the edge recycling, due to the insufficient pumping capability compared to the supplied particles with pellets. Consequently edge T_e decreases at the ending of the steady-state phase. The T_e gradient also becomes gentle.

The increase of edge neutrals degrades the SDC performance and finally brings about the radiation collapse [10]. FIG. 4 shows the neutral pressure n_0 dependence of the central plasma pressure $n_{e0}T_{e0}$. It is found that the central pressure decreases with the increase of the neutral pressure.

To avoid such a situation, strong pumping to compensate the massive fuelling by repetitive pellet injection is

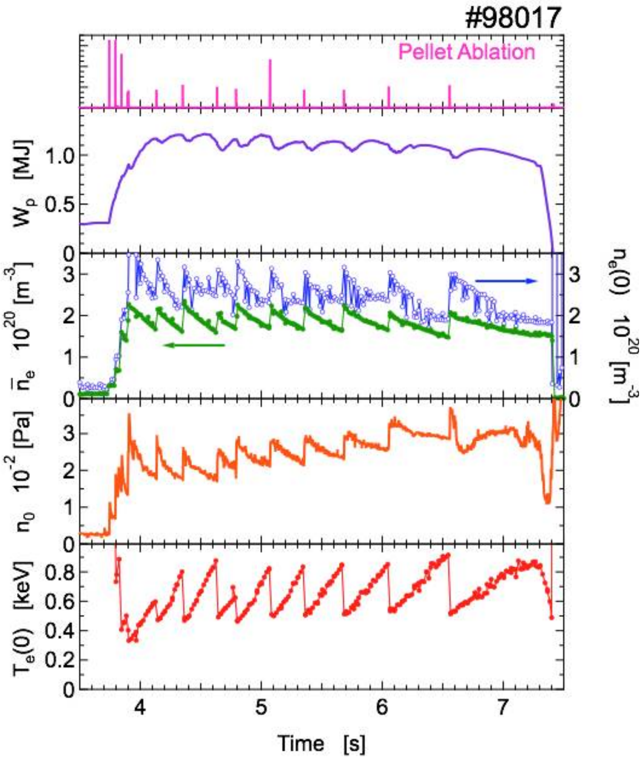

FIG. 2. Time traces of stored energy W_p, line averaged density n_e, central density $n_e(0)$, neutral pressure which is reflected with particle density n_0, and temperature $T_e(0)$, together with injection signal of pellet (top).

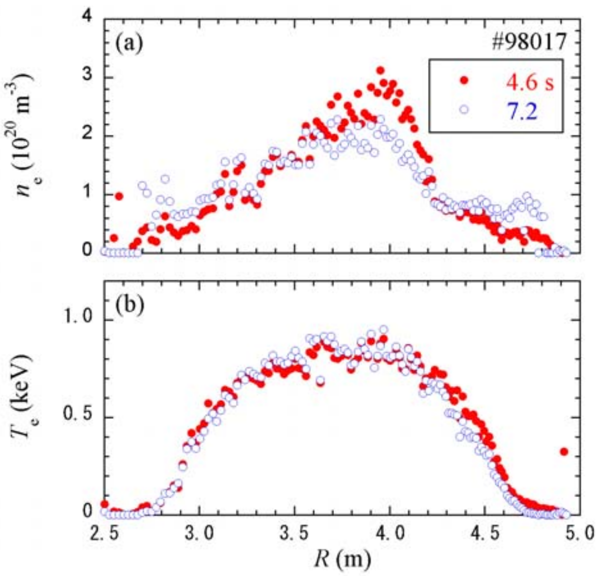

FIG. 3. Density and temperature profiles at beginning (t = 4.6 s) and ending (7.2 s) of quasi-steady-state phase of IDB-SDC discharge.

necessary. For the effective pumping, neutral pressure at the divertor region should be increased over ten times more than the present open helical divertor. To increase the neutral pressure, baffles should be installed near the striking point of the divertor. Construction of the closed helical divertor with the cryogenic pumping system has begun.

4. Particle transport in IDB-SDC plasma

During the IDB-SDC discharge, a large Shafranov shift due to the high pressure at the central region takes place, which modifies the magnetic topology. Especially in the edge region, magnetic structure becomes stochastic, where heat and particle transports are predicted to have different properties from those in the closed flux surface region [5].
In order to see the relation between the magnetic field structure and the transport properties, one-dimensional particle transport analyses are performed, together with numerical analyses of the magnetic field structure. For the one-dimensional particle transport analysis, time evolutions of electron density at different radial positions are employed to provide diffusion coefficients and convective velocities at each radial position, according to the following equations,

$$\boldsymbol{\Gamma} = \frac{1}{r}\int_0^r \boldsymbol{r}\left(\boldsymbol{S} - \frac{\partial n_e}{\partial t}\right)\mathbf{d}\boldsymbol{r} \qquad (1)$$

$$\frac{\boldsymbol{\Gamma}}{\boldsymbol{n_e}} = -\boldsymbol{D}\frac{\partial n_e}{\partial r} + \boldsymbol{v}. \qquad (2)$$

Resonant Magnetic Perturbations (RMPs) are applied to the IDB-SDC plasma to further modify the edge magnetic structure. Ten pairs of small normal conducting loop coils are installed at the top and bottom of the torus for the RMP application, as shown in FIG. 5. With this system, m/n = 1/1 and/or 2/1 RMPs can be applied, where

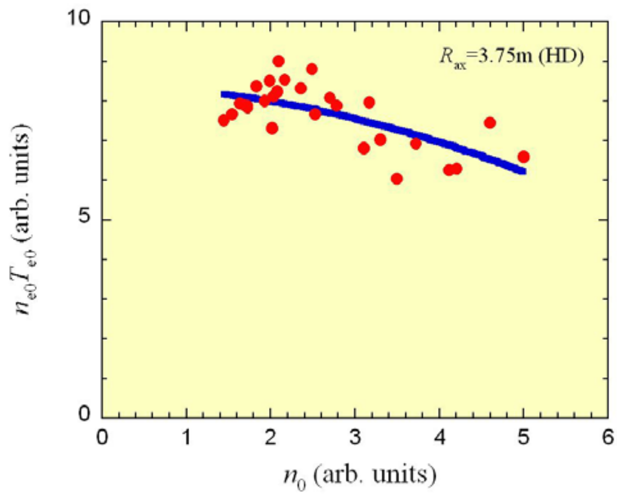

FIG. 4. Dependence of central plasma pressure $n_{e0}T_{e0}$ on neutral pressure n_0.

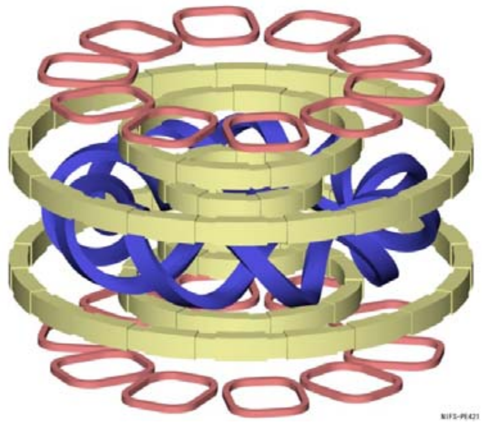

FIG. 5. Ten pairs of Resonant Magnetic Perturbation (RMP) coils (magenta).

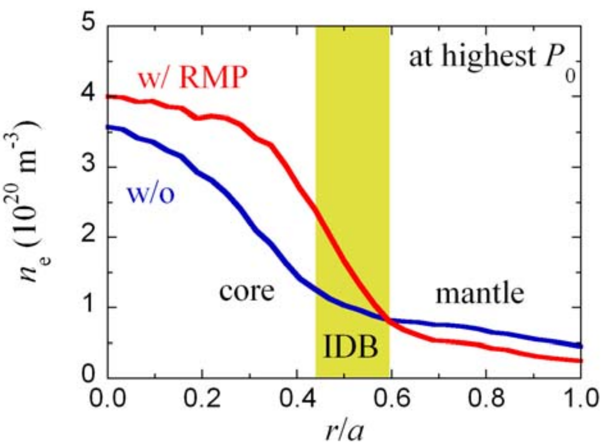

FIG. 6 Radial profiles of n_e with and without RMP.

m and n are poloidal and toroidal mode numbers, respectively.

FIG 6 shows the radial profiles of n_e with and without RMP, where r/a is the normalized minor radius. It can be seen that the steep gradient is formed at IDB in both cases, while outside the IDB (mantle region), gradients are relatively moderate. It is interesting, in the case with RMP, that n_e in the mantle region is reduced. This phenomenon is similar to the density pump-out observed in the tokamak RMP experiments [11-13]. Comparing the particle transport properties between with and without RMP cases, temporal behavior of n_e profiles is analyzed, according to eqs. (1) and (2). In FIG. 7, Γ normalized by n_e is plotted in the function of inversed density scale length, of which gradient indicates the particle diffusion coefficient. It can clearly be seen that the diffusion coefficient in the mantle region is increased by applying RMP, while it is not so affected in the core region. These results suggest that modification of magnetic topology in the mantle region where rotational transform is ~ 1 enhances the particle transport, which results in the density pump-out effect.

To investigate the RMP effect on particle transport in detail, RMPs with different amplitude are applied to the IDB-SDC plasma. Note that the RMP is turned on several seconds before the breakdown. FIG. 8 (a) shows density profiles with various RMPs of different amplitude b/B_t, where b and B_t are RMP and toroidal field strengths, respectively. In this experiment, b/B_t is varied from 0 to 0.12 %. It can be seen in the mantle region that the density pump-out occurs even with relatively small RMP amplitude. Furthermore higher central density is obtained with larger RMP.

The Kolmogorov length L_K is calculated to see how the stochasticity of the magnetic field structure is [14]. The calculation is performed, applying the RMP field analytically to the equilibrium

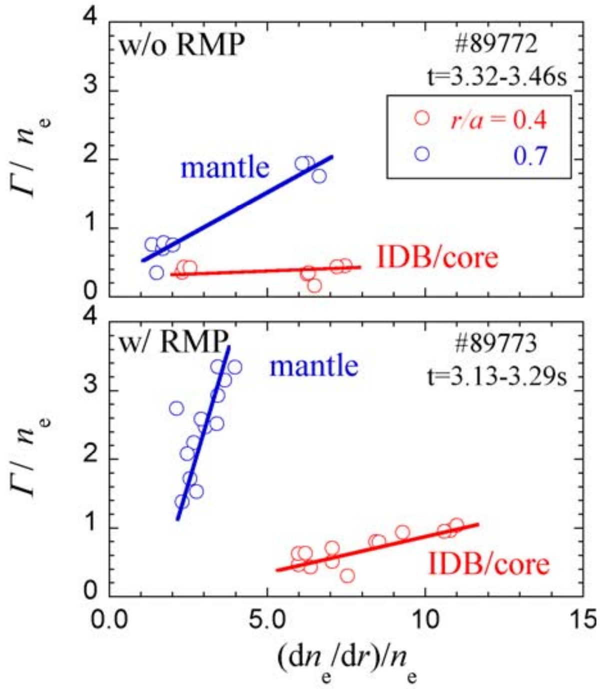

FIG. 7. Density normalized flux vs. density scale length. Gradient indicates diffusion coefficient.

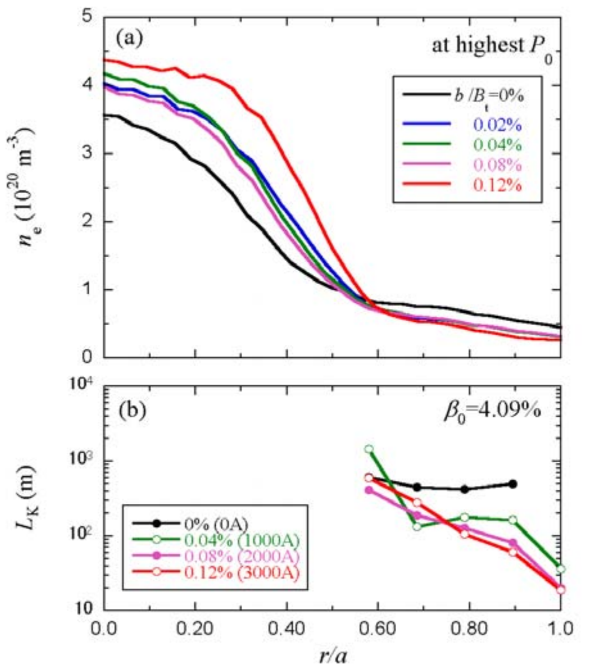

FIG. 8. Density and Kolmogorov length profiles with different RMP amplitudes.

provided by the HINT2 code [15]. FIG. 8 (b) presents L_K profiles in IDB-SDC plasmas with different RMP amplitudes. In the mantle region, L_K without RMP is around several hundred meters which is less than one-tenth of the connection length. This means that the mantle region in the IDB-SDC plasma is stochastic. Once applying RMPs, L_K rapidly decreases down to several tens meters, even if it is 0.04 %. It can be said that the mantle region of the IDB-SDC plasma is very sensitive to the external perturbation. This tendency is consistent with the experimental results mentioned before.

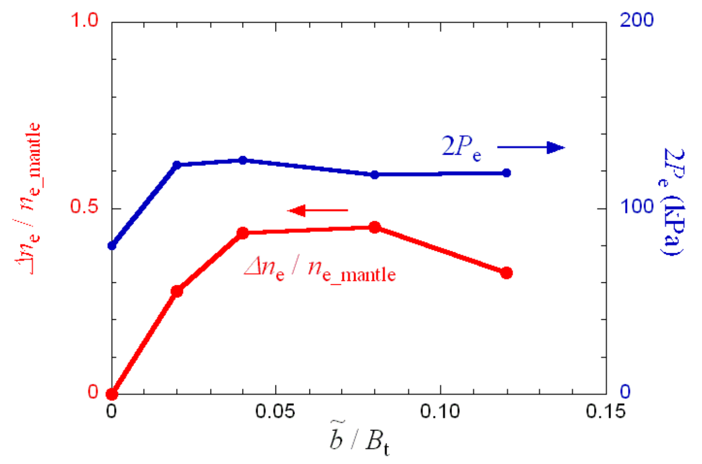

FIG. 9. Decreased mantle density Δn_e by RMP, depending on RMP amplitude b/B_t. Δn_e is normalized by n_{e_mantle} without RMP. Central plasma pressure $2P_e$ dependence on b/B_t is also depicted.

To see the relation between the RMP amplitude and the density pump-out quantitatively, the decrease of the mantle density due to the RMP is investigated. The density at the IDB foot represents the mantle density n_{e_mantle}, which is so-called "mantle height". A decreased mantle density Δn_e is defined as a difference of n_{e_mantle} with RMP from that without RMP. FIG. 9 shows the decreased mantle density Δn_e normalized by n_{e_mantle} without RMP in the function of RMP amplitude b/B_t, together with the central plasma pressure $2P_e$. It is found that the density pump-out occurs even with small RMP, and soon reaches the saturation level. The central plasma pressure also increases with RMP first, however it saturates with relatively small RMP amplitude. The dependence of the density pump-out and magnetic stochasticity on the RMP amplitude is similar, i.e. they are very sensitive to the external perturbation.

The density pump-out is also confirmed experimentally with divertor flux measurements. FIG. 10 shows the time evolution of the divertor flux measured with a Langmuir probe embedded in a divertor plate. Two discharges with (#93949) and without (#93948) RMP are compared. Although operational conditions are same for two shots, densities in the initial phase are slightly different, according to the previous discharges. The shot with RMP has smaller flux at the beginning of the discharge, however it gradually increases. A drastic change is seen after the plasma stored energy meets its peak at $t \sim 2.2$ s. The divertor flux rapidly increases, suggesting the strong density pump-out from the mantle region. There is a possibility that the increased stochastization with RMP enhances the particle transport in the mantle region.

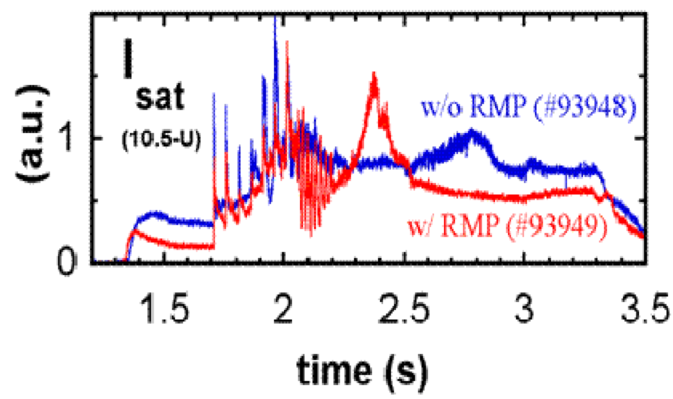

FIG. 10. Time evolution of divertor flux measured with a Langmuir probe embedded in a divertor plate.

Such a strong density pump-out effect sometimes leads the IDB-SDC plasma to the divertor detachment [16]. In FIG.10, indication or dithering of the divertor detachment can be seen from t = 2.05 to 2.23 s. During the dithering phase, the divertor flux is oscillating between high flux and detachment regimes.

5. Summary and discussions

The IDB-SDC plasma could be sustained for more than 3 s by additional pellet injection after the establishment of IDB. This experimental result convinced us that the IDB-SDC mode is not a transient phenomenon but can be sustained if only the core fuelling is available. Although the fluctuation of the stored energy is less than 20 %, the temperature fluctuation is quite large as ~ 45 %. Since the deep fuelling at the plasma center rapidly cools the core plasma, moderate penetration, e.g. to just inside the IDB, may be better for stable discharges. Optimization of the pellet injection is necessary to obtain the higher performance for steady-state IDB-SDC plasma [17]. In addition, it goes without saying that the effective pumping system is necessary to avoid the radiation collapse due to the edge degradation. As for the impurity behavior, no serious accumulation is observed, during the discharge. It is thought that the thick stochastic layer and/or islands surrounding the confinement region play an important role [18-21].

The particle transport in the IDB-SDC plasma was investigated. It was found that the diffusion coefficient in the mantle region is much larger than that in the core region. Furthermore, with RMP, the enhanced particle transport which is called “density pump-out” is observed in the mantle region. Numerical analyses of the magnetic structure indicate that the edge stochasticity is surely increased by RMP. However collisionality in the mantle region is so high that the mean free path of the collision along the magnetic field line is shorter than Kolmogorov length and connection length, except for the far edge region. Therefore it cannot always explain that the density pump-out is caused simply by the radial excursion of magnetic field lines in the stochastic region.

Further investigation is necessary to clarify the mechanism of the density pump-out [18,21], including the edge modeling with numerical calculations.

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