Estimation of Heat and Particle Transport by Means of Transient Phenomena

Tomohiro Morisaki and LHD Experiment Group
National Institute for Fusion Science

1. Background and introduction

Several years ago, the super dense core (SDC) mode with central electron density of more than ~ 1×10^{21} m^{-3} was discovered in LHD with the formation of an internal diffusion barrier (IDB) when a series of pellets was injected into the neutral beam (NB) heated plasma under the condition of low edge neutral pressure [1,2]. Recently, with the thorough wall conditioning in the outward shifted configuration, the SDC plasma with central electron density of ~ 2×10^{20} m^{-3} can successfully be sustained for more than 3 seconds. 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.

In tokamaks, for the ELM suppression or mitigation, the resonant magnetic perturbations (RMPs) are applied to modify the edge region where the ballooning or peeling/ballooning mode is sometimes unstable [3]. Although the modification of the magnetic topology may change the current profile or heat and particle transport in the edge region, clear physical explanations for the mechanism of the ELM suppression or mitigation have not yet been shown. In LHD, RMP is also applied to further modify the edge magnetic topology to investigate the effect of the stochastization on heat and particle transport in detail [4].

From the opposite viewpoint, it is possible to know the magnetic structure from the transport properties if they are well characterized according to the stochasticity or island structure. Thus it is crucially important to clarify the relationship between transport and magnetic topology.

In this study we focused on the edge particle transport during the SDC discharge in LHD, where the edge magnetic structure is strongly ergodized by the large Shafranov shift. The density pulse generated by the pellet injection was utilized for the transport analysis, measuring its propagation from the core to edge region.

2. Experimental results

The SDC mode can be obtained by the repetitive pellet injection and the strong NB heating. Figure 1 shows the time evolution of the stored energy measured with diamagnetic loop and electron density measured with Thomson scattering at different normalized radii of the typical SDC discharge. Eight pellets were injected to get the maximum central electron density of ~ 5×10^{20} m^{-3}. The maximum central electron density n_e and temperature T_e at $t = 3.1$ s in this typical SDC discharge are shown in Fig. 2. It is found that quite high electron density with steep gradient is maintained in the core region, while gradient in the edge

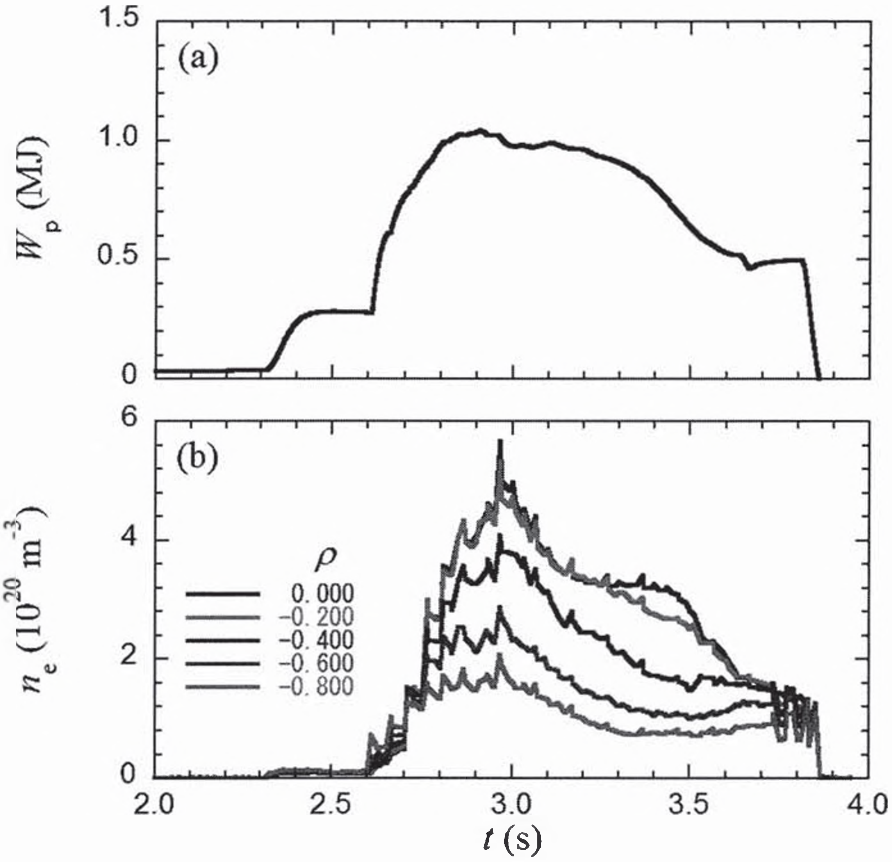

Fig. 1. Time evolution of (a) stored energy measured with diamagnetic loop and (b) electron density measured with Thomson scattering at different normalized radii.

region (mantle) is relatively low. This suggests the formation of the internal transport barrier for particles, namely, IDB. As for the temperature profile, it is almost flat inside the IDB, while it has a steep gradient in the mantle (outside the IDB), which is opposite to the density profile.

The RMPs are also applied to the SDC plasma to further modify the edge magnetic structure in LHD. Ten pairs of small normal conducting loop coils are installed on the top and bottom of the torus to apply the RMPs. With this system, m/n = 1/1 and/or 2/1 RMPs can be applied, where m and n are poloidal and toroidal mode numbers, respectively. It is interesting, in the case with RMP, that n_e in the mantle region is reduced, compared to that without RMP. This phenomenon is similar to the density pump-out observed in tokamak RMP experiments.

In order to see the relationship between the magnetic field structure and the transport properties, one-dimensional particle transport analyses were performed, together with numerical analyses of the magnetic field structure. For the one-dimensional particle transport analysis, time evolutions of electron

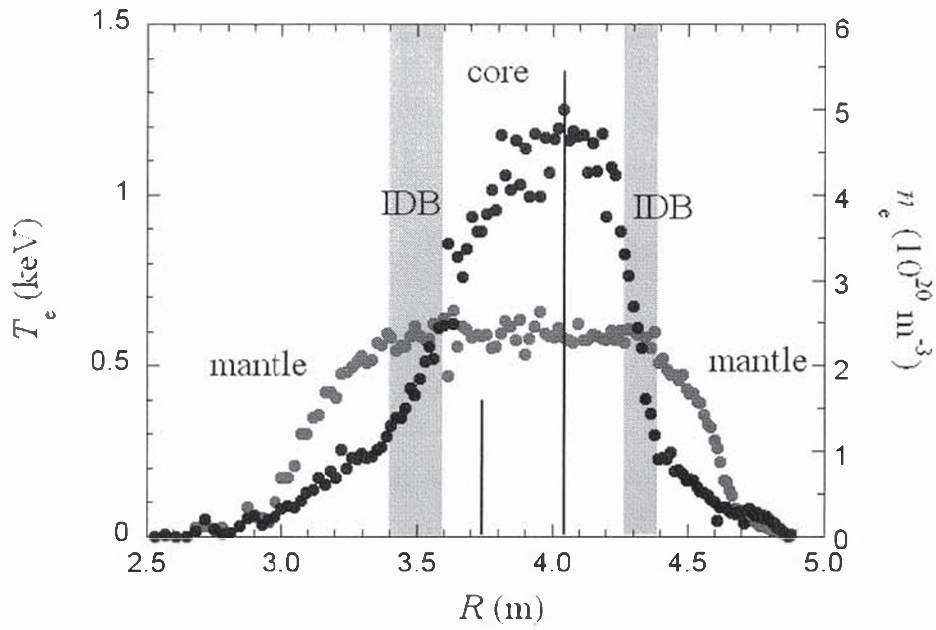

Fig. 2. Typical electron density and temperature profiles in SDC discharge. Original and Shafranov shifted magnetic axis positions are indicated with bars at R = 3.75 m and 4.04 m.

density at different radial positions are analyzed to provide diffusion coefficients and convective velocities at each radial position, according to the following equations,

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

$$\frac{\Gamma}{n_e} = -D\frac{1}{n_e}\frac{\partial n_e}{\partial r} + v. \qquad (2)$$

In Fig. 3, Γ normalized by n_e is plotted as a function of inversed density scale length $(\mathrm{d}n_e / \mathrm{d}r) / n_e$, of which gradient indicates the particle diffusion coefficient D. It can clearly be seen that the diffusion coefficient in the mantle region is higher than that in the core region. Furthermore, D in the mantle region is increased by applying the RMP, while it increases little in the core region. On the other hand, the convection in both region is always small (nearly zero), as shown in Fig. 3, since y-intercepts of Γ/n_e vs. $(\mathrm{d}n_e/\mathrm{d}r)/n_e$ lines indicate the convective term of the particle transport, as is known in Eq. (2). These results suggest that modification of the magnetic topology in the mantle region enhances the particle transport, which finally results in the density pump-out effect.

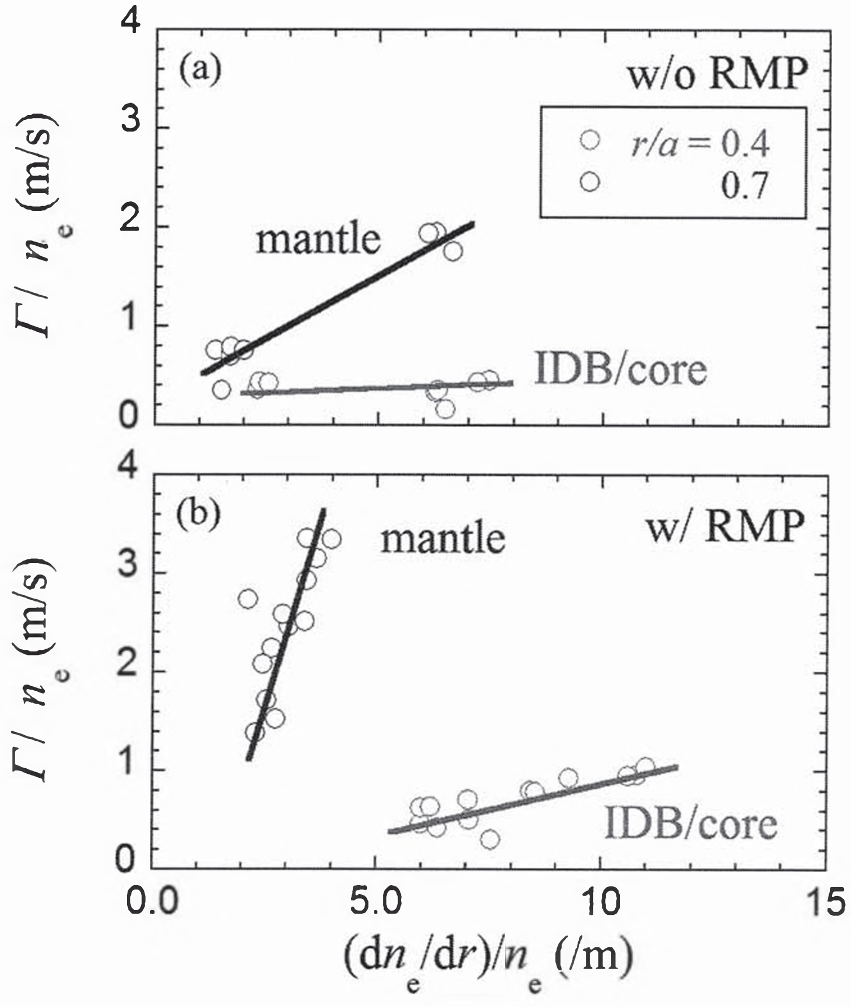

Fig. 3. Density normalized flux vs. density scale length. Gradient indicates diffusion coefficient.

3. Summary and future plan

From the preliminary results obtained in the LHD experiment, it was found that the modification of the magnetic topology affects the particle transport, which could be seen in the changes of diffusion coefficient *D*. In the mantle region, during the SDC discharge, where the magnetic structure is ergodized by the large Shafranov shift due to the high central pressure (beta value), *D* is larger than that in the core region. It was also observed that *D* is further increased by applying the RMP. These results agree well to those expected in the numerical study with the HINT2 code [5].

In this study, *D* and convection *v* were derived from the time evolution of the local electron density n_e, i.e. density pulse propagation. On the other hand, this technique can also be utilized as a diagnostic tool for the magnetic structure, e.g., nested surfaces, islands, or stochastic layers. The magnitude of the modification (stochasticity) may also be measured if precise observation and analysis are available. In this experiment, density pulses were made by the pellet injection. Though it is an easy and reliable technique to introduce the particle source to the core region, disturbance in the plasma along the flight path is relatively large. Thus smaller perturbation in the measurement is required. Recently some new passive methods using MHD activities have been proposed. In the SDC discharge, the core density collapse (CDC) sometimes occurs in the core region, which generates a density pulse propagating from the core to edge region. Thus one can use the CDC pulse as a particle source in the core region. No disturbance is left, introducing the source to the core region. In addition, saw-tooth oscillations destabilized on the inner rational surfaces can also be a candidate for the heat and/or particle source propagating to both directions.

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