Edge Plasma Control by Local Island Divertor in LHD

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Abstract. In the Large Helical Device (LHD) program, one of the key research issues is to enhance helical plasma performance through the edge plasma control. For the first time in the LHD program, the edge plasma control was performed with a local island divertor (LID) that is a closed divertor, utilizing an m/n = 1/1 island generated externally by 20 small perturbation coils, and fundamental LID functions were demonstrated experimentally. It was found that the outward heat and particle fluxes crossing the island separatrix flow along the field lines to the backside of the divertor head, where carbon plates are placed to receive the heat and particle loads. Accordingly high efficient pumping was demonstrated, which is considered to be the key in realizing high temperature divertor operation, resulting in an improvement of energy confinement. In the present experiment, a factor of ~1.2 improvement of the energy confinement time, τ_E, was observed at a magnetic axis position, R_{ax}, of 3.75 m over the International Stellarator Scaling 95. Results of edge modeling are also presented by using the EMC3-EIRENE code.

1. Introduction

The Large Helical Device (LHD) is a superconducting heliotron-type device at the National Institute for Fusion Science at Toki, Japan [1]. One of the key research issues in the LHD

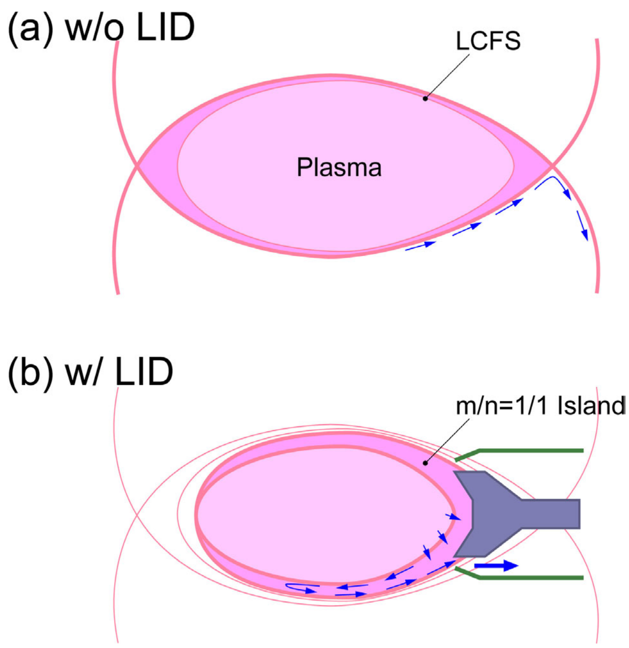

Fig. 1. Plasma cross sections (a) without and (b) with the LID. The intrinsic 1/1 island, due to error field, is eliminated with perturbation coils in (a), where LCFS represents the last closed flux surface. The experiment with the LID is the one, performed when the 1/1 island is formed and the divertor head is inserted, as shown in (b).

program is to control heat and particle fluxes to the wall and to enhance core plasma confinement. This control of the LHD edge plasma will primarily be done with a closed full helical divertor, which utilizes a natural separatrix in the edge region [1], as shown in Fig. 1(a). However, the closed full helical divertor is planed in the late stage of the LHD program. Instead we intended to use a local island divertor (LID) for the LHD edge plasma control [2]. The LID is a closed divertor that uses an m/n = 1/1 island, as shown in Fig. 1(b). The technical ease of hydrogen pumping is the advantage of the LID over the closed full helical divertor because the hydrogen recycling is toroidally localized.

The core region in the LID configuration is surrounded by the separatrix of the island, so that the outward heat and particle fluxes cross the island separatrix, and flow along the field lines to the backside of the island [2]. The particles recycled there are pumped out by a pumping system, designed to be a closed divertor system with overall pumping efficiency of > 30%. Unlike the conventional pump limiters, blades of the divertor head are located inside the island, thereby being protected from the high outward heat flux from the core. Thus there is no leading-edge problem.

High efficient pumping is the key in realizing high temperature divertor operation, where the divertor plasma with a temperature of a few keV is produced, resulting in a significant improvement of energy confinement [3]. A closed divertor also provides high plasma plugging efficiency required for the high recycling operation, where a low temperature and high density divertor plasma is produced for radiative cooling. These two operational modes can be realized in the LID [2]. These divertor functions allow the LID to pump out ionized impurities that are difficult to be pumped out in the presence of the magnetic field.

Results of LID experiments, obtained in the sixth and seventh experimental campaigns in 2002-2004, are described in this paper. The LID experiment has provided us critical information on the edge plasma behavior in the heliotron-type device, and helped us to optimize the design of the closed full helical divertor on LHD. It has also influenced the divertor design of W7-X [4], and helped us to explore advanced divertor concepts.

2. Experimental apparatus

The LID system consists of a divertor head, its driving system, a pumping duct, and an LID chamber and so on, in addition to 20 perturbation coils locating above and below the torus for controlling the islands [5]. The length of the LID head system is so long that the driving system requires the long LID chamber to take out the divertor head from the LHD vacuum vessel and to seal it up with a gate valve whose inner diameter is 1.4 m. These driving system and gate valve are necessary for maintaining the LID head system and performing experiments without the LID.

The size of the divertor head is 0.99 × 0.664 m in the front view, and the area of the divertor head, which receives the particle flux is ~0.3 m^2. The divertor head is divided into 8 elements, which consist of small planar carbon plates joined mechanically to a stainless-steel heat sink with a cooling tube, on the side that the particle flux strikes. The average heat flux onto the carbon plates was designed ~5 MW/m^2 for 3 sec. Another side of the divertor head, facing the core plasma, is covered mainly with the molybdenum plates by mechanical joint to protect the heat sink from high-energy neutral particles produced by charge exchange.

The particles recycled on the carbon plates are pumped out by the pumping system, which has 8 cryogenic pumps with a hydrogen pumping speed of 42,000 l/sec. The effective pumping speed is 1.3×10^5 l/sec at the gate valve located between the LID chamber and LHD vacuum vessel, and large enough to realize a molecular flow. The pumping capacity and maximum pumping flux are 3×10^5 torrl and 75 torrl/sec, respectively. These satisfy the values required for the LID pumping system to control the LHD edge plasma. The gap between the divertor head and pumping duct was usually fixed at 0.1 m in our experiment in order to form a closed divertor configuration with high pumping efficiency.

3. Experimental results and discussion

Before the start of the LID experiment, the magnetic flux surface measurement was performed to assure the formation of the m/n = 1/1 island. It was carried out using the diode technique, which utilizes an electron gun and a probe array. The experimental observations agreed well with the numerical result, and hence, a clear generation of the m/n = 1/1 island was demonstrated.

The effect of the LID on plasma performance was studied mainly using hydrogen puffing NBI discharges at magnetic axis positions, R_{ax}'s, of 3.6 and 3.75 m with the toroidal magnetic field of ~2.75 T. The NBI power, P_{NB}, was 4 - 6 MW. The plasma parameters change significantly with the LID. For example, the line-averaged electron density, $\bar{n}_e$, is reduced typically by a factor of ~2 at the same gas puff rate, compared with discharges without the LID.

The ion saturation currents, I_{is}, were measured with the Langmuir probes located on the carbon plates of the helical divertor and the divertor head of the LID, respectively. The latter carbon plates are, of course, located on the backside of the divertor head, to which the heat and particle fluxes flow along the field lines of the m/n = 1/1 island separatrix. It was clearly shown that the particle flux flowed to the helical divertor and struck upon its carbon plates, when the LID was turned off. No I_{is} signal was, of course, observed on the divertor head of the LID. On the contrary, I_{is} on the divertor head of the LID became large with the LID, while I_{is} on the carbon plate of the helical divertor was reduced to almost zero. This indicates that the LID carries out one of its functions, that is, collects almost all particle flux towards the helical divertor. To estimate the number of particles that strike upon the divertor head, we calculated the percentage P of the magnetic field lines that strike upon the divertor head, among a total of 240 field lines, which circulates around the torus 15 times [2]. The field lines started from the poloidally equally spaced points at distances of 0.04, 0.08 and 0.12 m from the last closed flux surface (LCFS) and toroidally at the same angle as the center of the divertor head. The perpendicular spreading of the starting points took into account the perpendicular diffusion of the particle flux to some extent. This calculation suggested that P reaches 90% when the size of the divertor head is larger than ~0.6 m [2], and this was demonstrated experimentally.

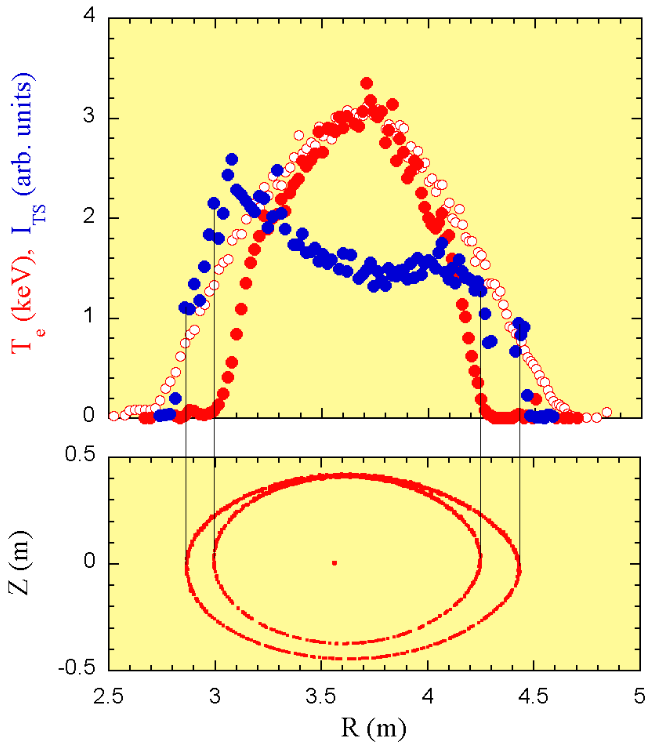

Fig. 2. Radial profiles of T_e with (red closed circles) and without (red open circles) the LID at R_{ax} = 3.6 m. Blue closed circles represent I_{TS} with the LID, which is a measure of n_e and measured with the Thomson scattering. A Poincare plot of the island separatrix at the toroidal position of the Thomson scattering system is also depicted in the lower figure.

Figure 2 shows the radial profiles of electron temperature, T_e, and I_{TS}, which is a measure of electron density, n_e, and measured with the Thomson scattering system. The magnetic axis position, R_{ax}, was 3.6 m. A comparison between two discharges with and without the LID was performed under the condition with almost the same $\bar{n}_e$ of ~1.9 × 10^{19} m^{-3}. It was clearly demonstrated with the LID that the T_e profile is bounded by the inner separatrix of the island, while the low-T_e plasma flows along the outer separatrix of the island. Since the toroidal position of the Thomson scattering system is 72 degrees apart from that of the LID head, the island separatrix can be seen to guide indeed particle fluxes to the LID head. The T_e profile with the LID rises steeply from the inner separatrix of the island, and the central T_e is as high as that without the LID. In the region outside the outer separatrix of the island, the low-temperature and low-density plasma is scraped off, which exists outside the LCFS without the LID, as shown in Fig. 2. Since almost no plasma exists between the outer separatrix of the island and the vacuum vessel, the recycling of particles is localized only near the LID head, located inside the pumping duct. This was confirmed by the H_α emission measurement at the plasma periphery. The neutral particle pressure, p_{vv}, between the plasma and wall was also measured with a fast-ion gauge located on the vacuum vessel. When the LID was turned off, p_{vv} increased monotonically with $\bar{n}_e$. This is because strong gas puffing is necessary for the production of the higher $\bar{n}_e$ under the condition that the heating power is kept constant. Accordingly, p_{vv} increases with $\bar{n}_e$. When the LID was turned on, stronger gas puffing was necessary than that without the LID in order to realize the same $\bar{n}_e$ as without the LID, because the pumping ability of particles is much higher than that without the LID. However, it was clearly shown that p_{vv} was almost constant and kept low, independently of $\bar{n}_e$, being different from the observations without the LID. This indicates that the number of recycled particles is small, and is reasonable because almost all the divertor plasma strikes upon the divertor head, and there is almost no particle flux to the wall and helical divertor, as mentioned before. The connection length of the magnetic field around the island, that is, from near the inner separatrix of the island on the equatorial plane to the divertor head is ~120 m in this case, and will be shortened by increasing the perturbation coil currents further. Thus, the density along the outer separatrix of the island, as shown in Fig.2, will decrease significantly, and hence, the I_{TS} profile will agree with the T_e profile, which exists only inside the inner separatrix of the island.

With the LID, the T_e and n_e profiles at the plasma periphery were realized, being very similar to expected ideal ones, as shown above. However, the energy confinement time, τ_E, measured using diamagnetic loops, was found to follow the ISS95 scaling law at R_{ax} = 3.6 m [6]. It is worse than that without the LID, that is, with the standard LHD magnetic configuration. The energy confinement without the LID is about 1.5 times better than that of the ISS95 scaling law, when R_{ax} is 3.6 m [7]. This reason is not clear at this stage.

When R_{ax} is 3.75 m, the energy confinement with the LID was found to be improved by more than 1.2 times, compared with that of the ISS95 scaling law, although it follows the ISS95 scaling law without the LID. The higher $\bar{n}_e$, and hence, the larger stored energy are realized with the LID at R_{ax} = 3.75 m, compared with those at R_{ax} = 3.6 m. There is a difference between the structures of magnetic configurations at R_{ax} = 3.6 and 3.75 m. The separatrix of the island is located inside the region of the closed nested magnetic surfaces at R_{ax} = 3.6 m, that is, isolated from an ergodic layer of the helical natural separatrix, while it touches the ergodic layer of the helical natural separatrix, and hence ergodized a little at R_{ax} = 3.75 m. In the other words, the island at R_{ax} = 3.75 m is located in the ergodic layer, that is, floating in

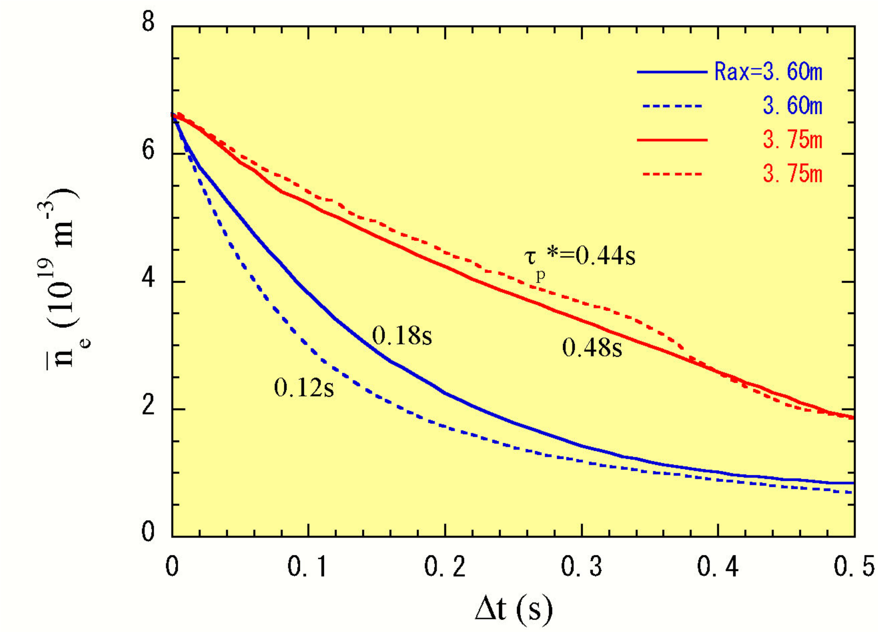

Fig. 3. Temporal evolution of $\bar{n}_e$ after turning off the gas puffing, whose characteristic time provides the effective particle confinement time, τ_p^*. Solid lines represent fuelling is by gas puffing, while broken lines by pellet injection.

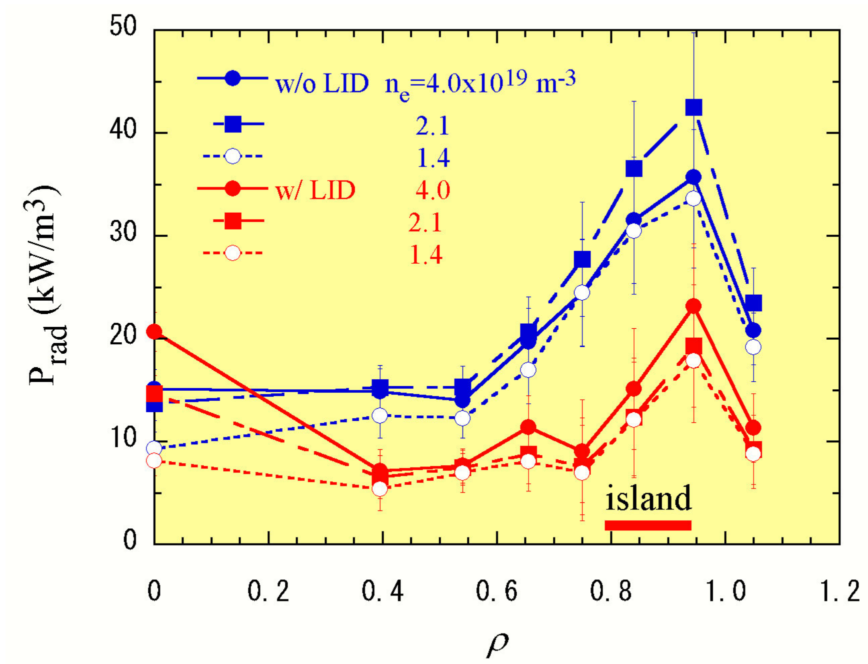

Fig. 4. Radiation profiles with (red lines) and without (blue lines) the LID, as a function of normalized radius ρ at R_{ax} = 3.6 m. With the LID, the island is in the region of $0.8 < \rho < 1.0$.

the "ergodic sea". Thus, some field lines reach the target plates of the natural open helical divertor, instead of striking the LID head, because of their radial excursions due to the ergodic effect. Then, some amount of particle recycling occurs on the target plates of the natural open helical divertor. In fact, a longer density decay time, τ_p^*, suggesting higher particle recycling, was observed at R_{ax} = 3.75 m, as shown in Fig. 3. Little difference between the two fueling methods, that is, pellet injection and gas puff, can be seen, suggesting that the fueling method has nothing to do with the recycling process. From the H_α light emission from the plasma periphery, it can be also confirmed that the edge recycling at R_{ax} = 3.75 m is larger than that at R_{ax} = 3.60 m. These recycled particles contribute to an increase in $\bar{n}_e$. Furthermore, the particle recycling at the LID head is also high at R_{ax} = 3.75 m, since the outer island separatrix hits the leading edge of the LID head a little. The present LID head is originally designed to fit the magnetic configuration at R_{ax} = 3.60 m, since it shows the best performance of the confinement [7].

The too effective pumping of ionized particles by the LID causes not only the low-density plasmas, but also a favourable aspect of preventing impurities from penetrating into the plasma, and this is an important function of the LID. Figure 4 shows radial profiles of radiation, P_{rad}, measured with the bolometer array, and depicted using the normalized radius, ρ, without the LID. Blue and red lines represent the radiation profiles without and with the LID, respectively. A distinct difference between these two kinds of profiles is the radiation power itself, that is, the radiation power with the LID is about 50% lower than that without the LID over the entire plasma except for the plasma center in the relatively high-density operation. The highly radiated region is different in these two kinds of profiles. The radiation power is high in the region of $\rho > 0.65$ without the LID, while it is localized in the island region outside the LCFS, as shown in Fig. 4. In the latter case, the cold plasma located in the island region, as shown in Fig. 2, may play an important role in the radiation process. The radiation power from the central region with the LID increases with $\bar{n}_e$, and exceeds that

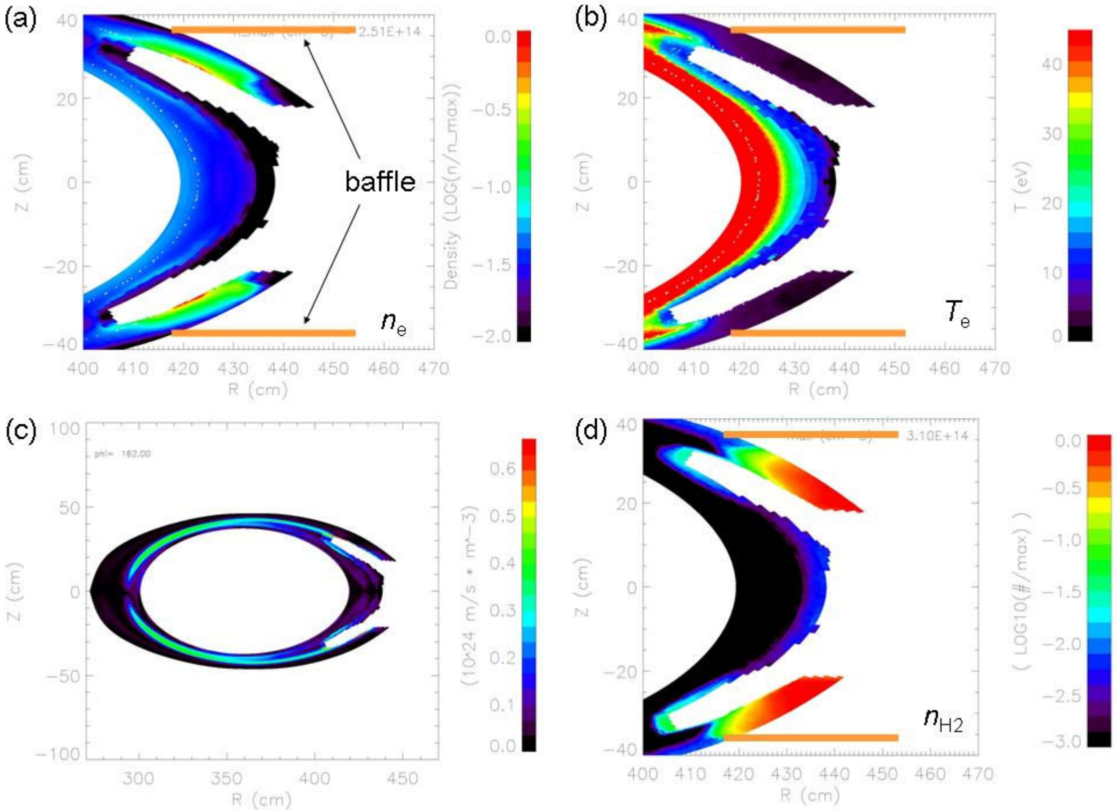

Fig. 5. 2D profiles of (a) n_e, (b) T_e, (c) particle flow, and (d) hydrogen density near the LID head, predicted by the EMC3-EIRENE code.

without LID at $\bar{n}_e$ of ~2 × 10^{19} m^{-3}. The main sources of radiation are metallic impurities, which may be released from the LID head facing the plasma. There is a possibility that this central radiation may degrade the core plasma performance if the impurities accumulate further. In the neon (Ne) gas injection experiment to the hydrogen plasma, it was found that the Ne density with the LID is much lower than that without the LID. Accordingly the LID was demonstrated to be very effective for impurity screening.

The edge transport physics has been analyzed using the 3D fluid edge-transport code, EMC3 [8], coupled with the kinetic neutral transport code, EIRENE. This EMC3-EIRENE code treats almost any three-dimensional geometries of plasma, magnetic field and plasma facing components, and provides 3D profiles of plasma parameters, that is, n_e, T_e, neutrals, and so on. Here, the EMC3-EIRENE code simulated a discharge with relatively low heating power, that is, with P_{NB} of ~1.4 MW. The electron density, n_e, at the inner island separatrix was chosen to be ~1.2 × 10^{19} m^{-3}, taking into account the experimental observations. Some results are shown in Fig. 5; two-dimensional profiles of (a) n_e, described using the logarithmic scale and normalized by the maximum value of 2.5 × 10^{20} m^{-3}, (b) T_e, (c) particle flux, and (d) neutralized hydrogen density, at the toroidal position of the LID head. The cross section of the LID head is outlined against the colored contour map of the above parameters. The pumping duct and the island separatrix are also depicted. It is seen in Figs. 6(a) and 6(c) that the parallel flow is formed along the island separatrix toward the LID head, and that the highest n_e is located at the strike point of the outer separatrix on the LID head, which agrees well with the experimental result. Accordingly, the particles are well demonstrated to be diffused from the confinement region, and to be guided to the LID head along the island separatrix. Figure 6(c) shows a small amount of unfavorable particle flow onto the leading edge and plasma-facing part of the LID head. This unfavorable flow consequently enhances the local recycling, which is seen in Fig. 6(d). However, its amount is simulated to be ~20% of the total particle flux, so that its effect is not so large that the LID scenario is destroyed. A pumping efficiency, ε, was obtained to be 50 – 60 % under the definition of $\varepsilon = \Gamma_{pump} / \Gamma_{head}$, where Γ_{pump} and Γ_{head} are the particle flux pumped out by the LID and the particle flux guided to the LID head, respectively. Particle flux recycled at the LID head is excluded from the definition of Γ_{head}, which accounts for 95 % of whole recycling.

4. Summary

The fundamental functions of the LID were clearly demonstrated. The particle flow is indeed guided to the divertor head along the island separatrix, and a high pumping efficiency is realized. The electron density, n_e, is bounded on the island separatrix as well as the electron temperature, T_e. Accordingly, almost no plasma exists between the outer island separatrix and the wall, and hence, a recycling rate of particles becomes low. This leads to a steep T_e gradient in the periphery, similar to that expected with the LID. The energy confinement with the LID is improved by more than 1.2 times at the magnetic axis position of 3.75 m, compared with that of the ISS95 scaling law. The simulation using the EMC3-EIRENE code provides the reasonable results, explaining the experimental observations.

The first step was taken towards the enhancement of helical plasma performance with the LID. For remarkable improvement of plasma confinement, the plasma density should be controlled by central fuelling or by changing recycling rate. By checking the results obtained by the simulation using the EMC3-EIRENE code, further experimental verification is also necessarily expected.

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