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Edge plasma control with a local island divertor

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Abstract

A divertor head of local island divertor (LID) that utilizes an $m/n = 1/1$ island was installed on the large helical device (LHD) after the fifth experimental campaign in 2001–2002. Up to the fifth campaign, the effect of the LID magnetic configuration on plasma performance was studied without the divertor head. It was found that the island itself deteriorates plasma parameters such as electron temperature, stored energy, etc., and that the ergodic layer around the natural helical separatrix plays a role on preventing impurities from penetrating into the core plasma.

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Keywords: LHD; Local island divertor; Ergodic layer; Improved plasma confinement

1. Introduction

In the local island divertor (LID) configuration, the outward heat and particle fluxes crossing the island separatrix flow along the field lines to the backside of the island, where divertor plates are placed on a divertor head to receive the heat and particle loads [1]. The particles recycled on the divertor plates are pumped out by a pumping system. The geometrical shapes of the divertor head and pumping duct were designed to form a closed divertor configuration with high pumping efficiency of over 30% [2]. Unlike conventional pump limiters, leading edges of the divertor head are located well inside the island, thereby being protected from the outward heat flux from the core. Highly efficient pumping of over 30%, combined with core fueling by pellet injection, is the key to realizing the high-temperature divertor operation, where a temperature of a few keV is achieved. The enhancement factor of the energy confinement time is expected to be two over the present scaling.

Since the 1/1 island is formed at the $\iota/2\pi = 1$ surface position inside the natural helical separatrix, the volume of the core plasma is reduced in the LID configuration. Accordingly, plasma parameters are expected to deteriorate, compared with those in the standard large helical device (LHD) configuration [3,4], unless plasma performance is enhanced in the LID configuration [5]. One of the most important functions of the ergodic layer, which is located around the natural helical separatrix, is a shielding effect on neutral particles, defined by the following. Since the ergodic layer connects with the wall or the carbon plates for the natural helical separatrix, the particles ionized in the ergodic layer flow along the field lines to the wall, and hence, both ionized fueling particles and impurities cannot penetrate into the core plasma. Thus the plasma density in the core plasma and, especially, in the edge plasma should be reduced with the thickness of ergodic layer. This is also true for all impurities such as iron, oxygen, and nitrogen. This function is coherent with the highly efficient pumping and core fueling, mentioned above, because the removal of ionized particles by the ergodic layer promotes the efficient pumping, and the reduction, especially, of the

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density in the edge plasma causes a deep penetration of the pellet into the core plasma. The thickness of the ergodic layer is an increasing function of a resonant perturbation field, and changes in the experiments from ~14 cm to ~20 cm at the maximum near the X-point, located inside the torus at the midplane of the horizontally elongated cross-section. On the contrary, there is a possibility that the particles ionized near the wall flow into the core plasma through the ergodic layer. The amount of these particles is very small, compared with the outward particles, because the volume of the ergodic layer surrounding the core plasma is much larger than that connecting the wall and the ergodic layer surrounding the core plasma. However, the amount of the inward particles is expected to become large, if the ergodic layer surrounding the core plasma touches the wall directly.

In this paper we intend to describe the LID head system installed on LHD and such experimental results relevant to the functions of the ergodic layer involved in the LID configuration.

2. LID head system

The LID head system consists of a divertor head, its driving system, a pumping duct, and an LID chamber, as shown in Fig. 1 [2]. The length of the LID head system is so long that the driving system requires the long LID chamber to take out the head from the LHD vacuum vessel and to seal up it with a gate valve whose inner diameter is 1400 mm. These driving system and gate valve are necessary for maintaining the LID head system and performing experiments without the LID.

The size of the head is 990×664 mm in the front view, and the area of the head, which receives the particle flux, is ~0.3 m^2. The head is divided into eight elements, which consist of small planar carbon tiles joined mechanically to a stainless-steel heat sink with a cooling tube, on the side that the particle flux strikes. Here, angles between the carbon tiles and particle orbits were designed to be less than 10° [2]. The average heat flux onto the carbon tiles was designed ~5 MW/m^2 for 3 s. Ideally the planar plates should be three-dimensional curved tiles that match the magnetic surface. Another side of the head, facing the core plasma, is covered 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 tiles are pumped out by the pumping system, which has eight cryogenic pumps with a hydrogen pumping speed of 42,000 l/s. The effective pumping speed is 1.3×10^5 l/s 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 Torr l and 75 Torr l/s, respectively. These satisfy the values required for the LID pumping system to control the LHD edge plasma [2].

3. Experimental results and discussion

The flux mapping carried out at a radial magnetic axis position, R_{ax}, of 3.6 m and the toroidal magnetic field, B_t, of 2.75 T showed that there are an $m/n = 1/1$ island with a maximum width of ~8 cm and 2/1 islands with a maximum width of ~5 cm. Both 1/1 and 2/1 islands can be, however, almost simultaneously eliminated by a perturbation coil system of the LID.

The effect of the islands on plasma performance was studied using hydrogen puffing NBI discharges at $R_{ax} = 3.6$ m and $B_t = 2.75$ T with the NBI power of ~4 MW. The electron temperature, T_e, profiles, which were

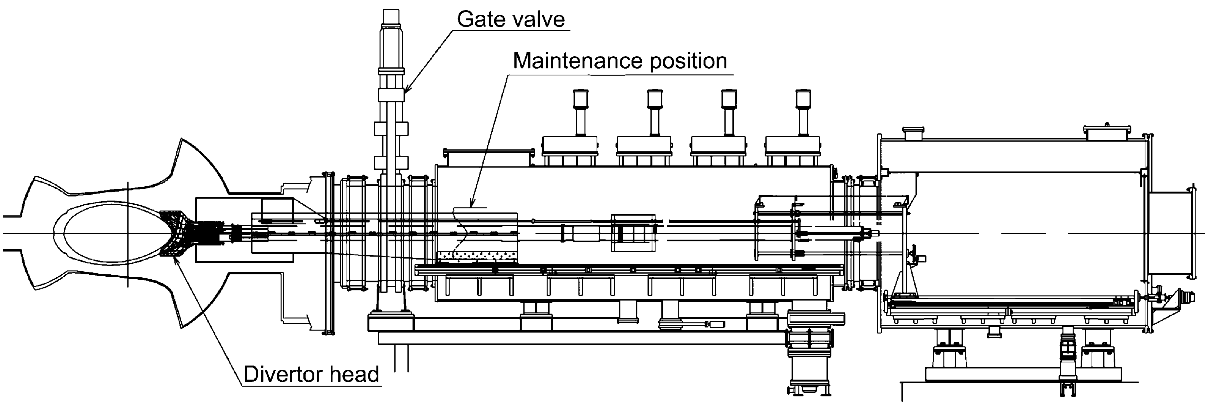

Fig. 1. The LID head system installed on LHD. The system consists of a divertor head, a driving system, a pumping duct, a pump system, and an LID chamber. The LID head system is ~13 m in length, and this length is necessary to take out it from the vacuum chamber for maintenance and for performing experiments without the LID.

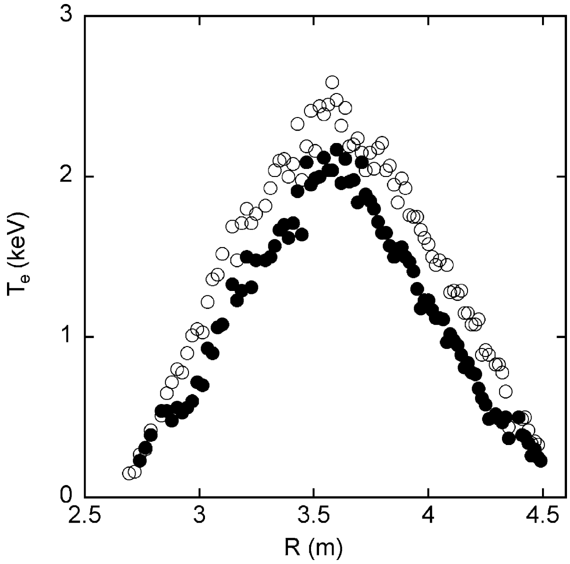

Fig. 2. Radial T_e profiles in the configurations without (a) intrinsic islands (open circles) and with (b) enlarged islands (closed circles). The current I_{LID}'s are −380 and 844 A in (a) and (b), respectively.

measured along the major radius, R, by the Thomson scattering at $t = 2$ s, are shown in Fig. 2. Here, I_{LID} is a current of the perturbation coil system. The current of 1760 A is required at this B_t for generating the standard 1/1 island of ~15 cm width when the intrinsic islands do not exist, while I_{LID} of −400 A is for eliminating the intrinsic islands. In Fig. 2, the existence of the 1/1 island is clearly recognized when $I_{LID} = 844$ A, at the $\iota/2\pi = 1$ surface positions of $R \sim 2.92$ and 4.33 m, forming the flat profiles around there. However, the island is not found in the configuration with $I_{LID} = -380$ A, since there is no flat part around the $\iota/2\pi = 1$ surface positions in the T_e profile. The island size thus measured using the T_e profile is different from that of the vacuum magnetic configuration, depending on the plasma [6]. Since the T_e gradients at the outer and inner edges of the 1/1 island are almost the same and the T_e profiles inside the 1/1 island seem parabolic shapes, T_e in the plasma center becomes higher in the configuration without the island than that with the enlarged island. The electron-density profile is almost flat inside the last closed flux surface, so that there is no difference between the density profiles with and without the 1/1 island. The averaged electron density, n_e, measured by a FIR interferometer, was, however, found to decrease with an increase in the thickness of the ergodic layer, as shown in Fig. 3. The reduced amount of n_e with an increase in the thickness of the ergodic layer also depends on the plasma [7]. Thus, the stored energy, W_p, decreases with the ergodic layer width. These changes in the plasma parameters are essentially attributed to the change in the core plasma

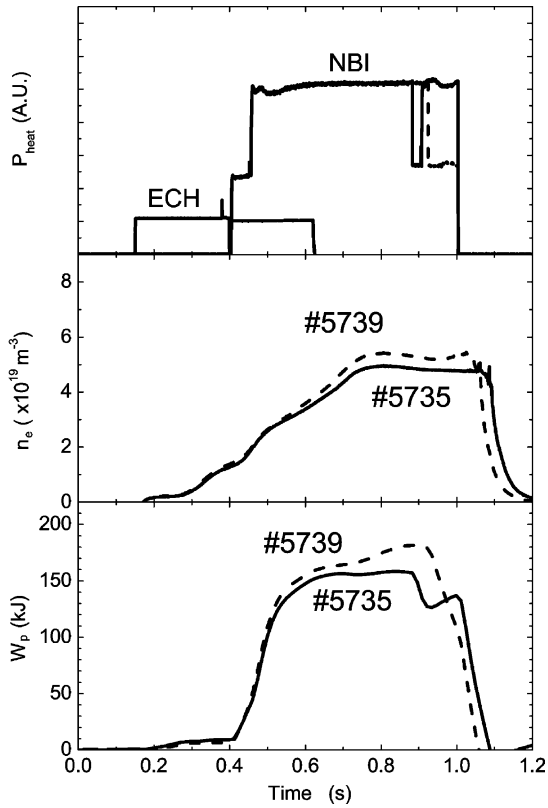

Fig. 3. Temporal evolutions of n_e and W_p at $R_{ax} = 3.75$ m and $B_t = 1.5$ T. Broken lines are obtaind with $I_{LID} = 0$ A, while solid lines with $I_{LID} = 940$ A. The NBI power is ~2.7 MW.

volume and the shielding effect of the ergodic layer on neutral particles.

A large difference was observed between W_p's in the two discharges in the configurations with and without the intrinsic 1/1 island, which cannot be explained by the change in the core plasma volume, as shown in Fig. 4. The maximum W_p jumps from closed circles to open circles in Fig. 4 when the intrinsic island is eliminated keeping other experimental conditions constant. The increment of W_p amounted to ~25%. This phenomenon was observed in the high-density NBI plasmas produced by pellet injection. A large difference was also observed between n_e's in these two discharges, and this causes directly the difference in W_p, as predicted by the International Stellarator Scaling 95 (ISS95) [8]. In other words, the limitation of W_p in the configuration with the intrinsic island is not caused by the deterioration of confinement, but by the density limit arising from the existence of the intrinsic island. The effect of elimination of the intrinsic island is recognized as the extension of preferable confinement in the higher density regime. The reason why this happens is not clear at this stage, but the pellet ablation was found mainly in the ergodic layer in

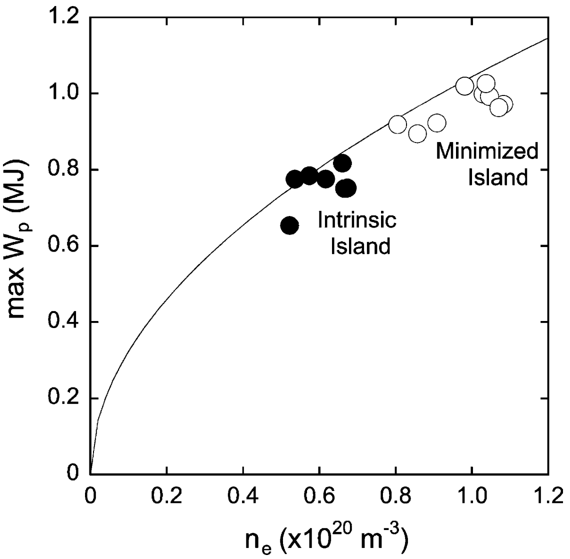

Fig. 4. Relations of n_e versus W_p in the configurations with and without the intrinsic $m/n = 1/1$ island.

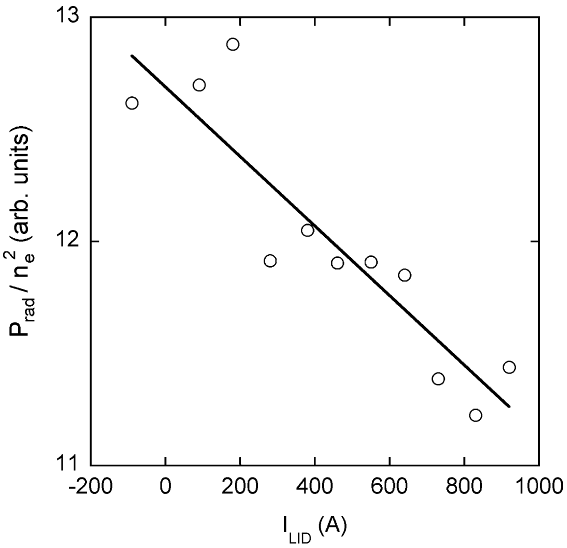

Fig. 5. Dependence of radiation power P_{rad} measured by a bolometer and normalized by n_e^2 on I_{LID}. The intrinsic 1/1 island is eliminated at $I_{LID} = -400$ A.

the configuration with the intrinsic island. Then a large amount of plasma flows to the wall quickly, leading to a decrease in n_e, and hence, a decrease in W_p. It is also expected that the high-density plasma produced by the ablation of the pellet at the outer edge of the island flows along the field lines of the 1/1 island to the inner edge of the 1/1 island before the pellet reaches, although the pellet goes across the island. The speed of pellet is much slower than that of the ionized particles. Thus this high-density plasma promotes the ablation of the pellet at the inner edge of the island in the ergodic layer, preventing the pellet from penetrating into the core plasma, and hence, decreasing n_e in the core plasma, although the dependence of the ablation on n_e is weaker than that on T_e.

Fig. 5 shows the radiation power emitted from the plasma, P_{rad}, measured by a bolometer and normalized by n_e^2, as a function of I_{LID}. This indicates the variation of the shielding effect of the ergodic layer on impurities, and it is clearly shown that the normalized P_{rad} decreases with an increase in I_{LID}, that is, the thickness of the ergodic layer. This demonstrates that the ergodic layer prevents impurities from penetrating into the core plasma as well as the fueling particles are prevented resulting in the decrease in n_e. Typically, this was demonstrated in the long-pulse discharges, as shown in Fig. 6. Fig. 6 shows emissivity-profile evolutions, measured in the hydrogen puffing NBI discharges, whose duration is over 35 s with the NBI power of ~0.8 MW. In Fig. 6(a), the intense-radiation area is located at $\rho \sim 0.8$ in the early stage of the discharge. Then it is moved to the plasma center. In Fig. 6(b), the ramp-up I_{LID} of 0–1800 A is imposed from 10 to 28 s, and then I_{LID} is kept constant. Thus the intrinsic 1/1 island is enlarged from

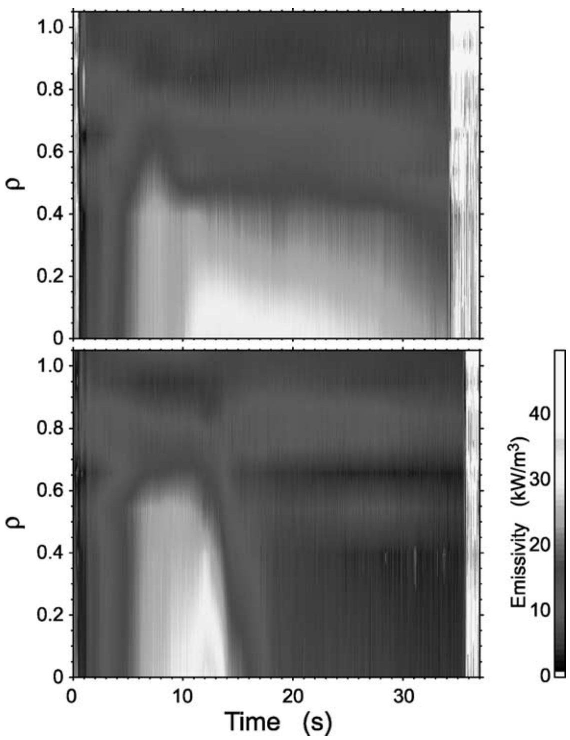

Fig. 6. Emissivity-profile evolutions in long-pulse discharges in the configurations with (a) intrinsic islands and (b) ramp-up I_{LID} of 0–1800 A imposed from 10 to 18 s.

$t = 10$ s. Apparently, the intense-radiation area shrinks with an increase in the island width from $t \sim 12$ s, and disappears from the plasma center before $t \sim 18$ s. There remains the intense-radiation area at $\rho \sim 0.8$. Accordingly, T_e in the plasma center increases by ~200 eV. This demonstrates clearly the shielding effect of the ergodic layer on impurities, which works better when the ergodic layer is thick and over ~15.5 cm wide near the X-point, located inside the torus at the midplane of the horizontally elongated cross-section.

The ergodic layer surrounding the core plasma can touch the wall directly, when the parameters fixing the helical configuration are varied. Its contact is confirmed by spectroscopic measurement, that is, the appearance of an abrupt increase in iron atom [7]. In this condition, n_e increases with the thickness of the ergodic layer if it is thick to some extend, indicting a large amount of the inward particles. The collapse of the discharge occurs when the ergodic layer is thick enough for impurities to penetrate deep into the core plasma.

4. Summary

The decrease in n_e and the prevention of impurity penetration into the core plasma were attributed experimentally to the existence of the ergodic layer in the LID configuration, where neutral particles are ionized and flow along the field lines to the wall. These are fundamental functions of the LID configuration. By using the divertor head, the reduction of n_e will be enhanced remarkably. Thus, combined with core fueling, the LID has the feasibility of realizing a low recycling operational mode, in other words, high-temperature edge plasmas, which could lead to a significant energy confinement improvement in LHD. The enhancement factor is expected to be two.

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