ORNL/CP-95578

IAEA-CN-64/C1-2

CONF-9710100--

EDGE PLASMA CONTROL BY A LOCAL ISLAND DIVERTOR IN THE COMPACT HELICAL SYSTEM

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Abstract

EDGE PLASMA CONTROL BY A LOCAL ISLAND DIVERTOR IN THE COMPACT HELICAL SYSTEM.

A local island divertor (LID) experiment was performed on the Compact Helical System (CHS) to demonstrate the principle of the LID. It was clearly demonstrated that the particle flow is controlled by adding a resonant perturbation field to the CHS magnetic configuration, and is guided to the back of an $m/n = 1/1$ island which is created by the perturbation field. The particles recycled there were pumped out with a pumping rate in the range from a few per cent to about 10%. As a result, the line averaged core density was reduced by a factor of about 2 in comparison with non-LID discharges at the same gas puffing rate. In addition to the demonstration of these fundamental divertor functions, a modest improvement of energy confinement was observed, which could be attributed to the edge plasma control by the LID.

1. INTRODUCTION

The Large Helical Device (LHD) is a superconducting heliotron type device under construction at the National Institute for Fusion Science at Toki, Japan [1]. One of the key research issues in the LHD programme is to enhance helical plasma performance through edge plasma control. The edge plasma behaviour is important in determining heat and particle fluxes to the wall and enhancing core plasma confinement. This control of the LHD edge plasma will primarily be done with a closed

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full helical divertor which utilizes a natural separatrix in the edge region [2]. However, the closed full helical divertor will not be ready in the early stage of the LHD experiment. Instead we plan to use a local island divertor (LID) for the LHD edge plasma control [3]. The LID is a closed divertor that uses an m/n = 1/1 island. The advantage of the LID over the closed full helical divertor is the technical ease of hydrogen pumping because the hydrogen recycling is toroidally localized. The experimental study to demonstrate the principle of the LID was done in detail on the Compact Helical System (CHS) in Nagoya, Japan. The results obtained are described in this paper. The LID experiment on CHS has provided critical information on the edge plasma behaviour in the heliotron type device, and helped us to optimize the design of the LID and the closed full helical divertor on LHD. It has also influenced the divertor design of W7-AS [4] and W7-X [4, 5], and helped us to explore advanced divertor concepts.

2. EXPERIMENTAL APPARATUS

For the CHS experiment, a resonant perturbation field $\tilde{b}$ necessary for an m/n = 1/1 island was generated by 16 small perturbation coils located above and below the CHS vacuum vessel. The outward heat and particle fluxes crossing the the island separatrix flow along the field lines to the back of the island, where carbon (or stainless steel) target plates of 10 mm (2 mm) thickness are placed on a divertor head, as shown in Fig. 1(a) [3]. Figure 1(b) shows the relation between the divertor head and the island separatrix. The particles recycled there are pumped out by a cryogenic pump with a hydrogen pumping speed of 21 000 L/s. The divertor head consists of 18 small planar plates, although ideally they should be three dimensional curved tiles which match the magnetic surface. The geometric shapes of the divertor head and the pumping duct are designed to form a closed divertor configuration with high pumping efficiency [3]. The gap between the divertor head and the pumping duct was fixed at 4 cm in our experiment. For the standard LID configuration, the leading edges of the divertor head, i.e. those of the target plates, are located well inside the island, thereby being protected from the outward heat flux from the core [3].

The CHS device was operated with a toroidal magnetic field B_0 of 0.9 T and a magnetic axis position R_{ax} of 99.5 cm [6]. The $\iota/2\pi = 1$ flux surface is well inside the vacuum vessel wall when $R_{ax} > 97.4$ cm. The plasma was produced by ion Bernstein wave (IBW) and/or second harmonic electron cyclotron heating and was heated by 0.82 MW tangential neutral beam injection (NBI) at 38 keV. The following instruments were used as the key diagnostic systems of this experiment: an IR TV camera for surface temperature measurements, a CCD TV camera with an optical filter for H_α measurements, Langmuir probes for edge plasma measurements and an ASDEX style fast ion gauge system [7] for measurements of the neutral hydrogen pressure in the pumping duct.

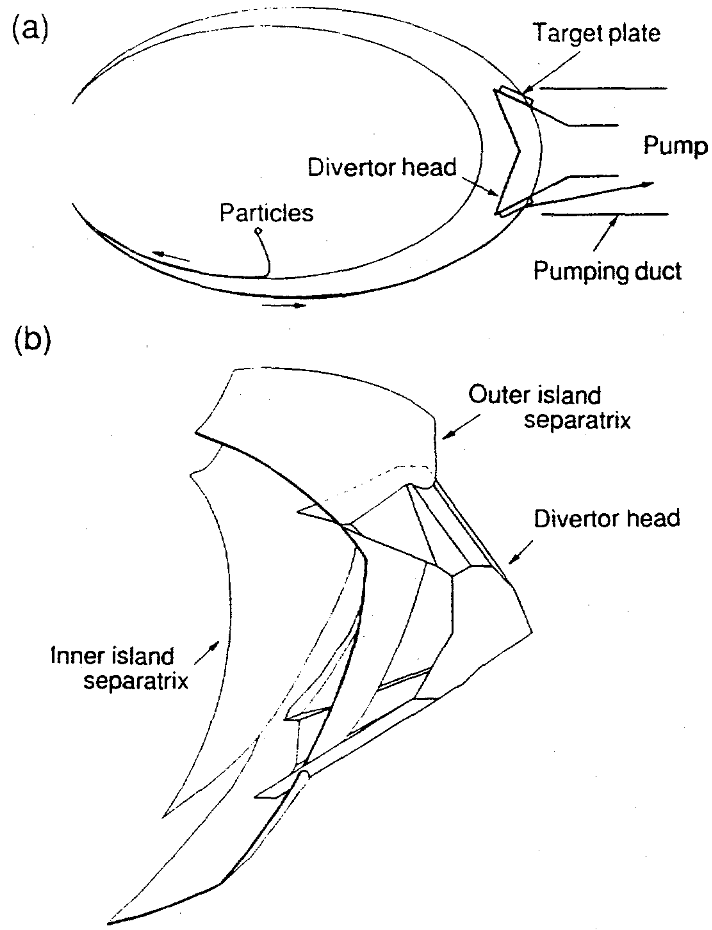

FIG. 1. LID concept. (a) LID configuration and particle flow to target plates; (b) relation between divertor head and island separatrix.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The m/n = 1/1 island geometryof the LID was confirmed by mapping the magnetic surfaces. The mapping was carried out by the fluorescent method, using an electron gun with a W filament and a fluorescent mesh which emits light if the electron beam collides with it. The arrangement of the mapping apparatus is shown in Fig. 2. The fluorescent mesh is situated at the same toroidal position as the divertor head. The magnetic surfaces were measured by taking pictures of the beam positions on the fluorescent mesh while changing the radial position of the electron gun. The mapping was performed in a steady state operation at low field (B_0 = 0.0875 T) and a clear picture of the m/n = 1/1 island was obtained [8]. The island is located at the radial position that is predicted theoretically. However, the width of the island is a little greater than the expected value, and the island is not symmetrical with respect to the equatorial plane. This is because a 'natural' m/n = 1/1 island exists even without $\tilde{b}$. The natural island remains even at the operating field B_0 = 0.9 T, and

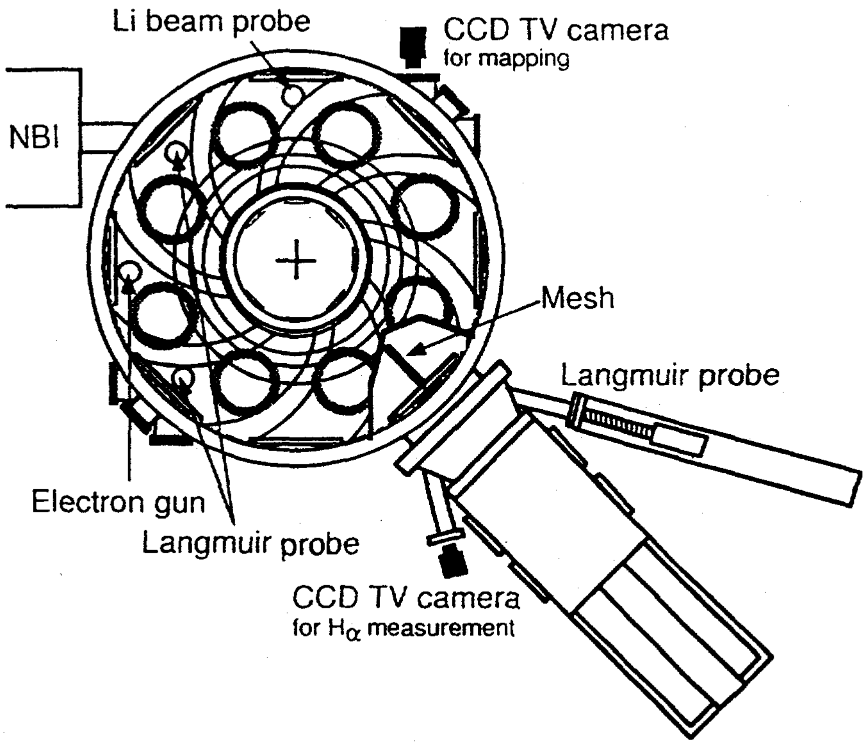

FIG. 2. Experimental apparatus.

this will be discussed elsewhere in detail. The poloidal phase of the natural island happens to be almost the same as that of the externally generated island. Thus the obtained configuration can be used for the LID experiment, although the divertor head was designed for the ideal island configuration without error fields. It was shown that there is an inherently high flexibility of the island configuration. By varying $\iota/2\pi$, the vertical field or the perturbation coil current I_{pert}, both island size and position can be modified. In our experiment, however, we mainly used the standard island configuration, whose external condition was utilized for the design of the divertor head.

We found that the plasma parameters change significantly when the island is formed. The line averaged electron density $\bar{n}_e$ and the OV radiation intensity decrease significantly with $\tilde{b}$ on, as shown in Figs 3(a) and (b), where a comparison between discharges with $\tilde{b}$ on and off is made at a fixed level of gas puffing. Figure 3 depicts temporal evolutions of n_e, the OV radiation intensity and the stored energy W_{dia} with and without $\tilde{b}$. The stored energy W_{dia}, measured by a diamagnetic loop, also decreases with $\tilde{b}$ on, but its reduction rate is much smaller than that of n_e because T_e increases, as shown in Fig. 4(a). Figure 4(a) depicts the radial T_e profiles with and without $\tilde{b}$ after the gas puffing, observed by a YAG Thomson scattering system. On the basis of these data, the temporal evolution of the energy confinement time τ_E is estimated. Figure 4(b) depicts the energy confinement time τ_E normalized by that of the LHD scaling law, $\tau_{LHD} = 0.17a^{2.0}R_m^{0.75}B_0^{0.84}n_e^{0.69}P_{tot}^{-0.58}$, where a, R_m and P_{tot} are the averaged plasma radius, the major radius and the total absorbed power. We found that τ_E/τ_{LHD} with $\tilde{b}$ is greater than unity and that without $\tilde{b}$ mostly less than unity, especially after the gas puffing. There is a little uncertainty in estimating P_{tot} with $\tilde{b}$ on because of lower n_e. To avoid this uncertainty, we compared W_{dia} with and without $\tilde{b}$ at a fixed level of n_e. We found that W_{dia} in the discharge with $\tilde{b}$ is about 20% higher than that without $\tilde{b}$. These experimental results confirm that the energy confinement is improved with $\tilde{b}$ on.

An IR TV camera was used to measure the temperature profile of the target surface, and it was found that the position of the maximum temperature rise changes as the position of the divertor head is changed. The position of the maximum temperature rise is situated about 1 cm away from the leading edges when these are well inside the island. This indicates that the outward heat flux from the core is guided to the back of the divertor head along the island separatrix. Thus there will be no leading edge problem in the LID configuration even if the input power is increased significantly. The maximum temperature rise on the target plates during the discharge was observed to be about 5°C.

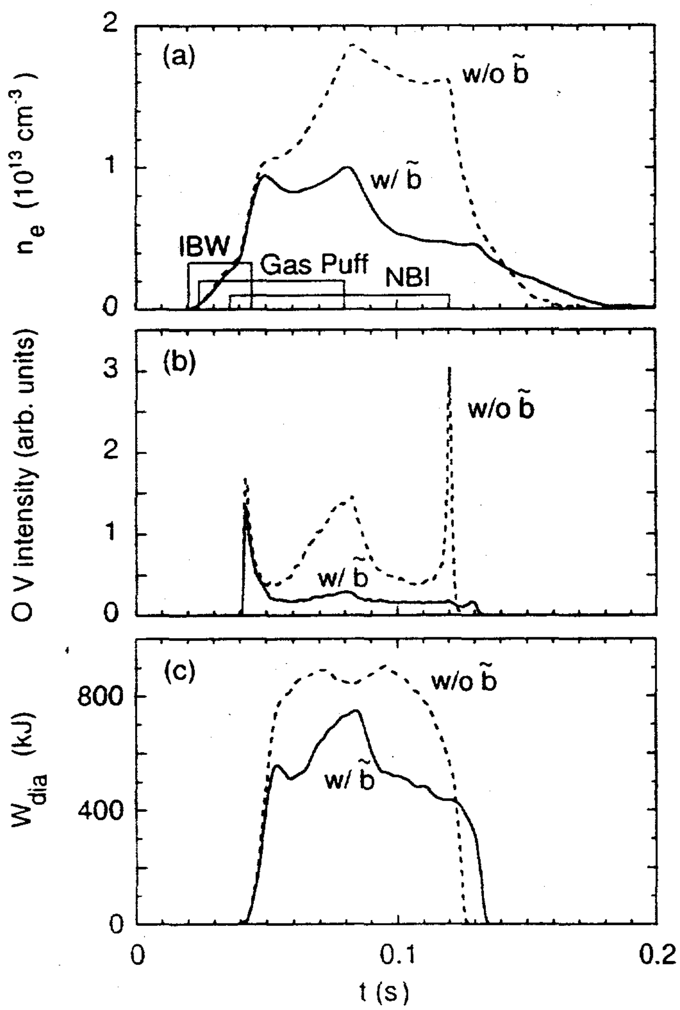

FIG. 3. Comparison of temporal evolutions of (a) averaged electron density n_e, (b) OV radiation intensity, and (c) stored energy W_{dia} between two discharges with and without $\tilde{b}$.

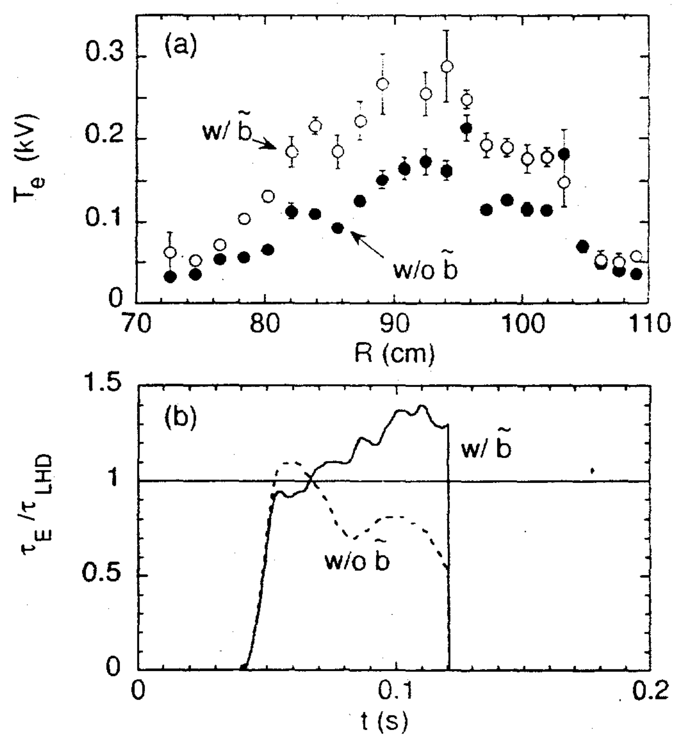

FIG. 4. (a) Radial T_e profiles with and without $\tilde{b}$, measured at $t = 0.1085$ s after the gas puffing (R is radial position from the major axis). (b) Energy confinement time τ_E normalized by that of the LHD scaling law, τ_{LHD}.

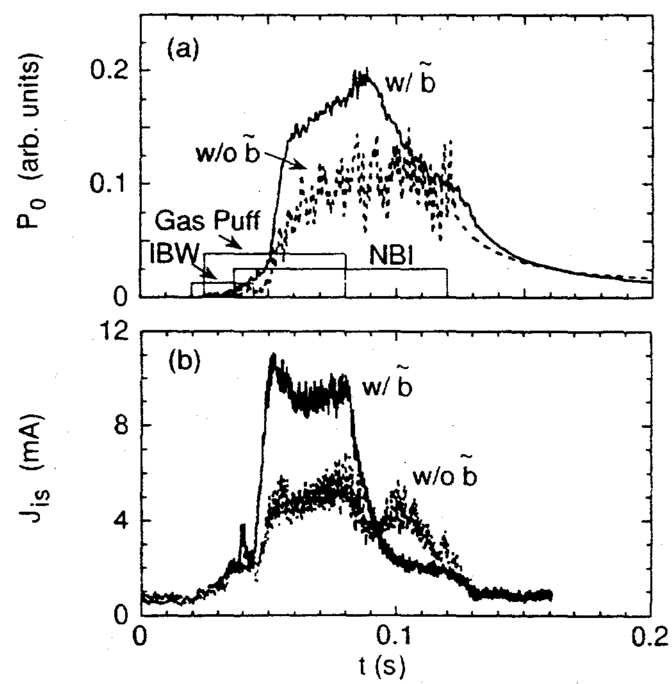

FIG. 5. Comparison of temporal evolutions of (a) neutral hydrogen pressure P_0, and (b) ion saturation current J_{is} behind the divertor head between two discharges with and without $\tilde{b}$.

The neutral particle pressure P_0 in the pumping duct was measured with a fast ion gauge [7] located just behind the divertor head. The pressure P_0 with a divertor head position $r_h = 0$ cm is shown in Fig. 5(a). Here the axis r_h is $R_{hs} - R_h$, where R_h is the major radial location of the divertor head and R_{hs} is that optimized in the design phase. When $\tilde{b}$ is turned on, P_0 becomes a factor of 1.5–2 higher than that without $\tilde{b}$ despite lower core density with $\tilde{b}$ on, as shown in Fig. 5(a). Figure 5(b) shows the ion saturation current J_{is}, which was measured with the Langmuir probe located behind the divertor head. It is clear that J_{is} with $\tilde{b}$ is a factor of 1.5–2 larger than that without $\tilde{b}$, and this is consistent with the fast ion gauge result. It should be noted that J_{is} without $\tilde{b}$ is kept almost constant even after the gas puff is turned off, while J_{is} with $\tilde{b}$ on decreases rapidly after the gas puffing. This suggests that efficient pumping of the recycled neutral particles takes place with the LID. On the basis of the particle flux calculated using J_{is} behind the divertor head, the pumping rate of the LID is roughly estimated to be in the range from a few per cent to about 10%. The radial T_e profiles behind the divertor head were also measured with the Langmuir probe. The temperature T_e during the gas puffing with $\tilde{b}$ is higher than that without $\tilde{b}$ by a factor of 2, and T_e after the gas puffing is also higher by a factor of 3 near the leading edge, whereas J_{is} is lower than that without $\tilde{b}$.

The dependence of P_0 and n_e on the island configuration was investigated by changing the perturbation coil current I_{pert} at a fixed position of the divertor head, as shown in Fig. 6(a). The size of the island was confirmed to change with I_{pert} by the mapping mentioned above. The position of the island O point is not affected by I_{pert}. When I_{pert} is gradually increased from 0 kA, P_0 increases abruptly at about 0.3 kA and is kept almost constant or decreases gradually until about 0.9 kA. A further increase in I_{pert} leads to an abrupt decrease in P_0. The pressure P_0 at $I_{pert} = 1.1$ kA is almost equal to that at $I_{pert} = 0$ kA. The pressure P_0 normalized by n_e has a clear peak at about 0.65 kA. On the other hand, n_e decreases gradually when I_{pert} is increased from 0 kA, and has a minimum at about 0.65 kA, corresponding to the value of I_{pert} for the maximum of P_0/n_e. This is an experimental demonstration that the LID function is sensitive to the LID geometry (island size, and position and shape of the head). When the geometry is optimized, the pumping efficiency is maximized, as evidenced by the maximum P_0/n_e, leading to the minimum n_e. The standard island configuration corresponds to that with $I_{pert} = 0.6$ kA.

To clarify the I_{pert} dependence of P_0, the plasma behind the divertor head was studied in detail with fixed Langmuir probes, which are mounted directly on the divertor head. The fixed probes are located radially 1 cm away from the leading edges of the divertor head. The radial J_{is} profiles at $t = 0.08$ s during the gas puffing with and without $\tilde{b}$ are shown in Fig. 6(b). They were measured by changing the head position r_h, so the horizontal axis shows the radial position r_h of the divertor head. The ion saturation current J_{is} without $\tilde{b}$ increases monotonically with r_h. When $\tilde{b}$ is turned on, J_{is} becomes larger for $r_h < 0$ cm, and J_{is} at $r_h = 1$ cm becomes smaller than that at $r_h = 0$ cm, as shown in Fig. 6(b). The peak of the profile at $r_h = 0$ cm corresponds to the outer island separatrix. Lower J_{is} at $r_h = 1$ cm

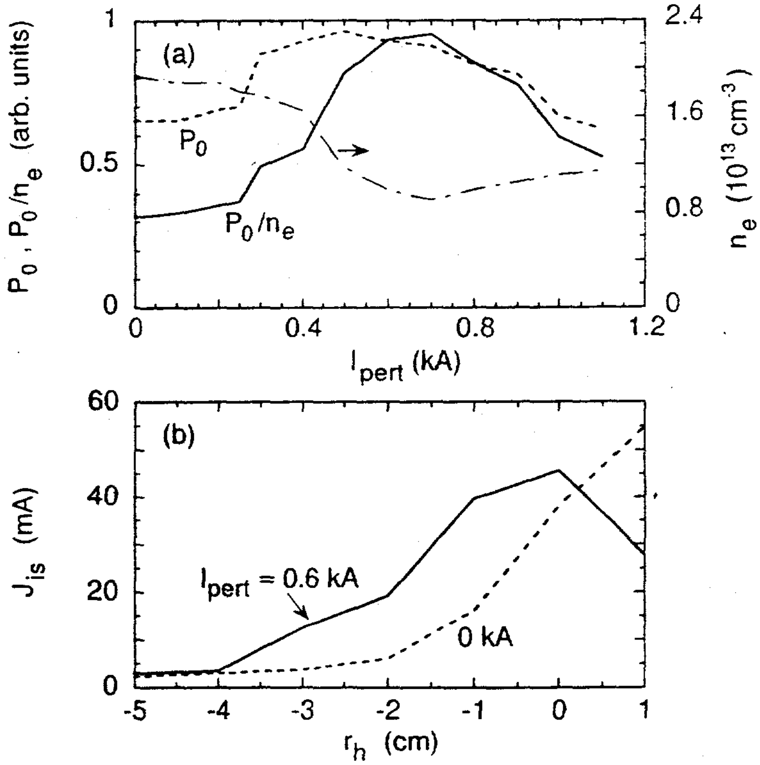

FIG. 6. Dependence of edge plasma parameters on LID geometry. (a) Dependence of P_0, n_e and P_0/n_e on perturbation coil current I_{pert}; (b) radial J_{is} profiles with and without $\tilde{b}$ at $t = 0.08$ s during the gas puffing, measured with a Langmuir probe fixed on the divertor head.

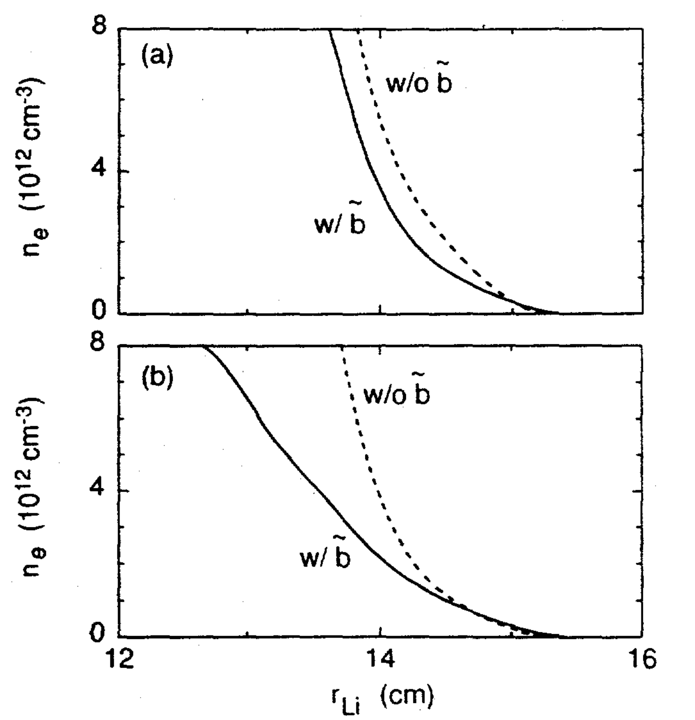

FIG. 7. Electron density profiles with and without $\tilde{b}$, measured with a thermal lithium beam probe. (a) Profiles during the gas puffing; (b) profiles after the gas puffing. The r_{Li} axis points towards the wall, and the separatrix is located at $r_{Li} \approx 14.3$ cm.

means that the plasma density just inside the outer separatrix is lower than that at the outer separatrix, because part of the divertor head is located inside the separatrix. As I_{pert} and hence the size of the island are increased, the peak position in the radial J_{is} profile moves towards the outside. The gap between the divertor head and the pumping duct, through which the edge plasma enters the duct, is fixed spatially, and hence the change in the peak position of the J_{is} profile explains well the I_{pert} dependence of P_0 shown in Fig. 6(a).

A CCD TV camera with an optical filter was used to measure the H_α radiation intensity near the target plates. The CCD TV camera is set behind the divertor head, as shown in Fig. 2, since the edge plasma enters the pumping duct and strikes the target plates. We found that the H_α radiation intensity behind the divertor head is higher with $\tilde{b}$ than without $\tilde{b}$. The H_α radiation intensity behind the divertor head behaves similarly to P_0 in the pumping duct.

The edge plasma behaviour with and without $\tilde{b}$ was measured with Langmuir probes and a thermal lithium beam probe [9], depicted in Fig. 2. Figure 7 shows the radial profiles of the electron density with and without $\tilde{b}$, measured with the lithium beam probe. The density profiles depicted in Fig. 7(a) were measured at $t = 0.09$ s during the gas puffing, whereas the profiles in Fig. 7(b) were obtained at $t = 0.11$ s after the gas puffing. The edge density with $\tilde{b}$ is found to decrease slightly during the gas puffing compared with that without $\tilde{b}$, and to decrease significantly after the gas puff is turned off. The J_{is} profiles, obtained with the Langmuir probes, are very similar [8]. The Langmuir probe measurement also yields the electron temperature T_e, which is higher when $\tilde{b}$ is turned on than without $\tilde{b}$, especially just after the gas puff is turned off and before the edge density becomes too low. This is consistent with the result obtained with the Langmuir probe behind the divertor head. The high temperature, low density edge plasma realized to some extent in our experiment suggests the feasibility of a low recycling operational mode in LHD that could lead to a significant energy confinement improvement [2]. The low recycling mode of operation will be pursued in the LHD experiment, combined with highly efficient pumping and core fuelling. The lithium beam probe was also used to measure the broadband density fluctuations in the edge region, and a correlation dimension and the largest Lyapunov exponent [10] were obtained. This study aims to achieve an understanding of the effect of chaos on particle transport, which could be helpful in substantially improving energy confinement in the LHD experiment.

4. SUMMARY

The fundamental functions of the LID have been clearly demonstrated in the experiment described. The leading edges of the divertor head, located inside the island, are protected from the outward heat flux from the core. The particle flow is guided to the back of the divertor head by the island magnetic field structure, and a high pumping efficiency can be realized to some extent even in CHS. A much higher pumping rate will be achieved in LHD, because the majority of the outward plasma flux is expected to be guided to the target plates on the divertor head without diffusing to the wall owing to the smaller diffusion coefficient and larger size of LHD. The LID has also been found to affect the core plasma parameters significantly, and especially to improve the energy confinement.

We have not yet completed the experimental analysis, but the results analysed so far are very encouraging in terms of the effectiveness of the LID. The LID experiment has provided critical information on the edge plasma behaviour, and helped us to optimize the design of the LID and the closed full helical divertor on LHD.

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DISCUSSION

K. LACKNER: You described low density operation in your divertor experiments. Do you also plan high density divertor operation in LHD, and do you plan to do pre-experiments also on CHS in this regime?

A. KOMORI: Yes, we plan both high density and low density divertor operation in LHD. In CHS, we have finished all the LID experiments, so we cannot do pre-experiments in the high density regime.