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Journal of Nuclear Materials 241-243 (1997) 967-971

journal of nuclear materials

Local island divertor experiments on CHS

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Abstract

A local island divertor (LID) was installed on the Compact Helical System (CHS) to demonstrate the principle of LID and to study its effects on the edge plasma. The particle flow was observed to be guided to the back side of the externally created magnetic island along field lines, and pumped out by a cryogenic pump with high pumping efficiency. As a result, a factor of about 2 reduction in the average core density was seen compared with non-LID discharges at the same gas puff rate. In addition to the demonstration of these fundamental divertor functions, we observed a modest improvement of energy confinement, which could be due to the edge plasma control by the local island divertor.

Keywords: CHS; Island divertor; Divertor plasma; Active pumping; Improved confinement mode

1. Introduction

The Large Helical Device (LHD), a superconducting heliotron-type device, is under construction at the National Institute for Fusion Science at Toki, Japan [1,2]. One of the key research issues in the LHD program is to enhance helical plasma performance by the edge plasma control. The plasma behavior in the edge is important in determining heat and particle fluxes to the wall and enhancing core plasma confinement. For LHD this control will primarily be done with a closed full helical divertor which utilizes a natural separatrix in the edge region [3]. In the early stage of the LHD experiment, however, the closed full helical divertor will not be ready, so a local island divertor (LID) will be used [4]. The LID is a closed divertor that uses an $m/n = 1/1$ island formed in the edge region. 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 LID experiment will provide us critical information on the edge plasma behavior in LHD, and help us to optimize the design of the closed full helical divertor. It will also influence the divertor design of the W7-X [5] and help us to explore advanced divertor concepts. The first experimental study to demonstrate the principle of the LID was done on the Compact Helical System (CHS) in Nagoya, Japan.

2. Experimental apparatus

For the CHS experiment, 16 small perturbation coils located above and below CHS were used to generate a resonant perturbation field $\tilde{B}_{\rm LID}$, and hence an $m/n = 1/1$ island. The outward heat and particle fluxes crossing the island separatrix flow along the field lines to the back side of the island, where carbon (or stainless steel) target plates of 10 mm (2 mm) in thickness are placed on a divertor

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PII S0022-3115(96)00641-1

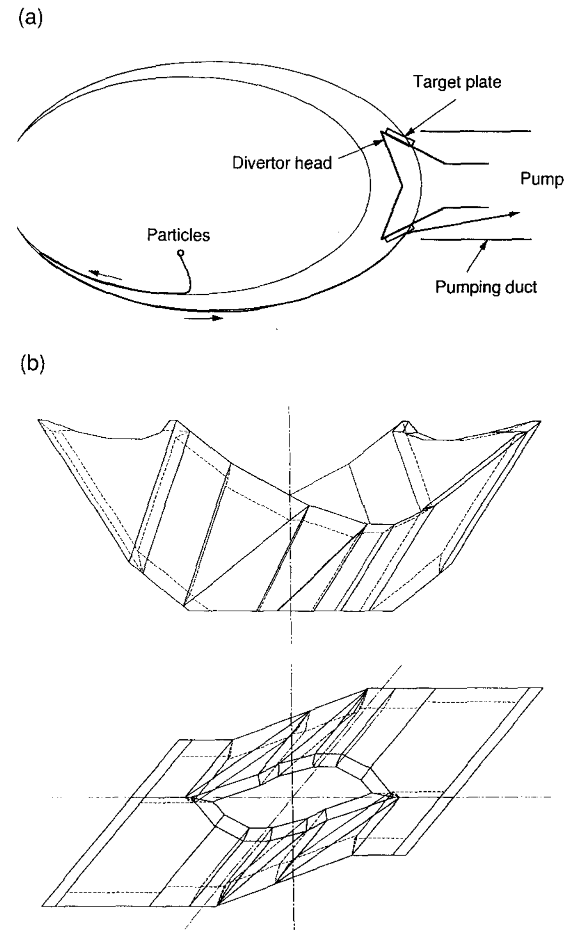

Fig. 1. Local island divertor concept. (a) LID configuration and particle flow to target plates. (b) The divertor head covered with carbon target plates.

head, as shown in Fig. 1(a) [4,6]. 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, as shown in Fig. 1(b), although ideally they should be three-dimensional curved target tiles which match the three-dimensional magnetic surface. The geometrical shapes of the divertor head and pumping duct are designed to form a closed divertor configuration with high pumping efficiency [4]. The gap between the divertor head and pumping duct is 4 cm in the experiment. For the standard LID configuration, the leading edges of the divertor head, i.e., those of the carbon or stainless steel target plates are located well inside the island, thereby being protected from the outward heat flux from the core [4].

CHS was operated with a toroidal magnetic field B_0 of 0.9 T and a magnetic axis position R_{ax} of 99.5 cm [7]. When $R_{ax} > 97.4$ cm, the $\iota/2\pi = 1$ flux surface is well inside the vacuum vessel wall. The plasma was produced by ion cyclotron range of frequency heating (ion Bernstein wave, IBW) and/or second-harmonic electron cyclotron heating (ECH) and was heated by 0.82 MW tangential neutral beam injection (NBI) at 38 keV. The key diagnostics systems of this experiment were an IR TV camera for surface temperature measurements, a CCD TV camera with an optical filter for Hα measurements, Langmuir probes for edge plasma measurements and an ASDEX style fast-ion gauge system [8,9] for measurements of the pressure in the pumping duct.

3. Experimental results and discussion

The $m/n = 1/1$ island geometry of the LID was confirmed by mapping the magnetic surfaces using an electron gun with a W filament and a fluorescent mesh which emits light if the electron beam collides with it. Fig. 2(a) shows the arrangement of the mapping apparatus. The fluorescent mesh is situated at the same toroidal position as the divertor head. We obtained the magnetic surfaces by tak-

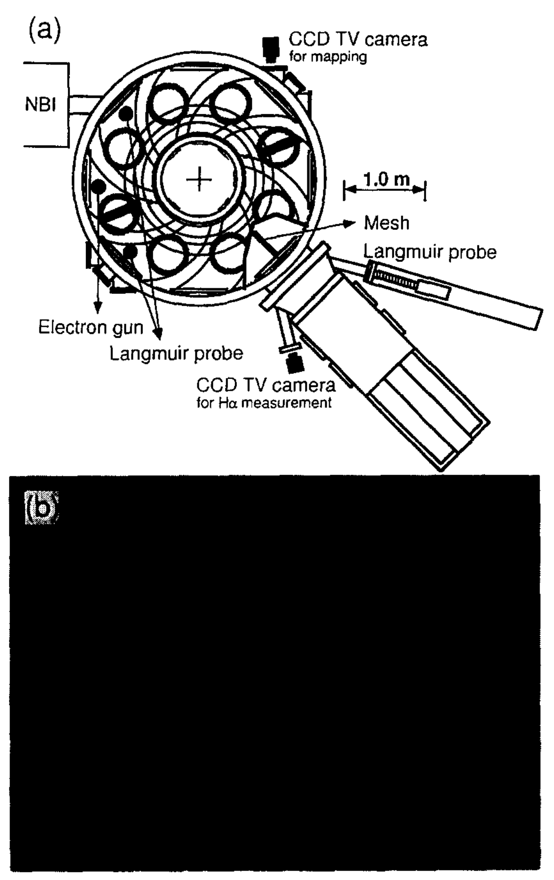

Fig. 2. Mapping of magnetic surfaces. (a) Schematic view of mapping apparatus. (b) An $m/n = 1/1$ island obtained by the fluorescent screen method.

ing 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. The $m/n = 1/1$ island thus obtained, shown in Fig. 2(b), is located at the radial position that is predicted theoretically. The width of the island is, however, a little wider than the expected value. This is because a 'natural' $m/n = 1/1$ island exists even when $\tilde{B}_{\mathrm{LID}} = 0$. The poloidal phase of the natural island happens to be almost the same as that of the externally generated island. The natural island remains existing even at the operating field $B_0 = 0.9$ T, and this will be discussed elsewhere in detail.

The plasma parameters are found to change when the island is formed. With $\tilde{B}_{\mathrm{LID}}$ (corresponding to the standard island configuration shown in Fig. 2(b)) and at a fixed level of gas puffing, the average electron density n_e and the OV radiation intensity decrease significantly, compared with those without $\tilde{B}_{\mathrm{LID}}$. Fig. 3(a) shows n_e's with and without $\tilde{B}_{\mathrm{LID}}$. Fig. 3(b) shows that the stored energy measured with a diamagnetic loop also decreases slightly, but its reduction rate is much smaller than that of n_e, because T_e increases, as observed by a YAG Thomson scattering system. Using these data, the temporal evolution of the energy confinement time τ_E is obtained, normalized by that of the LHD scaling law, $\tau_{\mathrm{LHD}} = 0.17a^{2.0}R^{0.75}B_0^{0.84}n_e^{0.69}P_{\mathrm{tot}}^{-0.58}$, where a, R, and P_{tot} are the averaged plasma radius, the major radius and the total absorbed power, respectively. The normalized τ_E with $\tilde{B}_{\mathrm{LID}}$ is larger than unity and longer than that without $\tilde{B}_{\mathrm{LID}}$, especially after the gas puffing. This indicates a modest improvement of the energy confinement, although the estimation of P_{tot} with $\tilde{B}_{\mathrm{LID}}$ is a little uncertain because n_e is low. A comparison of the stored energy is also made between the discharges with and without $\tilde{B}_{\mathrm{LID}}$ at the fixed average density. We found that the stored energy in the discharge with $\tilde{B}_{\mathrm{LID}}$ is about 20% higher than that without $\tilde{B}_{\mathrm{LID}}$.

The temperature profile of the target surface, measured by an IR TV camera, shows that the position of the maximum temperature rise changes as the position of the divertor head is changed. It is situated about 1 cm away from the leading edge when the leading edge is well inside the island. This means that the outward heat flux from the core is guided to the back side 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.

The neutral particle pressure p_d in the pumping duct was measured with an fast-ion gauge located directly behind the divertor head. Fig. 3(c) shows p_d with a divertor head position $r_h = 0$ cm. Here $r_h = R_{hs} - R_h$ where R_h is the (major) radial location of the divertor head and R_{hs} is that optimized in the design phase. The pressure p_d begins to increase at about 0.035 s. With $\tilde{B}_{\mathrm{LID}}$, p_d becomes a factor of 1.5–2 higher than in the case without $\tilde{B}_{\mathrm{LID}}$ despite lower core density with $\tilde{B}_{\mathrm{LID}}$, as shown in Fig. 3(c). Fig. 3(d) shows the ion saturation current J_{is}, measured with the Langmuir probe located behind the divertor head. It is clearly seen that J_{is} is a factor of 1.5–2 higher with $\tilde{B}_{\mathrm{LID}}$ than without $\tilde{B}_{\mathrm{LID}}$, which is consistent with the fast-ion gauge result. An interesting point is that J_{is} without $\tilde{B}_{\mathrm{LID}}$ is almost kept constant even after the gas puff is turned off, while J_{is} with $\tilde{B}_{\mathrm{LID}}$ decreases rapidly after the gas puffing. This suggests that efficient pumping of the recycled neutral particles takes place with the LID. The radial profiles of the electron temperature T_e behind the divertor head are also measured with the Langmuir probe. With $\tilde{B}_{\mathrm{LID}}$, T_e during the gas puffing is higher than that without $\tilde{B}_{\mathrm{LID}}$ by a factor of 2, and T_e after the gas

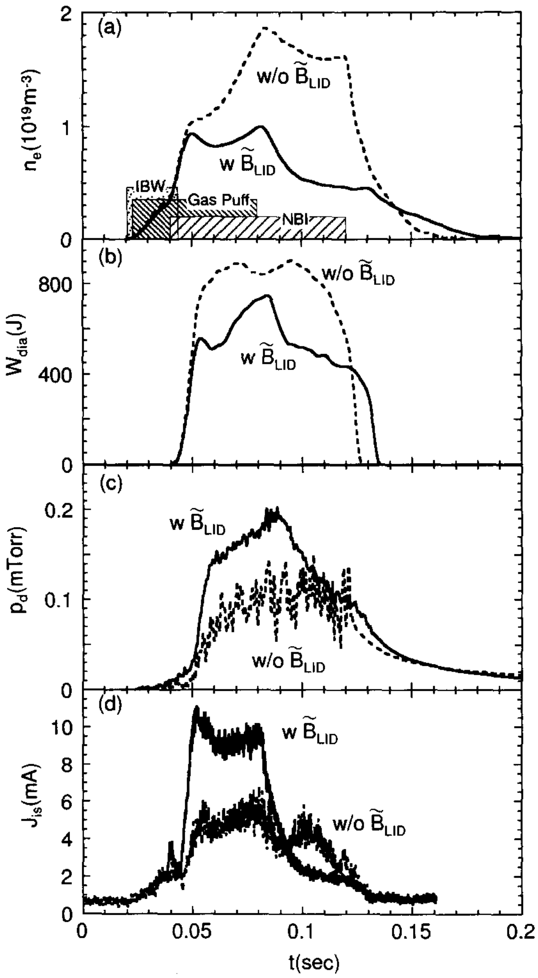

Fig. 3. Comparison of temporal evolutions between two discharges with and without $\tilde{B}_{\mathrm{LID}}$. (a) Average electron density n_e. (b) Stored energy W_{dia}. (c) Neutral gas (hydrogen) pressure p_d, measured in the pumping duct by a fast-ion gauge. (d) Ion saturation current J_{is}, measured behind the divertor head.

puffing is also higher by a factor of 3 near the leading edge, whereas J_{is} is lower than that without $\tilde{B}_{LID}$.

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 edge of the divertor head. Fig. 4 shows the radial J_{is} profiles measured with the fixed probes by changing the head position r_h, so the horizontal axis is the radial position r_h of the divertor head. The radial J_{is} profiles without $\tilde{B}_{LID}$ are shown in Fig. 4(a), where J_{is} increases monotonically with r_h. With $\tilde{B}_{LID}$, J_{is} becomes larger for $r_h < -1$ cm, as shown in Fig. 4(b), and it is clear that J_{is} at $r_h = 1$ cm becomes smaller than that at $r_h = 0$ cm. We believe that the peak of the profile at $r_h = 0$ cm corresponds to the outer island separatrix. Lower J_{is} at $r_h = 1$ cm means that the plasma density just inside the outer separatrix is lower than that at the outer separatrix, which is expected from the LID configuration. When $\tilde{B}_{LID}$ and hence the size of the island are increased, the peak position in the radial J_{is} profile moves towards the outside.

The Hα radiation intensity near the target plates was measured with a CCD TV camera with a optical filter. The CCD TV camera is located behind the divertor head, as depicted in Fig. 2(a), since the edge plasma enters the pumping duct and strikes the target plates, as shown in Fig. 1(a). When $\tilde{B}_{LID}$ is turned on, the Hα radiation intensity behind the divertor head is higher than that without $\tilde{B}_{LID}$. Thus, the Hα radiation intensity behind the divertor head behaves similarly as the neutral particle pressure p_d in the pumping duct.

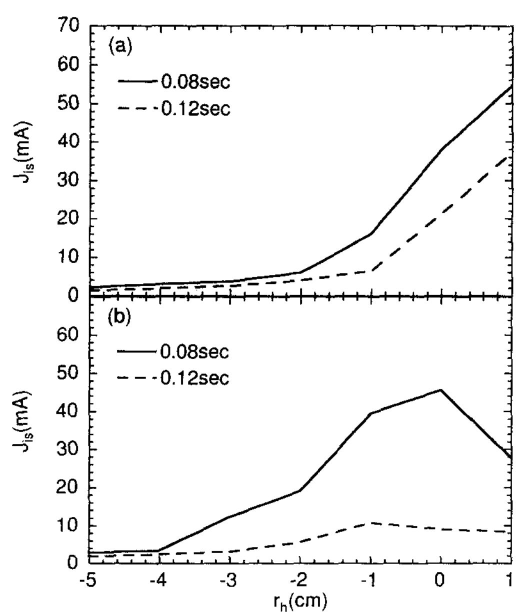

Fig. 4. Edge plasma behavior behind the divertor head, measured with fixed probes. (a) Radial J_{is} profiles at $t = 0.08$ s (during the gas puffing) and 1.2 s (after the gas puff) without $\tilde{B}_{LID}$. (b) Radial J_{is} profiles at $t = 0.08$ s and 1.2 s with $\tilde{B}_{LID}$.

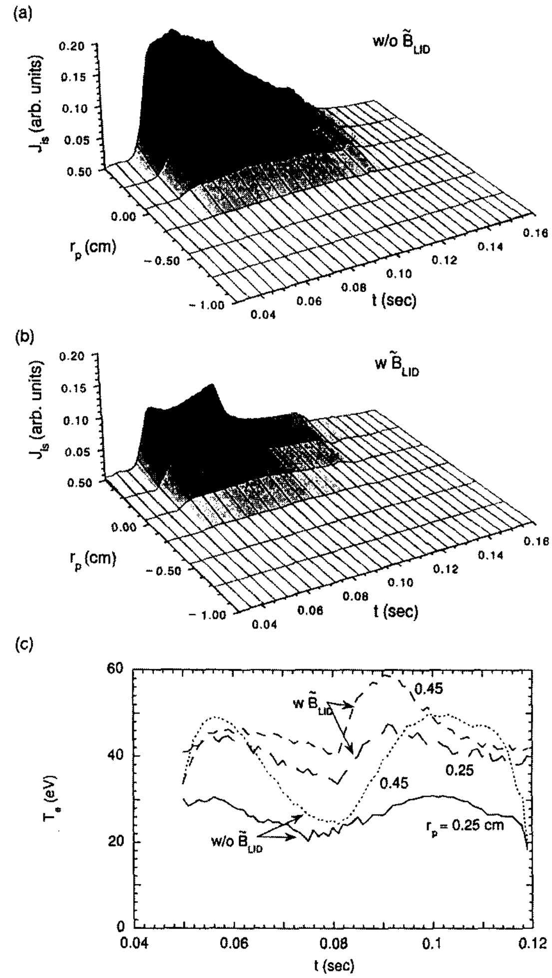

Fig. 5. Difference in edge plasma parameters between two discharges with and without $\tilde{B}_{LID}$. (a) Temporal evolution of the radial J_{is} profile without $\tilde{B}_{LID}$. (b) Temporal evolution of the radial J_{is} profile with $\tilde{B}_{LID}$. (c) Electron temperature T_e with and without $\tilde{B}_{LID}$. The r_p axis points toward the core plasma, and the separatrix is located at $r_p = 0$ cm.

The edge plasma behavior away from the divertor head with and without $\tilde{B}_{LID}$ was measured with Langmuir probes. Fig. 5(a) shows the temporal evolution of the radial J_{is} profile without $\tilde{B}_{LID}$. With $\tilde{B}_{LID}$, J_{is} in the edge plasma decreases significantly compared with that without $\tilde{B}_{LID}$, as shown in Fig. 5(b). The electron temperature T_e, measured with a triple probe, is also shown in Fig. 5(c), indicating that when $\tilde{B}_{LID}$ is turned on, T_e is higher than that without $\tilde{B}_{LID}$, 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 and low-density edge plasma realized somewhat in our experiment suggests the feasibility of a low recycling operational mode in LHD that could lead to a significant energy confinement improvement [3]. The low recycling mode of operation will be pursued in the LHD experiment, combined with highly efficient pump and core fueling.

4. Summary

The results obtained in our experiment have clearly demonstrated that the particle flow is indeed guided to the back side of the divertor head by the island magnetic field structure, the fundamental function of this type of divertor. On the basis of the particle flux calculated by J_{is} behind the divertor head, the pumping rate of the LID is roughly estimated to be in the range from a few percent to about 10%. Thus a high pumping efficiency can be realized even in CHS to some extent. A much higher pumping rate will be achieved in LHD because a majority of plasma flux flowing outwards is expected to be guided to the target plates on the divertor head without diffusing to the wall due to LHD's smaller diffusion coefficient and larger size. The leading edges of the divertor head, located inside the island, are also found to be protected from the outward heat flux from the core. The LID experiment has provided us critical information on the edge plasma behavior, and is helping us to optimize the design of the LID on LHD.

We have not yet completed the experimental analysis, but the results analyzed so far are very encouraging in terms of effectiveness of the LID.

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