Available online at www.sciencedirect.com

ScienceDirect

Journal of Nuclear Materials 363–365 (2007) 314–318

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Divertor plasma and neutral particles behavior under the local island divertor configuration in the Large Helical Device

S. Masuzaki *, T. Morisaki, M. Kobayashi, M. Shoji, N. Ohyabu, A. Komori, The LHD Experimental Group

National Institute for Fusion Science, Oroshi 322-6, Toki 509-5292, Japan

Abstract

In the Large Helical Device (LHD), the local island divertor (LID) experiment has been conducted to investigate how to improve the core confinement with edge plasma control. An advantage of the LID configuration over the intrinsic helical divertor is the high pumping efficiency with the closed divertor module (neutralizer and pumping duct) and high speed pump-system. The particle evacuation efficiency, evacuated particle number/fueled particle number, has been estimated in experiment. This efficiency depends on the relative position of the closed divertor module (divertor head) to $m/n = 1/1$ magnetic island's outer separatrix corresponding to the divertor leg, and the efficiency is revealed to be 0.6–1. A new operational regime with high core density ($>4 \times 10^{20}\ \mathrm{m}^{-3}$) and a strongly peaked density profile has been discovered in the LID discharges. It is considered that a large effective pumping efficiency is necessary to enter this operational regime.

PACS: 52.25.−b; 52.25.Ya; 52.55.Hc

Keywords: Density control; Divertor; Divertor geometry; Divertor plasma; LHD

1. Introduction

Particle control using a divertor is a crucial issue to realize a nuclear fusion reactor. In the Large Helical Device (LHD), the world's largest superconducting heliotron-type device [1], plasma experiments under two types of divertor configurations, the helical divertor (HD) and the local island divertor (LID), have been conducted.

The HD is intrinsic in the heliotron-type magnetic configuration, and has no baffle structure and no divertor pumping system at this stage in LHD [2].

The LID was installed in LHD in 2003 [3]. In Fig. 1(a), the basic concept of the LID is depicted. The perturbation field generated by 10 pairs of coils is resonant with the $q = 1$ surface, and generates an $m/n = 1/1$ magnetic island in the periphery of the LHD confinement region. A divertor head consisting of neutralizer plates and a pumping duct is inserted into the island in a horizontally elongated

* Corresponding author. Fax: +81 572 58 2618.
E-mail address: masuzaki@LHD.nifs.ac.jp (S. Masuzaki).

0022-3115/$ - see front matter
doi:10.1016/j.jnucmat.2007.01.028

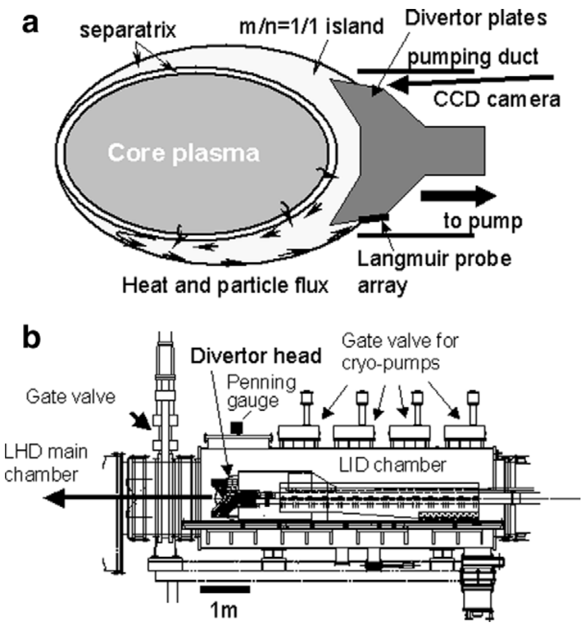

Fig. 1. (a) Schematic view of the LID system and (b) basic concept of the LID.

cross-section where the width of the island is maximum (about 20 cm). The pumping duct surrounds the neutralizer, and it works as a baffle. The outer separatrix of the island connects the neutralizer plates in the divertor head, and the last closed flux surface is determined by the inner separatrix of the island. Plasma–surface interaction occurs ideally only at the divertor head, and it is toroidally and poloidally localized. Therefore, high pumping efficiency and impurity control can be expected with the proper divertor head configuration and pumping system. In LHD, a field line tracing code which is coupled to a random walk process to simulate the diffusive particle behavior [5] predicted that over 80% of the particle out-flux from the confinement region is collected by the LID target plates [6]. From the results of neutral transport simulation using the DEGAS code, it was found that a pumping efficiency up to 50% could be achieved [6]. In discharges with the LID configuration in LHD, strong reductions of the particle flux and the heat load to helical divertor plates measured by Langmuir probes and thermocouples are observed. This indicates that most of the particle flux and the heat flux are collected by the LID divertor head as predicted, and recycling is localized in the LID region as expected [2]. In recent experiments, improved confinement with $\tau_E/\tau_{E,ISS95} \sim 1.2$, where $\tau_{E,ISS95}$ is the energy confinement time estimated using the International Stellarator Scaling 95, have been achieved in multiple-pellet fueled discharges [4], and a very high core density ($>4 \times 10^{20}$ m^{-3}) with a strongly peaked profile is achieved during those discharges [7].

In this study, divertor plasma and neutral particle behaviors are investigated, especially the pumping function of the LID configuration, and its impact to core plasma properties.

2. Experimental set-up

Fig. 1(a) shows a schematic view of the LID configuration. A divertor head is installed into the magnetic island. The LID pumping system with eight cryo-pumps (42 m^3/s $\times$ 8) and a turbo-molecular pump (4.4 m^3/s) is located outside of the LHD main chamber. These pumps are attached to a manifold (LID chamber in Fig. 1(b)). The effective exhaust velocity for hydrogen is about 200 m^3/s. That is almost the same as the effective exhaust velocity of the main pump-system in LHD. When a discharge under the HD configuration is conducted, the divertor head is drawn out, and the LID pump-system works as an additional main pump-system. To investigate neutral particle behavior, a Penning gauge is installed on the LID chamber. A Langmuir probe array (10 ch/array) is embedded in the divertor plates (see Fig. 1(a)). The shapes of probe electrodes are dome-type ($r = 1.5$ mm), and are made of isotropic graphite. The distance between electrodes is about 10 mm. Thermocouples are embedded in 16 divertor plates to monitor the divertor plate's temperature. They are 10 mm from the surface of the divertor plates.

An ASDEX-type fast ion gauge is installed in the LHD main chamber, and it monitored the neutral pressure at the torus inboard side helical divertor region in the same toroidal section as the LID head. A Langmuir probe array is embedded in a divertor tile near the ASDEX gauge.

A Thomson scattering measurement was utilized to obtain the electron density and temperature profiles on the center chord in the horizontally elongated cross-section that is 72° in toroidal angle away from the LID head.

$H\alpha$ monitors are distributed toroidally. In the experimental conditions described in this paper, no significant difference in $H\alpha$ behavior is observed in the toroidal direction, and the signal of the monitor about 108° in toroidal angle away from the LID head is used in this paper.

In this study, NBI heated hydrogen plasmas with the radial position of the operating magnetic axis, $R_{ax} = 3.75$ m, and field strength at the magnetic axis, $B_t = 2.64$ T, are utilized. The strength of the perturbation field for the LID configuration is about 0.1% of B_t. The shape of the divertor head was designed for a $R_{ax} = 3.6$ m configuration. However, much better core plasma performance has been obtained in the $R_{ax} = 3.75$ m configuration than in the $R_{ax} = 3.6$ m configuration [4].

3. Results and discussion

Fig. 2 shows waveforms of plasma parameters in typical multiple-pellet fueled discharges with the LID and the HD configurations, respectively. In these discharges, the NBI heating power is up to 14.7 MW. The line-averaged density, $n_{e,bar}$, is over 2×10^{20} m^{-3} at maximum. The spikes in the signals of the P_{rad} and the $H\alpha$ intensity are due to the pellet injections. After the termination of a series of pellet injections, the density starts to decrease, and the stored energy reaches its maximum value during the density decrease and temperature recovery. In the LID discharge, the $H\alpha$ intensity is about one-fourth of that in the HD discharge, and the ion flux to the divertor plate measured by embedded Langmuir probe arrays (not shown in Fig. 2) also reduced to one-fourth to one-fifth of that in the HD discharge. This means that a substantial amount of ion flux flows to the LID divertor head along the outer separatrix of the island. Fig. 3 shows the time evolutions of the neutral pressure during the discharges depicted in Fig. 2. In the LID discharge, the neutral pressure is the order of 10^{-1} Pa in the LID chamber, and 10^{-3} Pa order in the main chamber. On the other hand, neutral pressure in the main chambers is the order of 10^{-2} Pa, and 10^{-3} order in the LID chamber in the HD discharge. Neutral pressure in the main chamber in Fig. 3(a) is less than one-fourth of that in Fig. 3(b). This neutral pressure reduction is consistent with the reduction of ion flux to the helical divertor.

Fig. 4 shows the particle number evacuated by the LID and main pump-system as a function of the fueled particle number. In this figure, R_{head} means the radial position of the LID head. For the $R_{ax} = 3.75$ configuration, $R_{head} = 4.18$ m is optimal in the vacuum condition. A smaller R_{head} value means that the head is installed deeper in the island. Particles are fueled by pellet injection, gas-puffing and neutral beam injection. Three R_{head} cases are depicted in this figure. The evacuation efficiency, defined as (evacuated particles number)/(fueled particles number), decreases with increasing R_{head}. In the case of $R_{head} = 4.18$ m, the efficiency is almost 1, and the efficiency is about 0.6 for $R_{head} = 4.24$ m. This result is attributed to the shift of the divertor

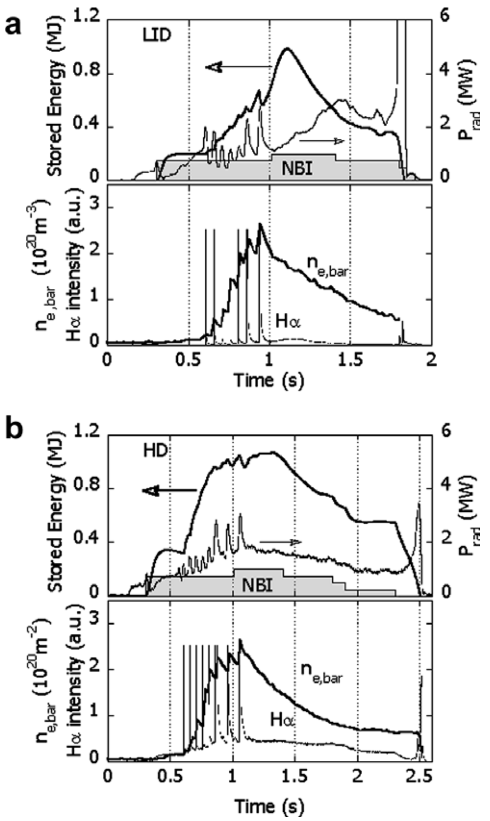

Fig. 2. Time evolutions of the plasma parameters in (a) LID with $R_{head} = 4.23$ m and (b) HD configurations, respectively. The $H\alpha$ intensity is saturated at 2.5 s. This HD discharge was conducted after a series of the LID discharges.

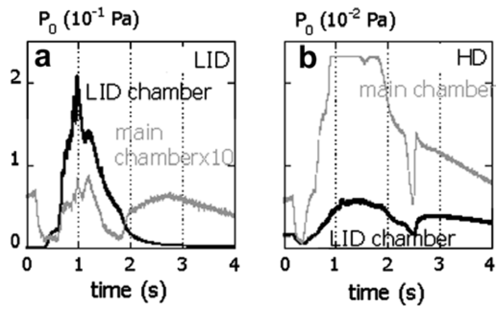

Fig. 3. Waveforms of neutral pressure in the LID and the main chambers during (a) the LID and (b) the HD discharges. Neutral pressure in the main chamber is saturated in (b). Unit of the vertical axis is 10^{-1} Pa for (a) and 10^{-2} Pa for (b).

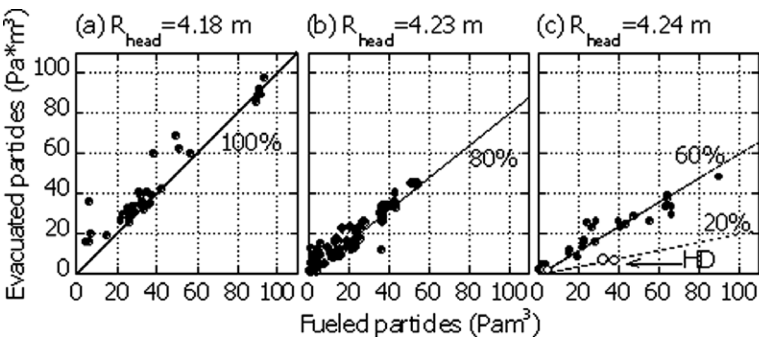

Fig. 4. Number of evacuated particles as a function of the fueled particle number. All numbers were estimated assuming hydrogen molecules. In (c), open circles show the case of the HD configuration.

particle flux peak on the head. Fig. 5 shows the ion saturation current profiles on the LID head measured by the embedded Langmuir probe array at the different head position (R_{head}). The R_{head} was changed shot by shot. With decreasing the R_{head}, the probe array approaches to the island's outer separatrix, and the ion saturation current increases. This means the ion saturation current peak shifts toward the inside of the pumping duct with decreasing the R_{head}. On the other hand, the peak shifts toward the LID head edge with increasing the R_{head}. As shown in Fig. 3(a), the neutral pressure in the LID chamber is over one order higher than that in the main chamber. Therefore, it can be concluded that good particle compression is achieved as expected. The evacuation efficiency for the HD configuration is also shown in Fig. 4(c), and it is about 0.2. To achieve a large evacuation efficiency, it is necessary that the particle retention rate on the first wall and the divertor plates is small. The particle load to the first wall is mainly caused by charge-exchanged particles [8]. Thus, the low neutral pressure in the main chamber during the LID discharge could lower the particle load to the first wall. In the LID discharges, particle and heat fluxes mainly flow to the divertor head. Because of the relatively small wet area (<0.5 m^2) and weak active cooling of the divertor head, the temperatures of the divertor plates connecting the outer separatrix of the island measured by thermocouples are kept over 800 K during a series of discharges with high input power (>8 MW, 2–3 s), and they exceed 1000 K during the discharges. On the other hand, in the HD configuration discharges, the temperatures of the divertor plates are 600 K at most during similar discharges. Therefore, particle retention in divertor plates should be smaller in the LID configuration than in the HD configuration.

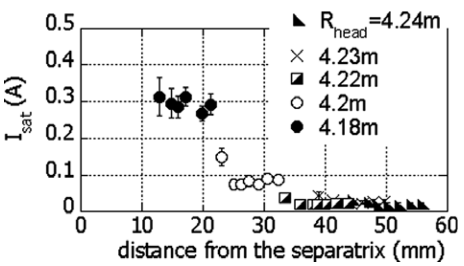

Fig. 5. The ion saturation current profiles at the different LID head position (R_{head}) measured by the Langmuir probe array embedded in the LID head. Horizontal axis is the distance from the $m/n = 1/1$ island's outer separatrix. The R_{head} was changed shot by shot.

Recently, a high core density (>4×10^{20} m^{-3}) operation regime with a peaked density profile has been discovered in the multiple-pellet fueled LID discharges. This operational regime was named 'super dense core (SDC) mode' [7]. Fig. 6(a) shows typical density and temperature profiles measured by Thomson scattering in the LID discharge depicted in Fig. 2(a). The peak density reaches 4.5×10^{20} m^{-3}, and there are sharp vends in the profile at $R \sim 3.4$ m and 4.4 m, that is an internal diffusion barrier (IDB) [7]. In this case, the electron temperature is 0.73 keV in the center region, and has a flat profile, unlike the tokamak internal transport barrier (ITB). Outside of the bends, the electron temperature has a large gradient. The β value in the center region is up to 4.4% (at $B_t = 2.64$ T), and the peak position is shifted about 0.25 m from the vacuum magnetic axis position ($R_{ax} = 3.75$ m) due to the Shafranov-shift. Such profile has advantages in neutral beam deposition, radiation collapse tolerability due to the relatively low edge density. Fig. 6(b) shows the density and temperature profiles observed in a multiple-pellet fueled HD discharge

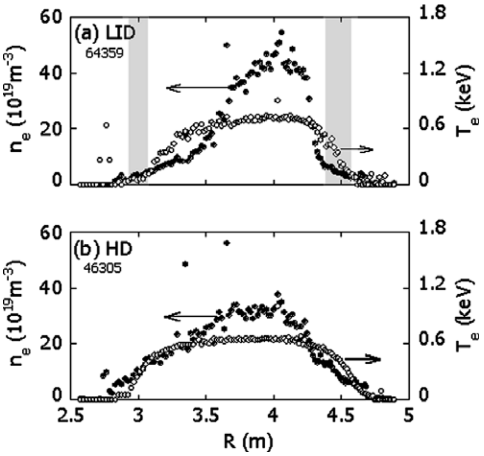

Fig. 6. (a) Peaked density profile with an internal diffusion barrier, and electron temperature profile observed in the LID discharge depicted in Fig. 2(a) at $t = 1.1$ s. (b) Density and temperature profiles in a multiple-pellet fueled HD discharge. The magnetic axis in the vacuum condition is $R_{ax} = 3.75$ m in both discharges. The hatched region indicates an $m/n = 1/1$ island under vacuum condition.

during a series of high density discharges. In this case, the IDB is not clear, and the edge density is relatively high. In gas-puff fueled discharges, the density profile is hollow or flat, and a peaked density profile has not been achieved. From these observations, core fuelling with pellet injection and particle pumping are key factors to produce the SDC mode. In the LID discharge, particle evacuation efficiency is large, and particle recycling is suppressed. Therefore, the SDC mode is obtained with reproducibility. Even in the HD discharge after a series of the LID discharge (Fig. 2(b)), the SDC mode was observed with slightly lower temperature. Density and temperature profiles are almost the same as Fig. 6(a). It is considered that for the low particle load to the first wall and helical divertor plates in the LID discharges, wall pumping was still active in this discharge. This observation encourages the experimental plan for a 'closed' helical divertor [2]. In W7-AS stellarator, an improved confinement mode was also discovered in high density operations with the island divertor configuration (High Density H-Mode, HDH) [9]. The features of the HDH mode are the Edge Transport Barrier formation and the strong expelling of impurities. On the other hand, the SDC mode in the LHD has transport barrier inside the core region. The position of the IDB foot moves with increasing plasma pressure, and is considered to relate to rotational transform profile [7]. Therefore, the mechanisms of these two modes in high density operations are considered to be different. In the case of SDC mode, impurities behaviors have not been investigated in detail. That is an experimental issue for the next experimental campaign.

4. Conclusion

Neutral particle behavior in the LID discharges is investigated with the operational configuration of $R_{ax} = 3.75$ m and $B_t = 2.64$ T. In the LID discharges, ion flux to the helical divertor was reduced to one-fourth to one-fifth, and neutral pressure in the helical divertor region was reduced to comparable level to the ion flux reduction. On the other hand, neutral pressure in the LID chamber was one order higher than that in the main chamber, and a very high evacuation efficiency (0.6–1) was obtained. The efficiency for the helical divertor is about 0.2.

A high core density operation regime with a peaked density profile, named the SDC mode induced by an internal diffusion barrier has been discovered in the multiple-pellet fueled LID discharge. This regime was also observed in the HD discharges after a series of LID discharges. Suppression of the particle recycling by effective pumping is a key factor to produce the SDC mode, and both the LID pumping and wall pumping can produce the SDC mode operational regime.

Acknowledgements

The authors would like to thank the technical staff for their great support. They are grateful to Professor O. Motojima (General director of NIFS) for his continuous guidance and encouragement. This work is funded by NIFS05ULPP506 and the Grant-Aid for Scientific Research from MEXT of the Japanese government.

References

[1] O. Motojima et al., Phys. Plasma 6 (1999) 1843.
[2] S. Masuzaki et al., Fusion Sci. Tech. 50 (2006) 361.
[3] A. Komori et al., Nucl. Fusion 45 (2005) 837.
[4] T. Morisaki et al., Fusion Sci. Tech. 50 (2006) 216.
[5] S. Masuzaki et al., Nucl. Fusion 42 (2002) 75.
[6] T. Morisaki et al., J. Plasma Fusion Res. SERIES 3 (2000) 188.
[7] N. Ohyabu et al., Phys. Rev. Lett. 97 (2006) 055002.
[8] M. Kobayashi et al., J. Nucl. Mater. 350 (2006) 40.
[9] K. McCormick et al., J. Nucl. Mater. 313–316 (2003) 1131.