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Abstract. In the Large Helical Device (LHD), plasma experiments with an intrinsic helical divertor (HD) and a local island divertor (LID) have been performed, respectively. The HD is an open divertor at this stage, and the LID is a closed divertor equipping a baffle structure and a pump-system. Particle balance study has been conducted in these two divertor configurations. In the LID configuration, the substantial part of fuelled particles is evacuated during discharge. On the other hand, in the HD configuration, the most part of fuelled particles are retained in the vacuum vessel. Therefore the discharge history strongly affects the density control in the HD configuration. The difference in the neutral particle behavior between the HD and the LID configurations is considered to be explained by following conditions in the LID configuration: (1) The low charge exchange particle flux to the first wall due to the relatively low edge neutral density reduces the amount of implantation of the neutral particles in the first wall. (2) The small carbon amount released by physical and chemical sputtering from the helical divertor plates due to the small ion flux to the plates in the LID configuration leads the co-deposited particles to be small. (3) For the high operational temperature (over 1000 K) of the LID divertor plates in the LID configuration, the amount of retained particle in the plates is small. On the contrary, in the HD configuration, the operational temperature of the helical divertor plates is typically less than 600K, and it is too low for the particle desorption from the carbon divertor plates.

1. Introduction

Achieving an effective particle control using a divertor is a crucial issue in fusion experiment. Particle balance studies are necessary for understanding neutral particle behavior, and are also important from the viewpoint of tritium inventory in vacuum vessel for next step fusion devices. In the Large Helical Device (LHD), plasma experiments with an intrinsic helical divertor (HD [1]) and a local island divertor (LID [2]) have been performed, respectively. The HD is an open divertor at this stage, and particle balance studies in this configuration have been conducted [3-6]. It have been revealed that the substantial part (50-80%) of fuelled particles are not evacuated by pumping system, but retained in the vacuum vessel and divertor plates, and any sign of wall saturation has been observed during an experimental day. Typically, the total amount of retained hydrogen atoms in the LHD vacuum vessel is the order of 10^{24} atoms in an experimental day corresponding to the averaged areal density of 10^{21}-10^{22} atoms/m^2 [6]. The LID is a closed divertor equipping baffle structure and pump-system (see Fig.1). In the LID configuration, most particles from the core are well guided by the outer-separatrix of m/n=1/1 island to the closed divertor module located locally in a toroidal section. In this paper, particle balance properties in these two divertor configurations in the LHD are described.

2. Experimental Set-up

In the LHD device, the total in-vessel area and volume of vacuum vessel including pumping system are about 700m^2 and 300m^3, respectively, and the plasma volume is about 30m^3. The first wall consists of a number of stain-less steel (SS) tiles, and HD and LID divertor plates are made of isotropic graphite and carbon fiber composite (CFC), respectively. There are three NBI facing armors in the vacuum vessel, and they are made of CFC. The ratio of carbon surface area to SS area is about 10%. The vacuum vessel wall temperature is limited below 95°C to avoid heat invasion to the super-conducting helical coils.

Figure 1 shows a schematic view of the HD and the LID configurations. In the LID configuration, a closed divertor module which consists of a divertor head and a pumping duct is installed into the m/n=1/1 magnetic island, and the last closed flux surface (LCFS) is determined by the inner separatrix of the island. The outer separatrix of the island becomes the divertor legs in this configuration. The effective pumping speed of the main pump-system in the LHD is about $200m^3/s$. When discharges under the HD configuration are conducted, the LID divertor head is drawn out, and the LID pump-system (~ $200m^3/s$) works as an additional pump-system. Therefore, total pumping speed is about $400m^3/s$ in the HD configuration. In the LID configuration, the conductance between the vacuum vessel and the LID pump system is so small because the gap between the divertor head and pumping duct is narrow. Thus the effective pumping speed for the vacuum vessel is $200m^3/s$.

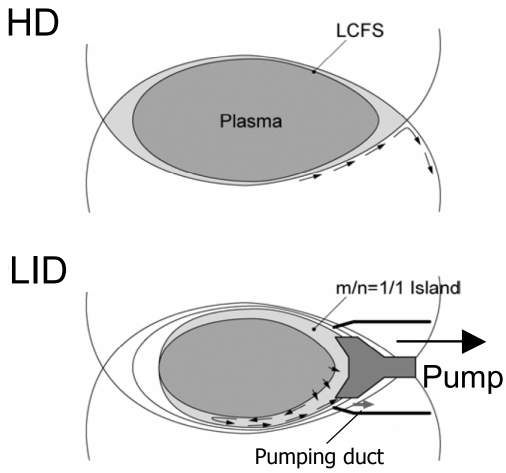

Fig.1. Schematic views of the two divertor configurations in LHD in horizontally elongated poloidal cross-section. Left hand side is torus inboard side.

To investigate neutral pressure properties, a Penning gauge is installed on the entrance of the LID pump-system. An ASDEX-type fast ionization gauge (FIG) is installed in the LHD vacuum vessel, and it monitors the neutral pressure at the torus inboard side helical divertor region in the same toroidal section as the LID head.

3. Results and Discussion

Particle balance is expressed as follows:

$$(N_w - N_{w0}) + N_0 + N_p = \int_{t=0}^{t} \left(\Gamma_{in} - \Gamma_{pump}\right) dt$$

In this expression, N_w is particle number retained in the first wall and divertor, and N_{w0} is that at t=0. N_0 and N_p are neutral and plasma particle numbers, respectively. Γ_{in} is fueling particle flux. It includes gas-puff, ice-pellet and plasma heating neutral beam. Γ_{pump} is particle flux evacuated by the pump systems. Figure 2 depicts the particle balance during typical ice-pellet fueled discharges in the HD and the LID configurations, respectively. The fueling particle amount includes ice-pellets and neutral beam injection in these discharges. The evacuated particle amount is calculated

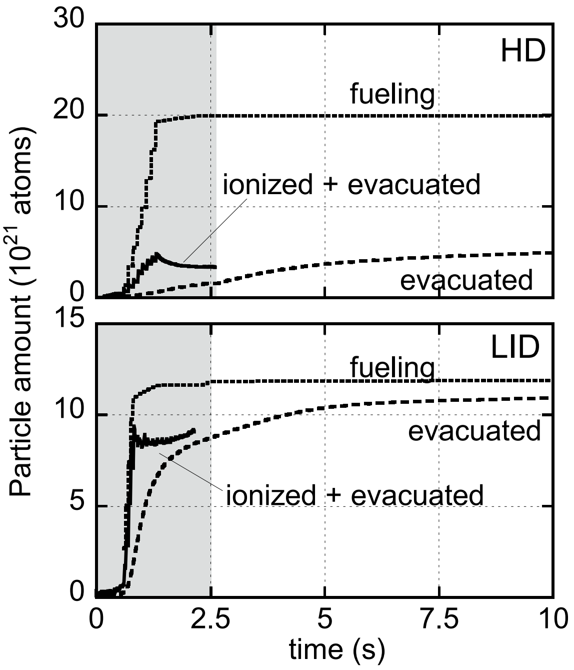

Fig. 2. Time evolutions of time integrated particle amounts during pellet fuelled discharges under the HD and LID configurations. The gray colored regions indicate the discharge durations. In both discharges, the maximum line averaged density is ~$2x10^{20}m^{-3}$.

using neutral pressure at the entrance of the pump-system and pumping speed. The ionized particle amount is estimated using line averaged density and plasma volume. Significant difference in particle balance property has been observed in these two divertor configurations.

In the HD case, the total amount of ionized and evacuated particles is about 25% of the input particles during the discharge. After the termination of the discharge, neutral pressure at the entrance of pump-system, P_0, increases as shown in Fig. 3, for the recombination of plasma particles and desorption from plasma facing components [3,6]. P_0 is the order of 10^{-2} Pa at the highest, and about 75% of fuelled particles remain in the vacuum vessel even at the start of next discharge. Fig. 4 depicts the amount of evacuated particles as a function of the amount of fueling particles in various discharges in the HD configuration. The former includes both particles evacuated during and after discharges. It can be seen that 25-67% of fueling particles are evacuated by the pump-system. The evacuated ratio varies with discharge condition. Fig. 5 shows the ratio of the evacuated particle number to the fueled particle number during a series of discharges with almost same fueling. The ratio is below one, though it increases with discharge number. This indicates that the wall pump is not saturated, but the capacity decreases during the series of the discharges. Figure 6 depicts the time evolutions of $n_{e,bar}$ and P_0 in the first (#64386) and the last (#64403) discharges shown in Fig. 5, and indicates the effect of the reduction of wall pump capacity on the discharge. Until t=0.3s, before the neutral beam injection, $n_{e,bar}$ and P_0 is almost same in these discharges, although they become larger after the start of neutral beam injections and ice-pellets injections in #64403 than them in #64386 even the fueled amount is almost same. P_0 rise after the termination of the discharge is also larger in #64403 than that in #64386. In

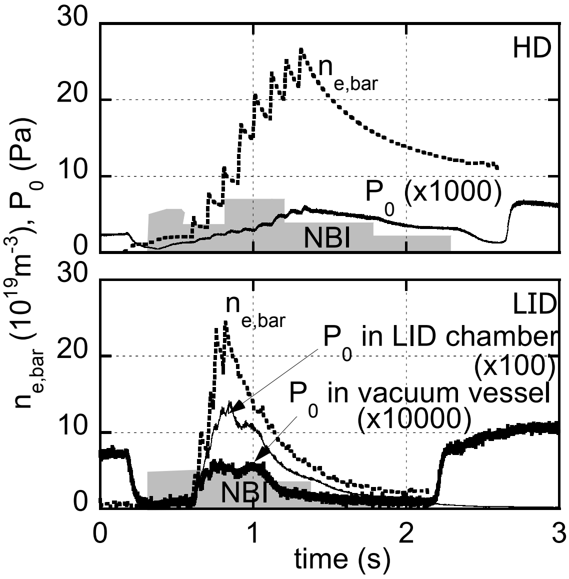

Fig. 3. Time evolutions of line averaged electron density ($n_{e,bar}$) and neutral pressure (P_0) in the same discharges as in Fig.2. P_0 indicates the neutral pressure at the entrance of pump system in the HD case and in the LID pump chamber and vacuum vessel in the LID case, respectively. Small peaks in $n_{e,bar}$ are caused by the multiple ice-pellet injections.

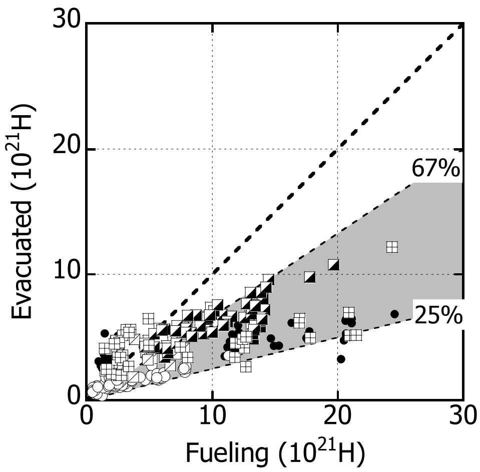

Fig.4. Evacuated particle number as a function of fueling particle number in the HD configuration discharges.

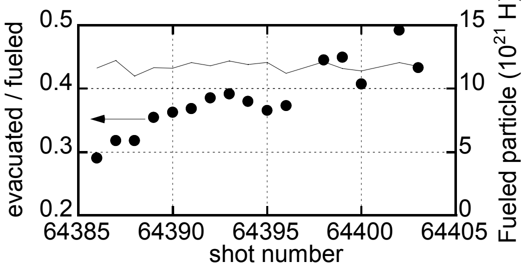

Fig. 5. The ratio of the evacuated particle number to the fueled particle number during a series of the HD *discharges with similar fueled particle number. Closed circles indicate the ratio, and the solid line indicates fueled particle number.*

Fig. 4, the evacuated ratio exceeds 67% in the small fueling discharges, below 10^{22} H, and it exceeds 1 in the discharges with fueling of below 5×10^{21}H. In such a small fueling discharges, particle fueling is done by neutral beam injection. Therefore, wall pump capacity can be recovered by using the NBI heated discharges with no additional fueling. During a series of such discharges the wall pump capacity is recovered. It should be noted that the evacuated amount in the recovery discharges is only a few times 10^{21} atoms as shown in Fig. 7, and it is very small compared to wall retention. As the result, total amount of the particle retention in the wall reaches up to the order of 10^{24} atoms after an experimental day [6]. Averaged areal density of retained atoms is 10^{21}-10^{22}H/m^2 under the assumption that the retained atoms are distributed first wall (700m^2). This areal density is higher than saturated amounts of hydrogen in SS [7], and the carbon deposit layer on SS first wall [8] is believed to be a reservoir.

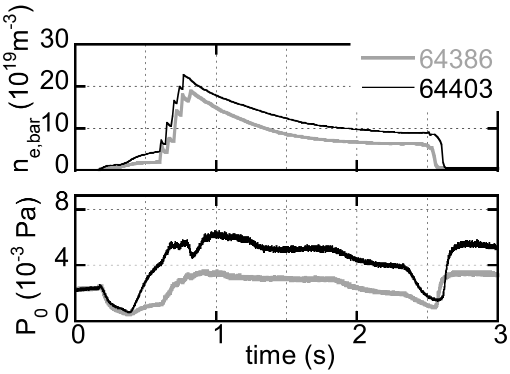

Fig. 6. Time evolutions of the line averaged dinsity (top) and P_0 (bottom) in #64386 and #64403.

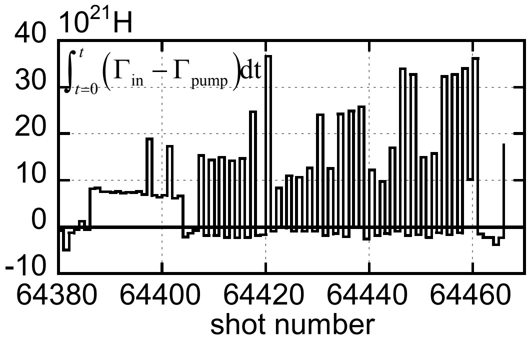

Fig. 7. The right hand side of the particle balance expression during a series of discharges. Positive and negative signs indicate wall retention and evacuation, respectively.

In contrast to the HD case in Fig. 2, the total amount of ionized and evacuated particles during a discharge is about 70% of the fuelled particles in the LID case. The total evacuated particles are over 80% during and after a discharge. In the LID discharge, the Hα intensity in plasma and the ion flux to the HD divertor plate measured by embedded Langmuir probe arrays are about 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. As shown in Fig. 3, the neutral pressure is the order of 10^{-1} Pa in the LID chamber in the LID discharge, and neutral pressure in the

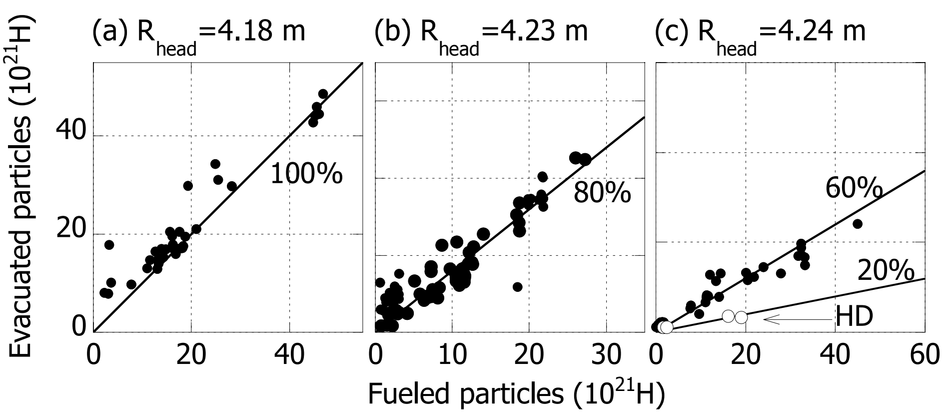

Fig. 8. Number of evacuated particles as a function of the fueled particle number. All numbers were estimated assuming hydrogen molecules. In (c), open circles show the case of the HD configuration.

vacuum vessel is less than one-fourth of that the HD case. This neutral pressure reduction is consistent with the reduction of ion flux to the helical divertor. The ratio of the evacuated particle to the fueled particle depends on the position of the divertor head. Figure 8 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}=4.18m is optimal in the vacuum condition. A larger R_{head} value means that the head locates outward. 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}=4.18m, the efficiency is almost 1, and the efficiency is about 0.6 for R_{head}=4.24m. This result is attributed to the shift of the peak of divertor particle flux profile on the head. As described previously, 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. 8(c), and it is about 0.2 in this case. To achieve 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. 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 discharge in Fig.3, P_0 in the LID chamber decreases monotonically after the termination of the discharge, although P_0 in vacuum vessel once increases. This suggests that the amount of retained particle in the LID divertor head and the LID chamber is so small. Because of the relatively small wet area (less than 0.5 m^2) and weak active cooling of the divertor head, the temperatures of the divertor plates measured by thermocouples are kept over 800°C during a series of discharges with high input power (>8MW, 2~3s), and they exceed 1000°C during the discharges. In such a high temperature operation, saturated retained amounts of hydrogen implanted into the carbon divertor plates are believed to be so small [7]. On the other hand, in the HD configuration discharges, the temperatures of the divertor plates are 300°C at most during similar discharges, and saturated retained amounts of hydrogen in carbon divertor plates are not largely reduced compared to them in room temperature graphite [9].

4. Conclusion

In the LHD, particle balance study has been conducted in the HD and the LID configurations. In the HD case, substantial part of fueled particles retained in vacuum vessel especially in discharges with large fueling amount (> 1×10^{22} H). The ratio of evacuated particle amount to retained amount is 25%-67%. The retained particle amount reaches 10^{24} H in an experimental day, and then the averaged areal density of hydrogen is 10^{21}-10^{22} H/m^2. Carbon deposit layer on the first wall is believed to be a reservoir. The ratio of evacuated particle amount to fueled particle amount increases during a series of discharges with similar fueling amount, and $n_{e,bar}$ and P_0 also increase with discharges. On the other hand, in discharges with small fueling amount (< 5×10^{21} H), it is observed that the evacuated particle amount is larger than retained particle amount. Therefore, small fueling amount discharge, for example the discharges fueled by only neutral beam injection can recover the wall pump capacity, and thus the density controllability.

Neutral particle behavior in the LID discharges is investigated with the operational configuration of R_{ax}=3.75m and B_t=2.64T. 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 very high evacuation efficiency (0.8-1) was obtained. Such high evacuation efficiency is considered to be caused by high temperature (>1000K) of divertor plates and reduced charge exchange particle flux to the first wall for reduced neutral pressure in vacuum vessel.

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