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Active Edge Control by LID for Steady State Plasmas

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Abstract

Numerical simulations to study the charged and neutral particle behavior in the LID configuration have been performed with preliminary experiments in LHD. For charged particles, a field line tracing code coupled with the random walk process, simulating the diffusion, provides striking point patterns on the LID head. It is found that particles can identify and follow the island structure with the diffusion coefficient less than 0.1 m^2/sec, i.e. LID works well as a divertor, and the head is free from its leading edge problem which will turn into severe issue in the steady state operation. On the other hand, LID acts like a conventional limiter with the diffusion coefficient larger than 0.1 m^2/sec. For neutral particles, 2D Monte Carlo code (DEGAS) is utilized to calculate pumping efficiency of LID, and it is shown that efficiency up to 50% can be achieved in the low recycling operation.

Keywords:

LHD, LID, magnetic island, edge plasma control, particle diffusion, recycling

1. Introduction

The Large Helical Device (LHD) has started its experiments since 1998 and explored new operational regime for helical devices [1]. One of the main objectives of the LHD project is to achieve high performance steady state plasmas to be able to extrapolate reactor-relevant conditions. In addition to the necessity of technical development of plasma heating equipments and plasma facing components, establishment of edge plasma control is a key issue to realize the steady state operation, since the recycling control of fueling and impurity particles should be more precise than that in the conventional pulse operation.

For the edge plasma control, inherent closed full helical divertor (HD) will be utilized in LHD, although baffle plates have not yet been installed up to now. Alternatively the Local Island Divertor (LID) is going to be used in the steady state operation for the active edge plasma control. The advantage of LID over a helical divertor is the technical ease of pumping in the closed system, since recycling is toroidally and poloidally localized in the small area. Theoretical and experimental studies in a small device were performed in advance of LHD experiments, and encouraging results to support the validity of the LID concept were obtained [2].

In LHD, preliminary LID experiments have been carried out since the first experimental campaign. Although the LID head and pumping system have not been constructed so far, perturbation coils to induce the magnetic island have already been installed in LHD. Using these coils, effect of the island on plasma properties was investigated, and degradation of the plasma stored energy and flattening of the electron temperature profile in the island were observed. These results will be discussed in another place. In addition to experiments, theoretical studies have also been performed simultaneously. Before trying new

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operational regime like steady state plasmas, it is important to survey some parameters widely and expect what would happen during the discharge. Using Monte Carlo codes, the condition of the diffusion coefficient required by LID was investigated, simulating the low and high recycling conditions, and the design study for the geometric structure of the head and pumping duct was also carried out to optimize pumping efficiency. In this paper, results of these theoretical investigations are mainly presented, taking the steady state operation into consideration. In sec. 2, the LID system is briefly presented. After describing results of numerical analyses in sec. 3, summary and discussion are given in sec. 4.

2. LID System

The LID is a kind of the island divertor which utilizes an m/n = 1/1 island on q = 1 surface and an LID head with the closed pumping system. Particles diffused from the core region cross the island separatrix and flow along the periphery of the island. After several toroidal turns, they reach the rear side of the island and strike the backside of the LID head where they are neutralized and finally pumped out efficiently with a well designed duct which realizes the closed divertor configuration. Since the LID head is inserted until the middle of the island, the leading edge of the head is kept away from direct strikes by particle, as shown in Fig. 1. Note that LID is not a pumped limiter because the LID head never scrapes off the confinement region.

The LID system consists of two parts, i.e., perturbation coils and the LID head system [3]. Ten pairs of small loop coils driven by three power supplies generate an m/n = 1/1 island whose width is about 15 cm in the steady state operation, while a factor of 1.4 wider island can be generated in the pulse operation for 10 seconds. These coils, of course, can be used to eliminate unfavorable islands due to error field induced by ferromagnetic materials located near LHD.

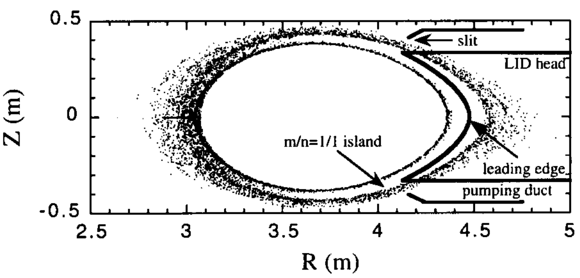

Fig. 1 Schematic of LID. Diffused particles are directed to the LID head along the island periphery, detouring to avoid the leading edge.

The LID head system consists mainly of a divertor head, a pumping duct, vacuum pumps and a driving system for the head and duct. The divertor head whose size is about 1 m × 0.6 m is covered with carbon tiles to which the water cooled copper heat sink is brazed. In order to withstand the steady state heat flux of 5 MW/m^2, great efforts have been paid for the design of the geometrical shape of the head, that is, angles between tiles and magnetic field lines are kept less than 10 degree everywhere.

By using eight cryogenic pumps with a hydrogen pumping speed of 42 m^3/sec, the effective pumping speed of 100 m^3/sec at the gate valve between LHD and the LID chamber is achieved, and the various operations from the low recycling to high recycling modes are available.

3. Results of Numerical Analyses

3.1 Effect of particle diffusion on LID function

For LID to function as an effective divertor, particles should be directed to the backside of the LID head along field lines in the island periphery. However, in the actual plasmas, there is the finite cross field diffusion due to collisions or the anomalous transport, by which trajectories of particles are deviated from magnetic surfaces of the island periphery. If the diffusion is too large, particles do not 'feel' the island and directly strike the leading edge without making detour to avoid it. In this situation, LID is no more a divertor but a conventional limiter, therefore the diffusion coefficient in the edge region should be less than a criterion for the ideal LID operation.

In order to estimate the diffusion coefficient appropriate to the LID operation, a field line tracing code coupled with the random walk process, i.e., Monte Carlo technique was employed [4] to simulate diffusive particle behavior. Two thousand particles are distributed uniformly a few cm inside the last closed flux surface (LCFS) on one poloidal cross section, and started excursions with deviations from field lines according to the effective diffusion coefficients D^*. The toroidal position of the initial poloidal plane for particles does not affect final results because a large number of deviations take place until each particle comes to the LID head or target plates of the helical divertor [5]. In the edge and divertor region where we are interested in, mean free path of the particle is ~0.6m if ion and electron temperatures are assumed to be ~50 eV and density ~5 × 10^{19} m^{-3}. In such a collisional situation, our simple simulation is valid as far as the bulk component of the plasma is concerned. High energy or large pitch angle particles due to auxiliary heatings cannot be dealt with by the code. However it has been clarified that the contribution of the high energy component to the stored energy is less than 10%, therefore, the neglect of such particles in the simulation does not affect results so much. Furthermore particle source by recycling is not considered.

Figure 2 shows striking point patterns on the LID head for different D^*s. It is clearly seen in (a) of D^* = 0.1 m^2/sec case that the leading edge is safe from direct strikes by diverted particles since it is completely in the island. Particles are well directed to the backside of the head, in other words, LID works as an island divertor. On the other hand, with D^* = 1.0 m^2/sec depicted in (c), the wetted area spreads out and the existence of island is hardly identified. In such diffusive plasmas, the slit between the divertor head and pumping duct should be wider, or diverted particles strike the pumping duct, leading to the impurity release from the surface of it. Pumping efficiency, of course, becomes low because neutrals can easily escape through the wide slit. In this case, LID acts like a conventional limiter. Note that similar striking points patterns like (c) are also obtained with any D^* by switching off the perturbation field, since the LID head is scraping off the region inside LCFS. Marginal situation is D^* = 0.5 m^2/sec shown in (b). Summarizing simulations about the particle diffusion, it is found that D is recommended for LID to be less than 0.1 m^2/sec.

Concerning the edge diffusion coefficient D, although direct or supporting measurements have not been performed in LHD, an experiment to estimate edge D indirectly was carried out by using a movable limiter [6]. In the experiment, particle flux to helical divertor plates through divertor legs was measured by Langmuir probes, changing the limiter position from ρ = 1.05 to 0.85 where ρ is a normalized minor radius. The more the limiter is inserted across LCFS, the less helical divertor flux comes to probes, since most of diffused particles are captured by the limiter before reaching helical divertor plates. Similar results can be reproduced by the simulation with the same configuration and diffusion process. The reduction rate of helical divertor flux in the limiter configuration was compared with that of the helical divertor configuration without the limiter. Adjusting D^* in the simulation to reproduce the experimental result, most appropriate value was determined to be ~ 0.1 m^2/sec. This is fortunately acceptable for LID, thus we believe LID works well in LHD.

Collecting efficiency of charged particles by LID was also estimated by the simulation, as shown in Fig. 3. In the figure $\Gamma_{total} = \Gamma_{LID} + \Gamma_{HD}$, i.e., total outward flux diffused from the confinement region, where Γ_{LID} and Γ_{HD} are particle flux to the LID head and helical divertor plates, respectively. It is found that more than 80% of diffused particles are collected by LID even with D^* = 1.0 m^2/sec, which is sufficient efficiency for LID to work well. Furthermore larger collecting efficiency up to ~98% is achieved with smaller D^*.

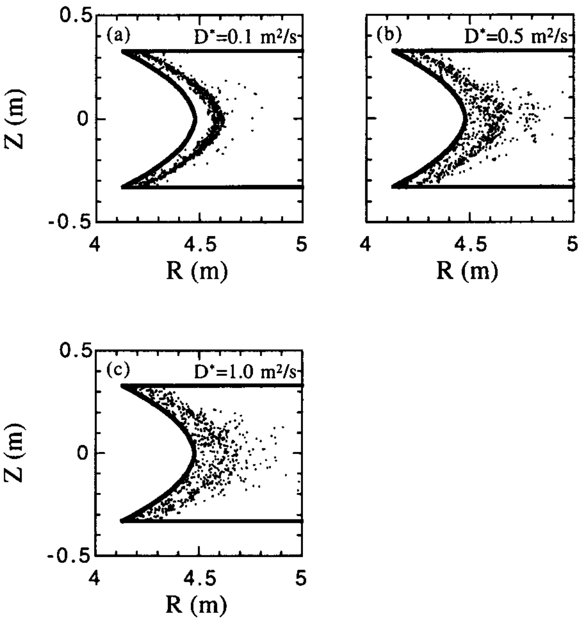

Fig. 2 Striking point patterns on LID head for (a) D^* = 0.1, (b) 0.5 and (c) 1.0 m^2/sec, respectively.

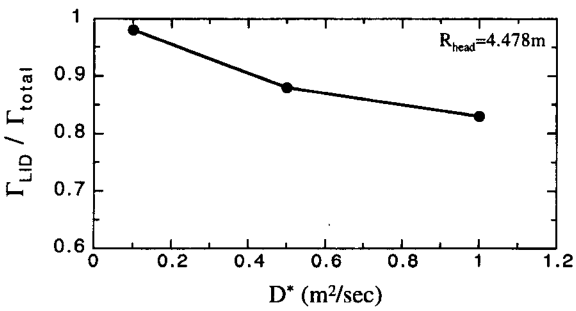

Fig. 3 Collecting efficiency of particles by LID. $\Gamma_{total} = \Gamma_{LID} + \Gamma_{HD}$, where Γ_{HD} and Γ_{HD}, are particle flux to LID head and helical divertor, respectively.

3.2 Neutral particle behavior in LID chamber

In order to estimate pumping efficiency of LID, a two-dimensional Monte Carlo simulation with the DEGAS code has been performed. Collected particles discussed in sec. 3.1 are neutralized on the LID head, after that, the DEGAS code follows the neutral particles until they are pumped out in the LID chamber or ionized again in plasmas near the LID head. Although charged particles striking the LID head have distribution on the surface of the head, neutral sources were assumed to be uniform in the simulation. Plasmas in front of the LID head are also assumed to be uniform.

Pumping efficiency in the simulation is defined as follows,

$$\varepsilon_{\text{pump}} = \frac{N_{\text{pump}}}{N_{\text{pump}} + N_{\text{slit}} + N_{\text{ionize}}} \tag{1}$$

where N_{pump}, N_{slit} and N_{ionize} are number of particle to be pumped out, to escape through the slit between the head and duct, and to be ionized in plasmas, respectively. The pumping effect by carbon tiles of the head is not taken into consideration. Summation of N_{pump}, N_{slit} and N_{ionize} is equal to the number of charged particles collected by the LID head.

It is found that, from Fig. 4, pumping efficiency up to 50% can be achieved if the plasma density and temperature in front of the LID head are low. In the high density or high temperature divertor operation, pumping efficiency becomes low, because ionization of neutral particles takes place very frequently near the LID head and they escape far away from the pumping duct. If recycling is localized near the duct, pumping efficiency may be higher. Note that the recycling process is not included in the simulation at present.

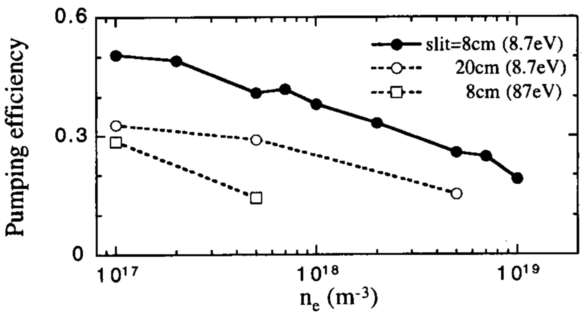

Fig. 4 Pumping efficiency of LID for different slit size and temperature.

Geometric effect like a slit size is also important for pumping efficiency as shown in Fig. 4, that is, a narrow slit is better from the view point of pumping. However the slit size practically has a minimum determined by the width of the plasma channel to be introduced to the head. If the edge diffusion coefficient *D* is small, the width of the plasma channel is, therefore, kept to be small as shown in Fig. 2, which is ideal for everything in LID. On the other hand, the diameter of the duct is not so important because its length is too short, compared with its diameter, to be worried about the conductance.

4. Summary and Discussion

Two Monte Carlo simulations, i.e. for charged and neutral particles, were carried out in the LID configuration. With regard to the diffusion coefficient, it is strongly requested for LID to be less than 0.1 m^2/sec, otherwise LID acts like a conventional limiter.

From the neutral particle simulation, it was found that pumping efficiency up to 50% can be achieved in the low density and temperature divertor operation.

Discussing overall pumping efficiency of LID, which is the most important parameter for divertors to be estimated their performance, results in Figs. 3 and 4 are referred to. It is concluded that overall pumping efficiency of LID is expected to be about 30–40%, which is extremely superior to tokamak divertors.

Acknowledgments

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