Experimental Observation of Plasma Flow Alternation in the LHD Stochastic Magnetic Boundary

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Though stochastic magnetic boundary so called ergodic layer is equipped intrinsically in the scrape-off layer in the ergodic divertor configuration tokamaks and heliotron-type devices, plasma flow properties in the region have not been understood well. In this study, we measured plasma flow using Mach probes in the Stochastic Magnetic Boundary to reveal the details of plasma flow. Spatial profile of the plasma flow was measured by using a movable multiple functions probe which consists of Mach probes and an ion sensitive probe. Ion saturation current obtained by the upstream and downstream probes suggest that the change of plasma flow direction in the stochastic magnetic boundary. Evaluated Mach numbers using the ion saturation current clearly show the existence of plasma flow alternation. The experimental results are indeed consistent with predicted results of the three dimensional simulation.

Keywords: plasma flow, stochastic magnetic boundary, Mach probe, ion saturation current, Mach number, Large Helical Device

1. Introduction

Plasma flow is the key parameters for characterizing the transport in the edge and divertor plasmas [1–5]. Recently, the field line structure in stochastic magnetic boundary has attracted attention from the viewpoint of the Edge Localized Mode (ELM) control and/or impurity transport in some tokamaks.

So far, numerical simulations regarding the edge transport in the Large Helical Device (LHD) boundary plasmas have been done by the three-dimensional plasma and neutral transport code, EMC3-EIRENE [6,7]. Since the remnant island width in the stochastic magnetic boundary is of order of cm or even larger at low field side, the of which is much larger than the ion Larmor radius, the plasma transport is considered to be affected by such the field line structure. The calculation result has predicted the change of the plasma flow direction in the LHD stochastic magnetic boundary [8,9].

Many sophisticated studies have been done by electron temperature (T_e), ion temperature (T_i) and electron density (n_e) measurements for the divertor region of LHD [10,11]. However, experimental observation of the plasma parameters and flow profiles in the stochastic magnetic boundary is still not enough achieved. Though the stochastic boundary is equipped intrinsically in the scrape-off layer in the ergodic divertor configuration tokamaks and heliotron-type devices, plasma flow properties in the boundary have not been understood well. The purpose of this paper is to report the first result of plasma flow measurement in the LHD stochastic magnetic boundary.

In this paper, we show experimental results of plasma flow measurement using Mach probe in the stochastic boundary in LHD. The results of ion saturation current (I_{isat}) measurement by means of the Mach probes suggest that the plasma flow direction is changed in the stochastic magnetic boundary. Comparing the experimental result with the simulation one, the existence of plasma flow alternation in the LHD stochastic magnetic boundary is discussed.

2. Experimental Setup

Figure 1 shows a schematic of the multiple functions probe head designed for measuring the plasma flow, T_e, T_i and n_e in the LHD stochastic magnetic boundary. The probe head consists of six single Langmuir probes and an ion sensitive probe (ISP). Pairs of probes of the opposite angle work as Mach probes. The probe tips were arranged at 60-degree intervals on the periphery of the shielding Boron-Nitride (BN) tube, which is 10 mm in diameter, such as the Gundestrup probe [13, 14]. The dimension of exposed area of each electrode is 1 mm in height and 1 mm in width. These electrodes are put 1 mm inside of BN tube. Tungsten (W) rods were used for the probe electrodes. The ISP for T_i and T_e measurements is

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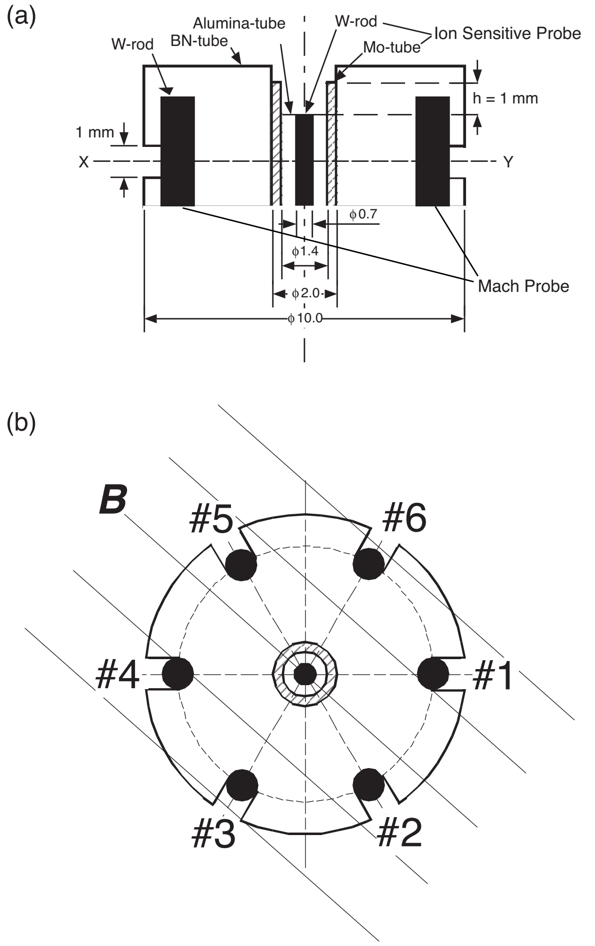

Fig. 1 The structure of the multiple functions probe head designed for the measurement in the LHD divertor and stochastic magnetic boundary. (a) Side view, (b) Cross section in $X - Y$ plane as seen in (a). Solid lines indicate the angle of the magnetic field lines in the measured stochastic magnetic boundary for each probe.

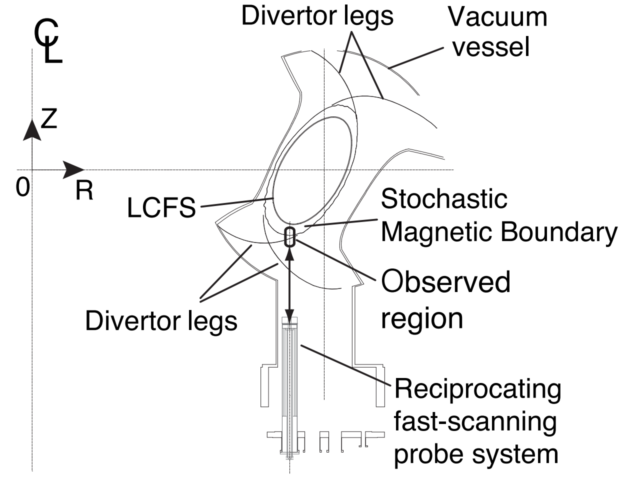

Fig. 2 Configuration of the reciprocating type fast scanning Langmuir probe system installed with the multiple functions probe head. The reciprocating paths of the head cross the divertor leg and the stochastic magnetic boundary as shown by arrows. The speed of reciprocating motion is 3 m/sec.

put on the top of the probe head. W rod and a molybdenum (Mo) tube were used for the inner and the outer electrodes of the ISP, respectively. Assuming the typical plasma parameters and magnetic field strength in the edge plasma in LHD, the distance between the tops of the inner and the outer electrodes is set on 1.0 mm according to the theory developed by Katsumata [12]. The both Mach probes and the ISP work simultaneously. However, we focus on the results obtained by Mach probes in this paper. The multiple functions probe was installed on the top of the reciprocating type fast scanning Langmuir probe system [15] as shown in Fig. 2. It was inserted from the bottom port of LHD. Using this system, the probe head can be reached in the LHD stochastic magnetic boundary. Notice the incident angle of the magnetic field line to each probe is different as shown in Fig. 1 (b). The probes were numbered from #1 to #6. In spite of the angle changes during the movement of the probe head in LHD, the angle is almost constant (40 $\sim$ 43°) in X-Y plane in the measured stochastic magnetic boundary in this study. The bias voltage for each Langmuir probe was set at -200 V in order to measure $I_{\rm isat}$ continually during the movement. The reference potential for all probe circuit was the ground (vacuum vessel's) potential. The resistances for detecting of $I_{\rm isat}$ were 100 Ω for each Langmuir probe. These voltage signals across the resistors were fed to a digitizer via isolation amplifiers. The resolution and the sampling rate of the digitizer were 14 bits and 1 MSamples/sec, respectively.

In order to estimate quantitative flow velocity or Mach number, precise analysis about particle flux is needed. It is important for the analysis to evaluate each effective collecting area of probe tip. The estimation of the area is strongly affected by the incident angle of magnetic field lines to the probe. Furthermore, sheath thickness around the probe electrode has also effect on the area. Using the pair of probes of the opposite angle, the difference of the incident angle is compensated because of the absolute angle is same for each probe.

3. Experimental Results and Discussion

Plasma flow measurements using the multiple functions probe in the stochastic magnetic boundary of LHD plasma were performed in hydrogen plasma with NBI heating in the operational configuration with the magnetic axis position ($R_{\rm max}$) of 3.75 m, a toroidal magnetic field strength of 2.64 T (Shot No. 84270).

Figure 3 (a) - (c) show the change of $I_{\rm isat}$ obtained by each Mach probe during the probe head movement in the stochastic magnetic boundary. The results obtained by probes located on the opposite angle in the probe head are compared in each figure. As shown in Fig. 3 (b), $I_{\rm isat}$ of the probe #5 shows larger value than the probe #2 in the probe position (Z) between -0.96 and -0.925 m. It means that probe #5 and #2 are located on upstream and downstream for the plasma flow, respectively. On the other hand, $I_{\rm isat}$ of the probe #2 becomes larger than that of the probe #5 in the position between -0.925 and -0.895 m. It indicates that the relation between probe positions and plasma flow is changed around Z = -0.925 and -0.895 m. The results suggest, namely, flow alternations exist around both of the positions. This behavior is also seen in the other pairs of probes as shown in hatched region of Fig. 3 (a) and (c). Here the difference of quantity of $I_{\rm isat}$ between Fig. 3 (a) - (c) can be mainly explained by the difference of the incident angle of magnetic field line to each probe. As shown in Fig. 1 (b), the incident angle is nealy normal to the probe #2 and #5. Hence, $I_{\rm isat}$ measured by these probes show large values compared with the other probes. Here, it must be mention that probe currents are also observed on probe #3 and #6 in spite of the shadow of the BN shield. The results might be explained by the Larmor motion of ions and/or the increasing of the thickness of sheath around these probes. After taking these results into consideration, it is found that the plasma flows from the side of probe #4, #5 and #6 to that of #1, #2 and #3 in -0.96 < Z < -0.925 m. The flow direction is changed to the opposite direction in -0.925 m < Z < -0.895 m.

Figure 3 (d) shows a calculated parallel particle flux using the three-dimensional plasma and neutral transport code, EMC3-EIRENE, under similar condition to the experimental one. Assumed input power was 2 MW as heat flux from the last closed flux surface (LCFS). Plasma density at the LCFS was set on 4 x 10^{19} m^{-3} as the boundary condition. The sign of the particle flux indicates the flow direction. The flux with a plus sign corresponds to the flow from the side of the probe #1, #2 and #3. Alternations of plasma flow are clearly shown at around Z = -0.925 and -0.895 m. The result is quite consistent with the observed profiles of $I_{\rm isat}$.

Figure 4 shows spatial profiles of ion acoustic Mach number of plasma flow (M_i) evaluated by following relation using the measured $I_{\rm isat}$;

$$M_{\rm i} = M_{\rm c} \ln \frac{i_{\rm up}}{i_{\rm down}} \qquad (1)$$

where $i_{\rm up}$ and $i_{\rm down}$ are measured current density of $I_{\rm isat}$ of upstream and downstream probes, respectively [16, 17]. The pairs of probes for evaluating M_i are the same with Fig. 3 (a)-(c), then the collecting areas of the both electrodes were assumed the same each other. $M_{\rm c}$ is the constant depending on a ratio of $T_{\rm i}$ to $T_{\rm e}$ and the ratio of specific heat of ion. Though several models for $M_{\rm c}$ have been proposed, $M_{\rm i}$ was evaluated by using $M_{\rm c}$ = 0.45 m, which is typical value under the experimental condition ($T_{\rm i}/T_{\rm e} \sim 1$). In order to avoid unexpected analytical error of the Mach number, spatially averaged $I_{\rm isat}$ was used. The average was taken for each 60 data point of measured $I_{\rm isat}$, which corresponds to the spatial average of about 10 mm width in Z direction. The error of M_i was estimated by using the standard deviation of the data for each position. Mach number is also calculated by EMC3-EIRENE code under the same condition as Fig. 3 (d). The experimentally evaluated Mach numbers obviously show the changes of plasma flow direction and the spatial profiles are the quite similar tendency with the result

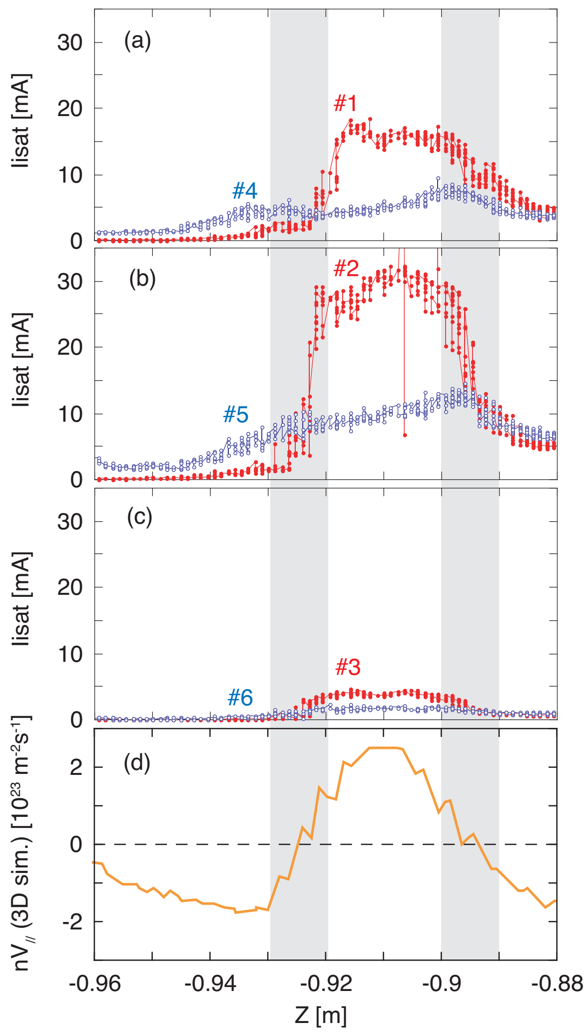

Fig. 3 Comparison of measured ion saturation currents with calculated particle flux using 3D simulation code. The numbers in (a) - (c) correspond to the probe numbers defined in Fig. 1. Flow alternations are clearly identified around Z = -0.925 and -0.895 m (hatched region).

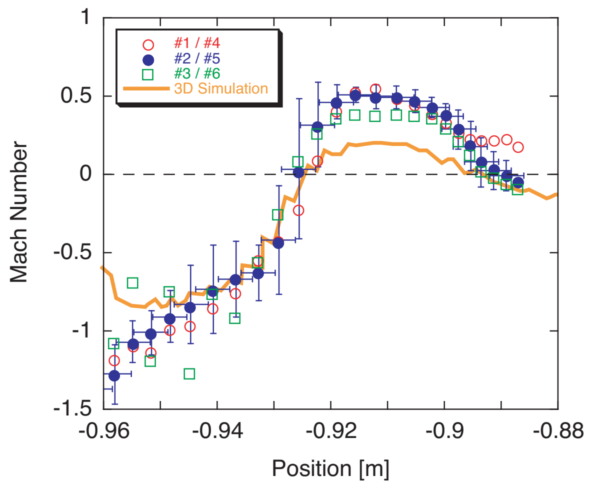

Fig. 4 Comparison of experimentally estimated Mach number with simulated one. Open circles, closed circles and open squares indicate the experimental results. Solid line shows the result of 3D simulation.

of 3D simulation.

As mentioned above, the remnant island width in stochastic boundary is of order of cm or even larger at low field side. The plasma transport is considered to be affected by such the field line structure, because the width is much larger than the ion Larmor radius. For particle/momentum transport, this appears as counter flow produced by the helical field lines inside the islands, as schematically shown in Fig. 5. Although the realistic field line in the edge is stochastic and there is no clear separatrix, the figure shows averaged field line trajectories, that is felt by plasma transport. The island is fed by the particle mostly via perpendicular transport across the separatrix region owing to the large pressure gradient of the radial direction. On the other hand, inside the island the parallel flow is driven by pressure gradient along the helical field lines, which results in counter flow in toroidal direction, as shown in the figure.

4. Conclusions

In this study, we show the first results of plasma flow measurement using Mach probes in the stochastic magnetic boundary in LHD. The results of $I_{\rm isat}$ measurement of the upstream and downstream probes suggest that the plasma flow direction is changed in the stochastic magnetic boundary. The evaluated Mach number using the measured $I_{\rm isat}$ is consistent with the result of 3D simulation. Comparing the experimental result with the simulation one, the existence of flow alternation in the LHD stochastic magnetic boundary is confirmed qualitatively.

Further investigation using the multiple functions probe in the stochastic boundary is expected to clarify the detail profiles of plasma flow and plasma parameters and to contribute to revealing the physics of the boundary plasma.

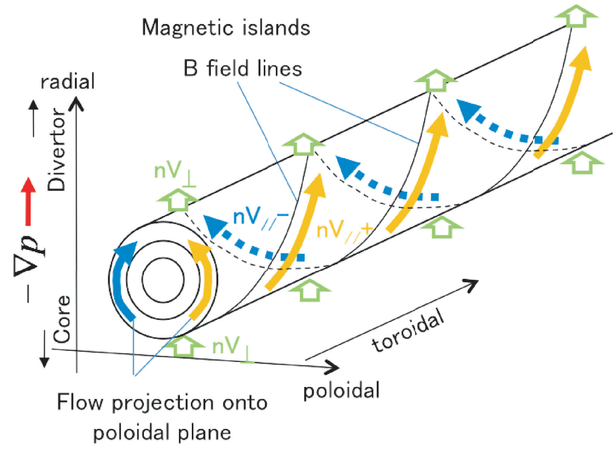

Fig. 5 Schematic model of plasma flow formation in stochastic magnetic boundary with remnant island.

Acknowledgments

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