INVESTIGATION OF THE HELICAL DIVERTOR FUNCTION AND THE FUTURE PLAN OF A CLOSED DIVERTOR FOR EFFICIENT PARTICLE CONTROL IN THE LHD PLASMA PERIPHERY

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The function of the divertor plasmas on the particle control in the plasma periphery is investigated from viewpoints of magnetic field line structures and neutral particle transport in the Large Helical Device (LHD). It shows that the particle and heat deposition on the divertor plate arrays are qualitatively explained by the distribution of strike points calculated by magnetic field line tracing including a particle diffusion effect. Control of neutral particle fueling from the divertor plates is a critical issue for sustaining long-pulse discharges and achieving superdense core plasmas. The behavior of neutral particles in the plasma periphery has been investigated by Hα emission measurements and a neutral particle transport simulation. It reveals that gas fueling from the toroidally distributed divertor plates heated by protons accelerated by ion cyclotron resonance frequency wave is necessary for explaining measurements in a long-pulse discharge, and the spatial profile of the neutral particle density in the plasma periphery in various magnetic configurations is explained by the strike point distribution. Based on these analyses, a closed helical divertor configuration optimized for the intrinsic magnetic field line structure in the plasma periphery is proposed for efficient particle control and heat load reduction on the divertor plates.

KEYWORDS: divertor, neutral particle transport, Large Helical Device

I. INTRODUCTION

The critical issues for realizing fusion reactors are reduction of heat loads on divertor plates and efficient particle/impurity control in the plasma periphery. Physical understanding of the divertor function is an important task for solving the above two issues. In the Large Helical Device (LHD), divertor plasmas have been fully measured with several plasma diagnostics: Langmuir probes, thermocouples, visible CCD cameras, an infrared camera, a pyrometer, visible and vacuum ultraviolet spectrometers, and so on. Experimental results measured with these plasma diagnostic systems in various magnetic configurations have been investigated by numerical calculations using magnetic field line tracing, a fully three-dimensional plasma fluid code, neutral particle transport simulation codes, etc.

Plasma discharge operations for ~10 yr in the LHD have demonstrated that the neutral particles released from divertor plates significantly affect plasma density control, especially in long-pulse discharges and high-plasma density operation. Suppression of uncontrollable neutral particle fueling from the divertor plates is essential for sustaining long-pulse discharges. Recent plasma discharge experiments demonstrate that peripheral plasma density control is an important issue for achieving superdense core (SDC) plasmas.†

A closed helical divertor can contribute to suppression of the peripheral plasma density by controlling the neutral particle fueling from the divertor plates. Detailed
understanding of neutral particle transport is essential for optimizing the design of the closed divertor configuration. For these purposes, three-dimensional neutral particle transport simulation codes have been applied to detailed investigation of the effect of the closed divertor on efficient particle control and reduction of the head load.

In this paper, intrinsic magnetic field line configurations in the LHD plasma periphery are briefly described in the next section. Measurements in two different magnetic configurations and numerical analyses by tracing magnetic field lines are shown in Sec. III. The location of neutral particle sources in an ion cyclotron resonance frequency (ICRF)–heated long-pulse discharge is investigated by a neutral particle transport simulation in Sec. IV. The effect of magnetic axis swing operation on dispersion of the heat load on divertor plates is described in Sec. V, and the analyses of neutral particle transport in the different magnetic configurations by $H_\alpha$ emission measurements and simulation are shown in Sec. VI. Optimization of the design of a closed helical divertor by neutral particle transport analyses is explained in Sec. VII.

II. MAGNETIC STRUCTURES IN THE LHD PLASMA PERIPHERY

The LHD is the largest superconducting helical machine, and its device parameters are major radius $R = 3.9$ m and averaged minor radius $a = 0.65$ m (Ref. 2). A helically twisted plasma ($\ell/m = 2/10$, where $\ell$ and $m$ are the polarity and the field period, respectively) is formed by the magnetic configuration due to two twisted helical coils and three pairs of circular poloidal coils without plasma currents (no large edge-localized modes and disruptions are induced). The nonaxisymmetric magnetic components due to the helical coils produce a three-dimensionally complicated magnetic field line structure (ergodic layer) around the last closed flux surface (LCFS). The magnetic field lines in the ergodic layer are bundled into four divertor legs on which magnetic field lines are directly connected to water-cooled isotropic carbon plates (divertor plates) installed along strike points on the vacuum vessel. One of the features of the LHD peripheral plasma is high rotational transform in the divertor region. Although the connection length of magnetic field lines in the ergodic layer reaches to several km, the connection length on the divertor legs is only a few meters because of the high rotational transform. The radial position of the magnetic axis $R_{ax}$ is controlled by changing the coil currents of the poloidal coils, which also varies the magnetic field line configuration in the ergodic layer and on the divertor legs.

Figure 1 shows the Poincaré plots of magnetic field lines in two different magnetic configurations ($R_{ax} = 3.60$ and $3.75$ m) in a horizontally elongated plasma cross section. It indicates that the region of the ergodic layer becomes broad with increase in the radial position of the magnetic axis. Although most of the magnetic field lines in the ergodic layer are bundled into two divertor legs in the inboard side of the torus for $R_{ax} = 3.60$ m, most of the magnetic field lines are connected to the outboard side for $R_{ax} = 3.75$ m.

III. PARTICLE AND POWER TRANSPORT IN THE LHD DIVERTOR

To achieve efficient particle control and the heat load reduction, understanding of the particle and power transport in the plasma periphery is an important task. The toroidal and poloidal distributions of the particle and power deposition on the divertor plates have been measured with Langmuir probes and thermocouples embedded in divertor plates.3

Figure 2a illustrates the top view of the equatorial cross section of the LHD vacuum vessel and divertor plate arrays. Single-channel $H_\alpha$ emission detectors are mounted on all outer ports for monitoring the toroidal distribution of neutral particles (hydrogen). The vertical and radial profiles of the $H_\alpha$ intensity have been measured with multichannel $H_\alpha$ emission detector arrays installed in an outer port (1-O) and an upper port (7.5-U), respectively.4 A visible CCD camera with an interference filter for $H_\alpha$ emission measurement is installed in an outer port (3-O) for monitoring the plasma periphery and plasma-wall interactions near a lower port (2.5-L). Three sets of ICRF antennas are set in 3.5, 4.5, and 7.5-U and -L ports for long–pulse discharge experiments and ion heating.6 Both sides of the antennas are protected by carbon limiters from heat load by the peripheral plasma. Figure 2b shows the divertor plate arrays in two helical sections viewed from an outer port. Langmuir probe arrays are embedded in five divertor plates (LP#1 through LP#5). Dome-type electrodes (2 mm in diameter) are
mounted along the edge of the divertor plates with 6 mm spacing. Thermocouples are located at the center of divertor plates (10 mm in depth) installed in every toroidal section where the plasma is horizontally and vertically elongated, as shown in Figure 2c, in order to measure the toroidal and poloidal distribution of the temperature of the divertor plates.

For estimating the distribution of the recycling neutral sources on the divertor plate arrays, magnetic field line tracing including a random walk process (as a particle diffusion) was carried out. The magnetic field lines are traced from uniformly distributed points on the LCFS. Figure 3a shows the toroidal distribution of the number of strike points along the traces A and B (see Figs. 2a and 2b) in the two different magnetic configurations ($R_{ax} = 3.60$ and $3.75$ m). It indicates that although most of the magnetic field lines terminate on the inboard side of the torus for $R_{ax} = 3.60$ m, they end locally at the upper and lower sides for $R_{ax} = 3.75$ m. The closed and open circles express the temperature rise of the divertor plates measured with thermocouples for the two magnetic configurations $R_{ax} = 3.60$ and $3.75$ m, respectively. The temperature rise is normalized by the maximum value in.

Fig. 2. (a) An equatorial cross section of the LHD vacuum vessel. (b) Schematic view of the divertor plate arrays (labeled A and B) for two toroidal pitch angles (72 deg). (c) Positions of the thermocouples embedded in the divertor plates in horizontally and vertically elongated plasma cross sections.

Fig. 3. (a) Toroidal distribution of the number of the strike points (lines) and normalized temperature rise of the divertor plates (circles). Thin (bold) lines and closed (open) circles correspond to $R_{ax} = 3.60$ and $3.75$ m. Traces A and B refer to the divertor arrays labeled A and B in Figs. 2a and 2b. (b) Toroidal distribution of the particle (squares) and the power (lines) depositions for the trace A calculated by the EMC3/EIRENE code in the two magnetic configurations ($R_{ax} = 3.60$ and $3.75$ m).
each magnetic configuration. The toroidal distribution of the temperature rise qualitatively agrees with the calculations of the number of the strike points in both magnetic configurations.

The toroidal distributions of the power and the particle deposition on the divertor plates are calculated by a three-dimensional plasma fluid code coupled with a neutral particle transport simulation code (EMC3/EIRENE) that includes the effect of the particle and the energy transport in the peripheral plasma, which can explain the measured profile of the electron temperature in the ergodic layer and that of neutral particles in the plasma periphery self-consistently. Figure 3b illustrates the calculation of the toroidal distribution of the power (lines) and the particle (squares) deposition for the trace A in the two magnetic configurations. The calculated profiles qualitatively agree with those of the number of the strike points obtained by the magnetic field line tracing, indicating that the toroidal distribution of the power and particle deposition is estimated by the plasma transport along magnetic field lines. One of the reasons there was no significant difference between the calculation by the magnetic field line tracing and that of the simulation codes can be low neutral density in the plasma periphery due to low neutral pressure \((<10 \text{ mPa})\) in the present divertor region (an open divertor configuration) in the LHD.

To investigate the relationship between the connection length of the magnetic field line \(L_C\) and the particle (ion flux) deposition on divertor plates, a test module with a Langmuir probe array was installed in an inner port. Figure 4a gives the experimental setup of a Langmuir probe array embedded in the test module installed in the inboard side of the torus. Figures 4b and 4c are the measurements of the ion saturation current profile (circles) for the two magnetic configurations. It shows some peaks whose positions correspond to those with the long connection length \( (> \text{several km})\) of the magnetic field lines (thin lines) and no contradiction between the measured profiles and those of the connection length. This supports that the estimation of the distribution of the power and particle deposition on the divertor plates by tracing the magnetic field lines from the LCFS is reasonable in the LHD plasmas.

The dependence of the distribution of the particle deposition on the radial position of the magnetic axis \(R_{ax}\) (shown in Fig. 3) is also experimentally confirmed by observations with the \(H\alpha\)-filtered visible CCD camera. Figures 5a and 5b give the Poincaré plots of the ergodic layer at a vertically elongated plasma cross section and images of \(H\alpha\) emission in the two magnetic configurations, respectively. Gray dotted squares represent the observation area of the CCD camera. The emission profiles in the two magnetic configurations are consistent with the magnetic field line distributions in lower divertor legs. This strongly suggests that the particle and power transport along the magnetic field lines are dominant in the LHD plasma periphery. These results also support the estimation of the particle and energy flux distributions on the divertor plate arrays by tracing magnetic field lines.

IV. NEUTRAL PARTICLE TRANSPORT ANALYSIS IN AN ICRF-HEATED LONG-PULSE DISCHARGE

Uncontrollable plasma density rise was observed in ICRF-heated long-pulse discharges (helium bulk and hydrogen minority heating) for \(R_{ax} = 3.60 \text{ m (Ref. 8)}\). The plasmas were terminated at around 150 s by radiation collapse. The single-channel \(H\alpha\) emission detector installed in the outer port (3-O) detected an observable \(H\alpha\)
intensity rise in the latter half of the long-pulse discharge (from \(\sim 90\) s), as depicted in Fig. 6. The toroidal and poloidal distributions of divertor plate temperature show the maximum temperature rise at 3-I port (\(\sim 400^\circ\)C). The CCD camera observed a hot spot on a vertically installed divertor plate near a lower port \(2.5-L\). The hot spot was observed only during ICRF heating by antennas installed in 3.5-L and 3.5-U ports. A bright thin line above a divertor leg near the lower port was also observed only during the ICRF heating.

To investigate the effect of accelerated protons by ICRF waves on the formation of the hot spot, the trajectories of the protons are calculated by a particle orbit analysis code in which the initial points of the protons locate along a minority ion cyclotron resonance layer just in front of the antennas in 3.5-L and 3.5-U ports. The calculation shows that the toroidal and poloidal distribution of the temperature rise of divertor plates is explained by the distribution of the strike points of the accelerated protons. It also indicates that the strike points of the accelerated protons concentrate on the position of the hot spot (2.5-L port). The bright thin line is also explained by the trajectory of the accelerated protons from the resonance layer in front of the lower antennas (3.5-L port).

For identifying the primary source of the neutral particle fueling that induced the uncontrollable plasma density rise in the long-pulse discharge, a three-dimensional neutral particle transport simulation code (DEGAS, version 63) was applied. In the simulation code, many test particles representing neutral hydrogen atoms and molecules are launched into a three-dimensional grid model, and the trajectories of the test particles are determined by the Monte Carlo method including the reactions of atomic and molecular processes in plasmas. The toroidal distribution of the \(H_\alpha\) intensity is calculated by integrating the emission along the line of sight of the detectors. Pure helium plasma is assumed in this simulation, the spatial profile of the plasma parameters inside the ergodic layer and on the divertor legs is based on the measurements, and the distribution of neutral particle source (hydrogen atoms and molecules) released from the divertor plates was defined by the distribution of the strike points calculated by the trajectory analysis of the accelerated protons.

Figure 7a gives the toroidal profile of the measured \(H_\alpha\) intensity rise [the ratio of the intensity at the plasma termination (150 s) to that before the intensity rise (90 s)], showing two peaks at 3-O and 10-O ports. Figure 7b is
the toroidal profile of the calculated $H\alpha$ intensity due to gas fueling induced by the accelerated protons. The calculation shows two peaks around 4-O and 9-O ports, which qualitatively agrees with the measured toroidal profile of the $H\alpha$ intensity rise. Open circles represent the calculation of the toroidal profile of the $H\alpha$ intensity in the case where the neutral particles are locally released from the vertically installed divertor plate (~2.5-L port) on which the hot spot was observed by the CCD camera. The calculation shows the locally peak profile of the intensity around 3-O port, which cannot explain the measured two peaks of the $H\alpha$ intensity rise. Open triangles indicate the calculated toroidal profile of the $H\alpha$ intensity due to neutral particles locally released from the carbon limiter for protecting the ICRF antennas installed in 2.5-U and 2.5-L ports. Although the calculation shows the peaked profile around 3-O port, the second peak around 10-O port cannot be explained by the neutral particles released from the carbon limiter.\textsuperscript{11}

The three-dimensional neutral particle transport simulation code reveals that local gas fueling from the position of the hot spot and of the carbon limiter alone cannot explain the measurement, indicating that toroidally distributed neutral particle sources are necessary for explaining the whole measured toroidal $H\alpha$ intensity profile in the long-pulse discharge. Neutral particles released from toroidally distributed divertor plates heated by the accelerated protons are indispensable for explaining the uncontrollable neutral particle fueling (the $H\alpha$ intensity rise) in the ICRF-heated long-pulse discharge. The dependence of particle desorption from the divertor plates on the temperature was investigated by an electron beam irradiation facility, indicating significant neutral particle desorption for $~300^\circ$C (Ref. 12). This can explain the measured $H\alpha$ intensity rise in the latter half of the long-pulse discharge, shown in Fig. 6. It strongly suggests that suppression of neutral particle fueling from the divertor plates heated by the accelerated protons is effective for extending the plasma duration in ICRF-heated long-pulse discharges.
V. MAGNETIC AXIS SWING OPERATION FOR HEAT LOAD REDUCTION ON DIVERTOR PLATES

The neutral particle transport analysis in the ICRF-heated long-pulse discharge strongly suggests that mitigation of the heat load on the divertor plates is effective for suppression of neutral particle fueling from divertor plates. The toroidal and poloidal distributions of the strike points are significantly different in the two magnetic configurations \( R_{ax} = 3.60 \) and \( 3.75 \) m. The heat load is mainly deposited in the inboard side and the lower/upper side of the torus in these two magnetic configurations, respectively, as shown in Fig. 3b. For this reason, it is effective for reduction of the heat load on the divertor plates to swing the radial position of the magnetic axis \( R_{ax} \) in the range between 3.60 and 3.75 m.

The magnetic axis swing operation was tried to optimize the range of the swing in ICRF-heated long-pulse discharges. Figure 8a shows the evolution of the temperature rise of divertor plates installed in an inboard side (\#1) and a lower/inner side (\#6) (see Fig. 2c) measured during a magnetic axis swing operation \( 3.62 < R_{ax} < 3.65 \) m. The temperature of the divertor plates monotonically increases, indicating no effective suppression of the temperature rise. Figure 8b shows the evolution of the temperature during a magnetic axis swing operation \( 3.65 < R_{ax} < 3.69 \) m. The temperature rise of the divertor plates was actively controlled and heat load was almost uniformly dispersed to the two divertor plates. The dispersion of the particle deposition on the two divertor plates by the magnetic axis swing operation was also observed with the Langmuir probe arrays.13

The magnetic axis swing operation \( 3.65 < R_{ax} < 3.69 \) m proved to be effective for dispersing the heat and particle deposition on the divertor plates. It successfully contributed to further extension of the plasma duration in ICRF-heated long-pulse discharges (>500 s) by suppressing the uncontrollable neutral particle fueling, which can be supported by installation of new divertor plates with a good heat removal efficiency.14

VI. ANALYSIS OF NEUTRAL PARTICLE TRANSPORT IN THE LHD PLASMA PERIPHERY

Control of the neutral particles released from the divertor plates is an important issue not only for long-pulse discharges but also for achieving SDC plasmas. Investigation of neutral particle transport in various magnetic configurations is essential for understanding the divertor function and for optimization of a future closed helical divertor configuration.

Neutral particles in the plasma periphery have been measured with multichannel \( H_\alpha \) emission detector arrays with polarization separation optics for identifying the location and the intensity of the emission on the line of sight of the detectors in various magnetic configurations.15 Figures 9a and 9b show the spatial profile of the \( H_\alpha \) emission on the poloidal cross section of the vertical array of the \( H_\alpha \) emission detectors in the two different magnetic configurations \( R_{ax} = 3.60 \) and \( 3.75 \) m, respectively. The measurements indicate that the \( H_\alpha \) emission locates in the edge of the ergodic layer or on the divertor legs. It also shows that the prominent \( H_\alpha \) emission area changes from the inboard side to the outboard side with the increase in the radial position of the magnetic axis \( R_{ax} \).

For detailed understanding of neutral particle transport in various magnetic configurations, a three-dimensional neutral particle transport code (EIRENE) was applied.16 The toroidal and poloidal distribution of gas fueling from the divertor plates was determined by the calculation of magnetic field line tracing from the LCFS including the particle diffusion effect. Plasma parameter profiles in the code are fixed to the experimental results measured with plasma diagnostic systems (a multichord far-infrared interferometer, YAG laser Thomson scattering, charge-exchange recombination spectroscopy, a reciprocating-type fast scanning Langmuir probe, and so on). Figures 10a and 10b indicate the calculated profiles of the \( H_\alpha \) emission on the
detector’s surface of the vertical array for $R_{ax} = 3.60$ and 3.75 m, respectively. It reproduces the change of the position of prominent H$_a$ emission area from the inboard side to the outboard side with the increase in the radial position of the magnetic axis $R_{ax}$ (Ref. 17).

Line integrated H$_a$ intensity profiles along the line of sight of the detectors can also be calculated by the simulation code. Figure 11a shows the intensity profile measured with the vertical and the horizontal detector arrays for $R_{ax} = 3.60$ m. The line of sight of the two H$_a$ emission detector arrays is also indicated in the figures. Figure 11b gives the intensity profiles calculated by integrating the H$_a$ emission along the line of sight of the vertical and the horizontal arrays. The calculations are qualitatively in agreement with the measurements, indicating that the neutral particle transport simulation is effective for the analysis of the divertor function and of neutral particle transport in the peripheral plasma because of reasonable agreement with the measurements in the two different magnetic configurations.

VII. DESIGN OF A CLOSED HELICAL DIVERTOR CONFIGURATION FOR EFFICIENT PARTICLE CONTROL

For efficient particle control in the LHD plasma periphery, installation of a closed helical divertor (CHD) is planned in the near future. It can be effective for controlling the plasma density and for achieving divertor detachment, which has not stably sustained in LHD plasmas yet. On the basis of the neutral particle transport analysis in various magnetic configurations, the inward-shifted magnetic configuration ($R_{ax} = 3.60$ m) is the best choice for the closed divertor configuration because the neutral particle density is relatively high in the inboard side, which is advantageous for efficient particle pumping from the inboard side, and the best plasma confinement time has been achieved in this magnetic configuration. Measurements with a fast-ion gauge installed in the inboard side indicate that the typical neutral particle pressure is $<10$ mPa for $R_{ax} = 3.60$ m (Ref. 19). A simple particle balance analysis during fueling pellet injection predicts that the neutral particle pressure is not enough for achieving efficient particle control. Thus, enhancement of the neutral pressure by more than one order of magnitude is necessary.

The CHD configuration has been optimized for achieving enhancement of the neutral particle pressure in the inboard side. Figure 12 shows a schematic view of the plan of the CHD configuration, which practically utilizes the three-dimensional structure of the magnetic field lines in the LHD plasma periphery for $R_{ax} = 3.60$ m. The components of the CHD are installed along the space between the two helical coils only in the inboard side because the magnetic field line tracing shows that more than 80% of the strike points locate there. The CHD consists of the following three components:

1. a V-shaped dome that can efficiently confine the neutral particles in the inboard side and hinder penetration of neutral particles into the ergodic layer and ionization near X-points in the inboard side. The plasma produced by the ionization inside the ergodic layer moves along the long magnetic field lines, which increases the...
peripheral plasma density. The neutral particles released from the divertor plates are accumulated behind the dome and pumped out with vacuum pumps installed along the space between the two helical coil cans.

2. slanted divertor plates to the inboard side such that neutral particles/impurities released from the divertor plates go toward the backside of the dome. The arrangement of the divertor plates functions as a baffle for preventing the outflow of the neutral particles from the divertor region into the main plasma. Most of the neutral particles in this configuration are ionized by plasmas on the divertor legs due to the small conductance between the divertor plates and the dome.

3. target plates vertically installed at both toroidal ends of the CHD components. The plates hinder toroidal outflow of neutral particles along the space between the two helical coil cans toward upper/lower ports and change the distribution of strike points from the upper/lower side to the inboard side because the target plates intersect the magnetic field lines on the divertor legs. The directions of magnetic field lines on two adjacent divertor legs...
across X-points are opposite; that is, while magnetic field lines on a lower divertor leg are directly connected to the inboard side, magnetic field lines on another divertor leg connect to the outboard side. The target plates are placed so as to intersect only the latter divertor leg for enhancing the neutral particle density in the inboard side.

Figure 13 is the Poincaré plots (including the diffusion effect) of the magnetic field lines in the plasma periphery for $R_{ax} = 3.60$ m in a poloidal cross section where the plasma is horizontally elongated in the case with the CHD components. The CHD has the following three main advantages over other closed divertor concepts:

1. The strongly ergodized divertor legs in the inboard side for $R_{ax} = 3.60$ m contribute to extending the plasma wetted area on the slanted divertor plates, which is roughly estimated to be $\sim 5$ m$^2$ by the magnetic field line tracing. Thanks to the large plasma wetted area, it is effective for mitigation of the heat load on the divertor plates. The plasma on the ergodized divertor legs prevents the outflow of the neutral particles from the divertor region to the main plasma due to the effect of the ionization of neutral particles on the divertor legs.

2. The curved divertor legs toward the inboard side of the torus are favorable for efficient particle control/pumping from the inboard side. This is because most of the neutral particles and impurities released from the slanted divertor plates go toward the entrance of the vacuum pumps.

3. Most of the strike points ($\sim 80\%$) are directly connected to the divertor and the target plates for $R_{ax} = 3.60$ m. This is favorable for neutral particle control because the neutral particles are efficiently pumped out from the inboard side with no interference with plasma heating and diagnostic systems that have to be installed in the outboard side.

In addition to these three advantages, the ergodic layer functions as a shield against impurity penetration, which has been experimentally confirmed by comparing the measurements of carbon emission profiles and the calculations by the three-dimensional plasma fluid code $^{21}$ (EMC3-EIRENE). The analysis indicates that friction force and remnant magnetic islands have significant effect on impurity retention in the ergodic layer. It is possible that the long magnetic field lines in the ergodic layer are effective for cooling down the plasma temperature due to radiation by impurities in the plasma periphery $^{22}$.

The spatial profile of the neutral particle density was calculated in the CHD configuration by using the neutral particle transport simulation code coupled with a one-dimensional plasma fluid analysis on the divertor legs in which volume source effects by recombination processes is included. In this calculation, the spatial profile of plasma parameters inside the ergodic layer is fixed to the calculation by the plasma fluid code (EMC3-EIRENE) in the case of $P_{\text{input}} = 8$ MW, $n_{\text{LCFS}}^{\text{LCFS}} \sim 4 \times 10^{19}$ m$^{-3}$, $\Gamma_{\text{total}} = 3.6 \times 10^4$ A, where $P_{\text{input}}$ is the input power from the LCFS into the ergodic layer, $n_{\text{LCFS}}^{\text{LCFS}}$ is the plasma density at the LCFS, and $\Gamma_{\text{total}}$ is the total plasma outflow current transported from the ergodic layer. A recycling coefficient on the divertor plates $R_{\text{div}}$ is assumed to be 0.65, which leads to a reasonable neutral particle pressure, being consistent with the measurements in the inboard side for the present open divertor. The particle reflection coefficient on the surface of the vacuum pumping system is set to 0.9 in this calculation. The spatial profile of the neutral particle density and plasma parameters on the divertor legs is determined by an iteration process between the plasma parameter profiles on the divertor legs and the neutral particle density profiles. Figure 14 gives the calculation of the three poloidal cross sections of the pressure profile of neutral hydrogen molecules in the CHD configuration for $R_{ax} = 3.60$ m. The molecular hydrogen density behind the dome in the inboard side is high (more than $\sim 0.3$ Pa), which is enough for achieving efficient particle pumping. Most ($\sim 80\%$) of neutral particles in the divertor region are ionized on the divertor legs. This indicates that plasmas produced by the ionization of neutral particles released from the divertor plates are almost recycled in the divertor region. A CHD configuration has been successfully designed for the LHD, which can contribute to further extension of the plasma duration time in ICRF-heated long pulse discharges, sustenance of SDC plasmas with reduced peripheral plasma density, and divertor detachment due to high density of neutral hydrogen molecules in the divertor region.
VIII. SUMMARY

The functions of the helical divertor have been investigated from viewpoints of measurements and numerical calculations by magnetic field line tracing. It indicates that the toroidal and poloidal distribution of the power and particle deposition on the divertor plates is estimated by tracing magnetic field lines in the plasma periphery with a particle diffusion effect. It is numerically supported by the calculation of a three-dimensional plasma fluid code (EMC3/EIRENE) that includes the effect of recycling neutral particles and energy transport self-consistently. A Langmuir probe array embedded in the test module installed in the inboard side shows some peaked profiles of the ion saturation current. The positions of the peaks correspond to those with the long connection length of the magnetic field lines (more than several km). This supports that the distribution of the power and particle deposition on the divertor plates is estimated by tracing the magnetic field lines. The neutral particle transport simulation indicates that control of the neutral particle fueling from the divertor plate is a critical issue for extending the plasma duration time in ICRF-heated long-pulse discharges. Measurements of the spatial profile of Hα emission and the neutral particle transport analyses in various magnetic configurations clearly show that an inward-shifted magnetic configuration ($R_{ax} = 3.60$ m) is favorable for the CHD configuration. By practically using the intrinsic three-dimensional magnetic field line structure in the LHD plasma periphery, efficient particle control can be achieved in the optimized CHD configuration. The CHD is also effective for sustaining ICRF-heated long-pulse discharges by actively pumping neutral particles released from divertor plates heated by protons accelerated by ICRF waves.

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