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Study of the effect of a closed divertor configuration on neutral particle control in the LHD plasma periphery

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Abstract

An optimized closed divertor configuration for effective particle control in LHD is proposed from the viewpoints of the distribution of the strike points and neutral particle transport. Calculations of the distribution of the strike points indicate that 50% of the strike points locate in the inboard side of the torus in a standard magnetic configuration (R_{ax}=3.60m). The ratio increases to 80% by installing target plates near lower/upper ports. A three-dimensional neutral particle transport simulation shows that installation of closed divertor components with the target plates raise the neutral pressure in the inboard side by more than one order of magnitude compared to that in the present open divertor case. The analysis of the neutral particle transport predicts that enhancement of the neutral pressure becomes moderate in outward shift configurations (R_{ax}>3.75m).

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PSI-18 Keywords: Divertor modeling, EIRENE, Hydrogen, LHD, Particle control

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1. Introduction

Control of the plasma density and neutral particles in the plasma periphery is found to be essential for super dense core plasmas and long pulse discharges [1, 2]. In the next experimental phase in LHD, a closed divertor configuration is planned for active control of the plasma periphery [3]. An issue for designing the closed divertor configuration is the low neutral pressure (<10mPa) in the divertor region. Enhancement of the neutral pressure by more than one order of magnitude is required for effective particle control. Magnetic field components produced by two super-conducting coils (helical and poloidal coils) form a complicated three-dimensional magnetic field line structure. For this reason, we started the optimization of the closed divertor configuration by using a three-dimensional neutral particle transport code with a one-dimensional plasma fluid analysis [4].

Previous analysis suggests that a closed divertor configuration in the inboard side of the torus is reasonable because the neutral density in this region is relatively high in a standard magnetic configuration (R_{ax}=3.60m) in which good plasma confinement has been achieved. The measurements of polarization resolved H_α spectra and the vertical profiles of the line integrated H_α intensity are in good agreement with the calculations by the simulation [5, 6]. It predicts that the closed divertor configuration can enhance the density of neutral hydrogen molecules in the inboard side by more than one order of magnitude compared to that in the present open divertor [4]. This paper proposes a further optimized closed divertor configuration with vertical target plates. The effect of the closed divertor components is investigated from the viewpoints of the distribution of the strike points and neutral particle transport in various magnetic configurations.

2. Magnetic field line configuration in the plasma periphery and the distribution of strike points

The magnetic components by the super-conducting coils form an ergodic layer around the last closed magnetic flux surface (LCFS). Four bundled magnetic field lines (divertor legs) are deviated from the ergodic layer at the position of X-points. Magnetic field lines on the divertor legs directly connect to divertor plates (carbon). The magnetic configurations in the plasma periphery are changed by the magnetic axis R_{ax} which is controlled by electric currents in the super-conducting coils.

There are two typical magnetic configurations such as R_{ax}=3.60 and 3.75m, which have significantly different magnetic structures in the plasma periphery. Figure 1 (a) gives the Poincare plots of the ergodic layer in vertically elongated plasma cross section. Figure 1 (b) shows images of H_α emission in a lower divertor region, which are taken with a tangentially viewing CCD camera. Blue broken squares in the plots represent the observation area. The measurements of the H_α emission profile in the two magnetic configurations are explained by the presence of the peripheral plasma along the magnetic field lines in the lower divertor region (Figure 1 (b)), showing that the distribution of the strike points and the plasma flow onto the divetor plates are significantly changed by the magnetic configuration. The changes of the plasma flow are experimentally confirmed by temperature increments of divertor plates measured with thermo-couples and ion saturation current profiles on the divertor plates [7].

Magnetic field line tracing including a particle diffusion effect gives the distributions of the strike points. Figure 2 (a) shows the calculation of the three-dimensional plots of the strike points in the present open divertor case for

R_{ax}=3.60m. Red dots express the strike points on the divertor plates (expressed as dark gray) installed along the four divertor legs (I~IV) in the helically twisted vacuum vessel (light gray). The calculation shows that the strike points concentrate in the inboard side of the torus (purple shaded area) in this magnetic configuration.

3. The distribution of strike points in closed divertor configurations

Figure 2 (b) gives the distribution of the strike points in the closed divertor configuration which consists of baffle plates (blue), a V-shaped dome (green) and slanted divertor plates (dark gray) (all components are made of carbon) installed along the space between the two helical coils in the inboard side. The divertor components are designed to raise the neutral pressure at the backside of the dome. From the strike points on the slanted divertor plates, neutral particles are released toward the backside of the dome. The baffle plates suppress outflow of the neutral particles from the divertor region to the main plasma.

Installation of vertical target plates (red) (made of carbon) near lower/upper ports can contribute further enhancement of the neutral pressure in the inboard side. This is because the target plates change the position of the strike points from the lower/upper side to the inboard side by intersecting divertor legs. Additionally, the target plates confine the neutral particles in the inboard side.

As shown in Figure 2 (c), the target plates intersect the two divertor legs in which the magnetic field lines directly connect to the lower/upper side of the torus. While the target plates change the position of the strike points in R_{ax}=3.60m, it is not effective in R_{ax}=3.75m. This is because the magnetic field lines on the right (left) divertor legs in the broken squares in Figure 1 (a) connect to the lower/upper (inboard) side of the torus. Most of the magnetic field lines on the divertor legs for R_{ax}=3.75m are connected to the inboard side as shown in the left divertor leg in Figure 1 (b). These magnetic field lines should not be intersected by the target plates.

Concentration of the strike points in the inboard side is desirable for the closed divertor configuration for efficient particle pumping. The ratio of the number of the strike points in the inboard side ($N_{inboard}$) on that of all strike points (N_{all}) is investigated in various magnetic configurations (3.50m<R_{ax}<4.00m). We counted the strike points locating on the closed divertor components including the target plates as that in the inboard side. Figure 3 is the histogram of the ratio $N_{inboard}/N_{all}$ in various magnetic configurations, showing that the ratio is the maximum for R_{ax}=3.60m in both cases with and without the target plates as shown as open and shaded bars, respectively. While the ratio stays high (about 0.8) in the case with the target plates in inward shift configurations (R_{ax}<3.65m), the ratio and the contribution from the target plates diminish in outward shift configurations (R_{ax}>3.75m). It indicates that the inward shift configurations are advantageous for efficient particle control by the closed divertor.

4. Neutral particle transport simulation with a one-dimensional plasma fluid analysis

EMC3-EIRENE code has been widely used for detailed analysis of the plasma and neutral particle transport [8]. The code solves the plasma fluid equations of mass, momentum and electron/ion energy self-consistently in a three-dimensional geometry, which is coupled with the parameters of neutral particles calculated by the EIRENE. In application of EMC3 in LHD plasmas, the plasma parameters along divertor legs have been neglected because the large rotational angle of the magnetic field line on the divertor legs is not acceptable to the code [9]. Thus the calculation domain is extended so as to include the divertor legs with an assumption that the plasma parameter profiles inside the ergodic layer are fixed to the calculation of the EMC3-EIRENE code during the iteration process between the plasma and neutral particle transport on the divertor legs. Three differential fluid equations for plasma density, momentum and energy are solved along the magnetic field lines on the divertor legs by using the Runge-Kutta method from the upstream of the divertor legs [10]. For solving the differential equations, the electron temperature is assumed equal to the ion temperature.

The connection length of the magnetic field lines on divertor legs is short (few meters), where one-dimensional plasma fluid analysis is applicable, because the plasma transport transverse to the magnetic field lines can be ignored. Iterative calculation of the equations coupled with the parameters of neutral particles (hydrogen atoms and molecules) gives a solution under the following boundary conditions:

1. The plasma flow velocity ($v_{//}$) on the divertor plates is fixed to be a sound speed c_s for satisfying the Bohm criterion,
2. Three invariants (plasma density, momentum and energy) at the upstream of the divertor legs are fixed to be the calculations by the EMC3-EIRENE code in the case of P_{input}=8MW, n_e^{LCFS}~4×10^{19}cm^{-3}.

Conversion of the one-dimensional plasma parameter profiles along the magnetic field lines on the divertor legs to that in the three-dimensional grid model for the EIRENE code is based on the procedure in a track-length estimator [11].

5. Profiles of neutral particle pressure in the closed divertor configuration

For detailed analysis of neutral particle transport for the closed divertor configurations, three-dimensional grid models of the vacuum vessel (stainless steel) and the divertor components are constructed as shown in Figure 2. The divertor components consist of triangles, and the plasma is composed of hexahedrons in which the plasma parameters are defined. These parameters are from the calculations of the EMC3-EIRENE and the one-dimensional plasma fluid analysis. The target plates are included in the grid model (Figure 2 (c)). The parameters of released neutral particles from the target plates are determined from a plasma-wall interaction database calculated by the TRIM code. The calculation of the one-dimensional plasma fluid analysis gives plasma parameters on the divertor plates.

Figure 4 (a) shows four poloidal cross sections of the calculations of the pressure profile of hydrogen molecules in the closed divertor configuration with the target plates for R_{ax}=3.60m. The absolute neutral pressure depends on the particle reflection ratio of the divertor plates. The ratio (R_{div}) is set to be 0.6 so that the neutral pressure of the molecular hydrogen in the inboard side for the open divertor configuration is about 10mPa which agrees with recent detailed measurements with a fast ion gauge. The presence of strong particle pumping on the divetor plates and the vacuum vessels is experimentally proved by a particle balance analysis in relativley short pulse plasma discharges (<10s) [12, 13]. Ion beam analyses of the divertor plates show that large amounts of hydrogen are trapped in thick carbon deposition layers on the surface of the plates. The microscopically complicated structure of the deposition layer and deposited Ti (by gettering) on the divertor plates and the vacuum vessel may form very strong trapping site for hydrogen [14].

A simple particle balance analysis during fueling pellet injection indicates that formation of an area where molecular hydrogen pressure in the order of 100mPa is required for achieving efficient particle control. The neutral particle transport simulation predicts that the closed divertor configurations can enhance the neutral pressure in the inboard side to about 140mPa. The simulation also shows that the pressure of molecular hydrogen is locally high (~150mPa) near the target plates as shown at toroidal angles ϕ=10 and 28°. The reason for this is that hydrogen molecules released from the target plates are confined in secluded spaces surrounded by the target plates, the vacuum vessels and the baffle plates.

Figure 4 (b) gives the calculated pressure profiles of neutral hydrogen molecules for R_{ax}=3.75m, which shows that the pressure of neutral hydrogen molecules in the inboard side is moderate (~30mPa). While the neutral pressure in the secluded space is quite low, the pressure is relatively high at the back side of the dome near the target plates (~40mPa) as shown at ϕ=10 and 28°. The ratio of the number of the strike points on the target plates decreases with the magnetic axis R_{ax} in the outward shift configurations (R_{ax}>3.75m) as shown in Figure 3, meaning no significant neutral gas source on the target plates. The change of the distribution of the strike points in the inboard side by the magnetic axis R_{ax} causes the difference of the neutral pressure profile.

6. Summary

For studying the effect of the closed divertor configuration, the distribution of the strike points and neutral particle transport are investigated in various magnetic configurations. The ratio of the strike points in the inboard side increases from about 0.5 to 0.8 for inward shift configurations by installing the target plates. The ratio of the strike points and the effect of the target plates diminish for outward shift configurations.

The neutral particle transport simulation with the one-dimensional plasma fluid analysis of the divertor legs for R_{ax}=3.60m shows that the closed divertor configuration can enhance the neutral pressure so as to achieve efficient particle pumping from the inboard side. The simulation predicts that formation of high neutral pressure of hydrogen molecules in the secluded space near the target plates. It indicates that installation of vacuum pumping systems in the inboard side and the secluded space is favorable for the inward shift configurations (R_{ax}<3.65m). The effect of the closed divertor configuration on enhancement of the neutral pressure is moderate for R_{ax}=3.75m. The region with relatively high neutral pressure is formed at the backside of the dome near the target plates, meaning that particle pumping from this area is effective in the outward shift configurations (R_{ax}>3.75m).

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Figure captions

Fig. 1. (a) Poincare plots of the ergodic layer for R_{ax}=3.60 and 3.75m. (b) Measurements of the H$_\alpha$ emission profile in a lower divertor region in the two magnetic configurations.

Fig. 2. Three-dimensional plots of the strike points (red dots) for R_{ax}=3.60m in the case of the present open divertor (a) and a closed divertor configuration without (b) and with target plates (c). Closed divertor components installed in the inboard side are shown in this three-dimensional model which is viewed from the outboard side.

Fig. 3. Ratios of the number of the strike points locating in the inboard side on that of all strike points in the cases with and without the target plates in various magnetic configurations (3.50m$<R_{ax}<$4.00m). It shows that the target plates are effective for increasing the ratio by changing the position of the strike points to the inboard side in inward shift configurations ($R_{ax}<$3.65m).

Fig. 4. Four poloidal cross sections of the calculated pressure profiles of neutral hydrogen molecules for R_{ax}=3.60m (a) and 3.75m (b) in the closed divertor configuration with the target plates.

Figure

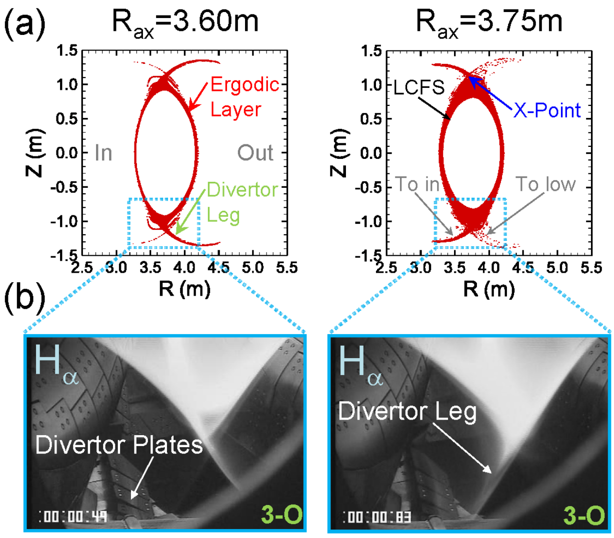


Figure 1

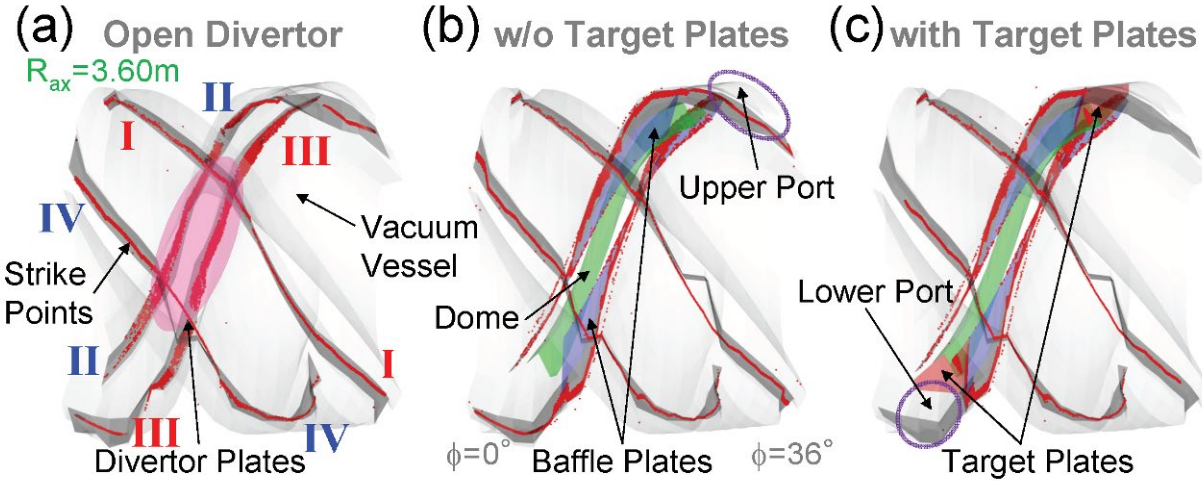
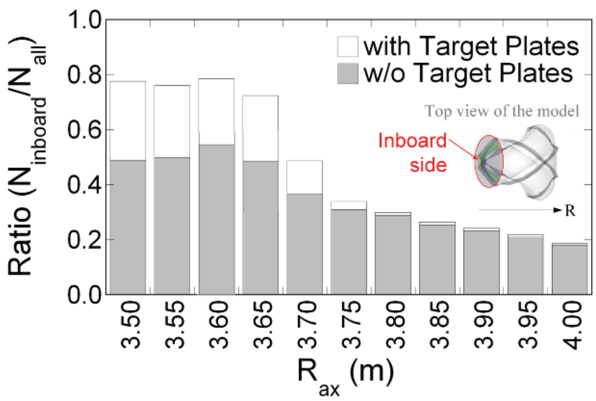

(a) Open Divertor
R_{ax}=3.60m
I
II
III
IV
Strike Points
Vacuum Vessel
II
I
III
IV
Divertor Plates
(b) w/o Target Plates
Upper Port
Dome
ϕ=0°
Baffle Plates
ϕ=36°
(c) with Target Plates
Lower Port
Target Plates

Figure 2



1.0
0.8
0.6
0.4
0.2
0.0
Ratio (N_inboard/N_all)
with Target Plates
w/o Target Plates
Top view of the model
Inboard side
R
3.50
3.55
3.60
3.65
3.70
3.75
3.80
3.85
3.90
3.95
4.00
R_ax (m)

Figure 3

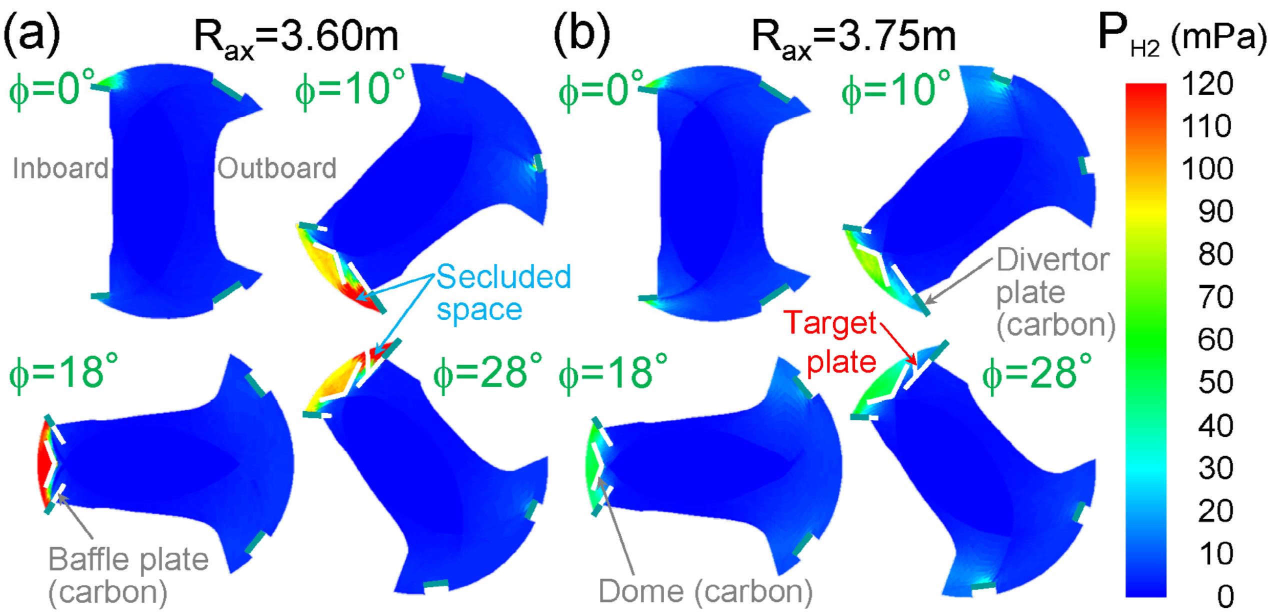

(a)
R_{ax}=3.60m
(b)
R_{ax}=3.75m
P_{H2} (mPa)
ϕ=0°
ϕ=10°
ϕ=18°
ϕ=28°
Inboard
Outboard
Secluded space
Baffle plate (carbon)
Divertor plate (carbon)
Target plate
Dome (carbon)
120
110
100
90
80
70
60
50
40
30
20
10
0

Figure 4