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M. Shoji*, S. Masuzaki, T. Morisaki, M. Tokitani, R. Sakamoto, H. Yamada and the LHD Experiment Group

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292,Gifu, Japan

Abstract

A closed helical divertor (CHD) has been designed for efficient particle control in the plasma periphery and for retaining neutral particles and impurity ions in the divertor region. The effect of impurity retention by divertor legs for the CHD configuration is investigated from the viewpoints of neutral impurity transport and force balance of impurity ions along magnetic field lines. A fully three-dimensional neutral particle transport simulation proves that the plasma on the divertor legs is effective for retaining neutral particles/impurities in the CHD region. A one-dimensional impurity ion transport analysis predicts that friction force by plasma flow from the main plasma sweep impurity ions toward the divertor plates even in high neutral density case in which a steep temperature gradient is formed. It shows that the CHD configuration is promising for enhancing LHD plasma performance by effective control of the neutral particles and the impurity ions in the plasma periphery.

JNM Keywords: Theory and Modeling (T0100), Impurities (I0100), Carbon (C0100)

PSI-19 Keywords: Divertor modeling, EIRENE, Carbon impurities, LHD, Impurity transport

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**Corresponding Author Address:* National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*

**Corresponding Author e-mail:* shoji@LHD.nifs.ac.jp

Presenting Author: Mamoru Shoji

Presenting Author e-mail: shoji@LHD.nifs.ac.jp

1. Introduction

Recent plasma discharge experiments in the Large Helical Device (LHD) demonstrate that control of the peripheral plasma density is essential for sustaining super dense core (SDC) plasmas and achieving high ion temperature with an internal transport barrier (ITB) [1]. The plasma density control has been found to be critical to sustain long pulse plasma discharges heated by ICRF waves [2]. A closed helical divertor (CHD) has been designed for controlling the peripheral plasma density by neutral particle pumping. One of the major concerns for designing the CHD configuration was low neutral particle pressure in the divertor region (less than the order of 10mPa) in the present open divertor cases. The neutral pressure is not sufficient for efficient particle pumping by a realistic vacuum pumping system (planned). A fully three-dimensional neutral particle transport simulation for the CHD configuration predicts that enhancement of neutral particle density behind a dome structure by more than one-order of magnitude compared to that in the open divertor cases in an inward magnetic axis shift configuration (R_{ax}=3.60m), which means enhanced neutral density (>0.1Pa) is high enough for the efficient particle pumping [3]. The next concern of the CHD configuration is impurity transport in the divertor region, because neutral impurities can escape from the CHD region through gaps between the divertor plates, and the connection length of magnetic field lines on divertor legs is very short, which means that impurity ions released from the divertor plates can easily reach to the main plasma. In order to examine the performance of the CHD configuration, impurity transport is investigated by the neutral particle transport simulation code and an analysis of the force balance of impurities on the divertor legs.

2. Closed helical divertor configuration

The LHD is the largest super-conducting heliotron-type machine, with a set of l=2, m=10 helical coils and three pairs of poloidal coils. The edge magnetic field line structure outside the last closed flux surface (LCFS) consists of an ergodic layer, residual islands, and an edge-surface layer [4]. Four bundled magnetic field lines (divertor legs) deviate from the ergodic layer at two X-points and directly connect to divertor plates at strike points. While the connection length of the magnetic field lines in the ergodic layer is more than several km, the connection length on the divertor legs is very short (only a few meters).

Figure 1 shows the CHD configuration which consists of three components: slanted divertor plates, target plates and a dome structure, which confine neutral particles released from the divertor plates behind the dome [5]. The CHD components are installed only in the inboard side of the torus because a calculation of magnetic field line tracing shows that about 80% of the strike points locate on the CHD components in inward magnetic axis shift configurations in which the best plasma confinement has been achieved [6]. The neutral particles behind the dome structure are pumped out by a vacuum pumping system installed along the space between two helical coils in the inboard side (the position is shown as a transparent red curved line).

3. Neutral particle transport analysis for the closed helical divertor configuration

A fully three-dimensional neutral particle transport simulation code (EIRENE) has been applied to detailed analysis for the CHD configuration [7]. Figure 1 shows the three-dimensional model used for this analysis, in which the shape of the plasma, the vacuum vessel and the geometry of the CHD components for one toroidal pitch angle (0°<ϕ<36°) are included as precise as possible. Neutral density profiles are calculated by tracking the trajectories of many test particles which are representative of neutral particles (hydrogen atoms/molecules and impurities). The two poloidal edge surfaces in the model are treated as periodic surfaces to simulate the full torus geometry.

It is assumed that the surface of all divertor plates and the vacuum vessel are fully covered with carbon. Reflection and absorption of neutral particles on the surfaces are determined by the database of a plasma surface interaction code (TRIM) implemented in the neutral transport simulation code. The CHD components consist of many triangular 'additional surfaces' from which the neutral particles are released into the model. Carbon atoms are released by physical and chemical sputtering from the CHD components [8, 9].

The plasma parameter profiles inside the ergodic layer are determined by the calculation of a three-dimensional plasma fluid code [10]. This code cannot calculate the plasma parameter profiles on the divertor legs because of the high rotational transform of the magnetic field lines near the helical coils. This is because, on making a three-dimensional mesh model for this code, several poloidal cross-sections of grid models of the plasma and the vacuum vessel are interconnected along the magnetic field lines. In the high rotational transform conditions, one cannot construct a geometrically consistent mesh model by a finite unit of the poloidal cross-sections by unacceptable distortion of the grids due to the strong curvature of the magnetic field lines.

To overcome this restriction, the calculation domain is extended so as to include the divertor legs by applying a one-dimensional plasma fluid analysis. It is assumed that the three invariants (plasma particles, momentum and energy) at the boundary of the upstream of magnetic field lines on the divertor legs (near X-points inside the ergodic layer) are fixed to the calculation of the plasma fluid code during an iteration process between the two codes (the neutral particle transport code and the one-dimensional fluid analysis code). In this plasma fluid analysis, electron temperature is treated as the same as ion temperature, and no impurity effects are included for simple calculation. The assumption of the equality of the electron and ion temperatures is guaranteed by the short energy equipartiton time and long connection lengths (more than several km) in the ergodic layer in the inboard side. Three one-dimensional differential equations for particle, momentum and energy are solved along the magnetic field lines using the Runge-Kutta method using the calculations of the neutral particle transport code. The effect of transverse diffusion across the magnetic field lines on the divertor legs is not considered, which is an appropriate assumption because of the short connection length on the divertor legs. The plasma parameter profiles along the magnetic field lines are obtained by the iteration process under two boundary conditions: the Bohm criterion on divertor plates, the three invariants at the upstream of the magnetic field lines. When the electron and ion temperature on a magnetic field line become nearly zero, it is assumed that a recombination process occurs (a volume source of neutral hydrogen atoms is generated).

4. Calculation of the density profile of neutral impurities

Figure 2 gives the three poloidal cross sections of the calculated density profile of neutral carbon atoms in the three-dimensional model. The plasma parameter profiles inside the ergodic layer is set to be the calculation of the plasma fluid code in a typical LHD plasma discharge: R_{ax}=3.60m, P_{SOL}=8MW, S_{total}=3.6×10^{4}A, $<n_e>$~5×10^{19}m^{-3}, where P_{SOL} is the input power from the main plasma to the SOL region, S_{total} means the total plasma current flowing from the ergodic layer to the divertor legs, $<n_e>$ is an averaged plasma density. The neutral carbon atoms are localized in the CHD region in the inboard side, and the density in the outer edge of the ergodic layer is seen to remain of the order of $10^{16}m^{-3}$, which shows a good performance of the CHD configuration to retain the impurities in the divertor region. The volume integrated source rate of carbon ions (C^+) inside the ergodic layer in the open divertor and the CHD cases for the full torus geometry is calculated at 1.42×10^2A and 1.35×10^2A, respectively. The source rate for the CHD is almost same as that in the open divertor case, suggesting that the main source of carbon ions in the ergodic layer originates from the vacuum vessel (not from the divertor plates). The volume integrated source rate in the case without the sputtering on the vacuum vessel is calculated at 3.0×10^1A by the simulation code. The calculated source rate is significantly reduced to less than one fourth of that with the sputtering, which indicates the main source of the carbon ions in the ergodic layer is from the vacuum vessel. This because the distance between the outer edge of the ergodic layer and the vacuum vessel is short (only about a few cm), which means that neutral carbon atoms are produced near the ergodic layer due to the sputtering by charge exchange neutral particles. It suggests that vacuum vessel conditioning is essential for reducing the impurity content in the ergodic layer even in the CHD configuration.

5. Impurity ion transport analysis on the divertor legs

One of the major concerns of the CHD configuration is retention of impurity ions in the divertor region. It is numerically predicted that impurity transport results from the balance between the thermal force due to a plasma temperature gradient and the friction force by plasma flow [11]. When the thermal force is dominant over the friction force, impurity ions are transported toward the ergodic layer and the main plasma. This may cause impurity contamination in the main plasma and cooling of the peripheral plasma temperature, which can induce radiation collapse and terminate the plasma discharge.

In order to investigate the performance of the CHD for impurity (carbon) ion retention, impurity transport is calculated along magnetic field lines on the divertor legs by a one-dimensional particle balance analysis. The following two equations are solved:

$$\frac{\partial \Gamma_Z}{\partial x} = n_e n_{Z-1} I_{Z-1\to Z} - n_e n_Z \left(I_{Z\to Z+1} + R_{Z\to Z-1} \right) + n_e n_{Z+1} R_{Z+1\to Z}. \quad (1)$$

Here, Γ_Z is the flux of the Z charged carbon ions, x is the coordinate of the distance along the magnetic field line, n_e and n_Z mean the density of electrons and Z charged carbon ions, respectively. The parameters $I_{Z\to Z+1}$ and $R_{Z\to Z-1}$ are ionization and recombination rate coefficient for Z charged carbon ions.

$$\Gamma_Z = -D_{//Z} \frac{dn_Z}{dx} + V_Z n_Z. \quad (2)$$

Here, $D_{//Z}$ is a carbon ion diffusion coefficient parallel to the magnetic field line, and V_Z is a convective velocity. The two parameters are expressed as:

$$D_{//Z} = \frac{kT_Z}{m_Z \nu_{Zi}}, \; V_Z = \frac{1}{m_Z \nu_{Zi}} \left[-\frac{\partial kT_Z}{\partial x} + ZeE + \alpha_Z \frac{\partial kT_e}{\partial x} + \beta_Z \frac{\partial kT_i}{\partial x} \right] + V_{i//}. \quad (3)$$

Here, m_Z is the carbon ion mass, ν_{Zi} is the collision frequency between electrons and carbon ions, T_Z, T_e and T_i are the temperatures of Z charged carbon ions, electrons and ions in the plasma, respectively, and E is the parallel electric field. The parameters α_Z and β_Z are coefficients of order Z^2, k is Boltzmann constant, and $V_{i//}$ means a plasma flow velocity.

For solving the above two differential equations, the following four assumptions are introduced for simple calculation:

1. the density profile of neutral carbon atoms (n_{C0}) is obtained by the calculation of the EIRENE code including physical/chemical sputtering,
2. parallel electric field is evaluated from the electron momentum balance equation [12],
3. carbon ion temperature is as the same as the back ground ion temperature T_i,
4. carbon ion densities (n_{C+}, n_{C2+}, ... , n_{C6+}) are assumed to be zero at the upstream edge of the magnetic field lines (inside the ergodic layer). This assumption is justified later because of the presence of strong plasma flow from the ergodic layer. In addition, the production rate of the carbon ions at the upstream side is negligible compared to that in the divertor region by virtue of good retention of the carbon atoms in the CHD.

Background plasma parameter (temperature, density and flow velocity) profiles along magnetic field lines are calculated by the one-dimensional plasma fluid analysis without the effect of the impurities. The following impurity ion transport analysis gives the calculations for the worst case for the impurity retention because of high sputtering yields under high ion temperature conditions without impurity radiation near the divertor plates.

Carbon ion transport on divertor legs for the CHD configuration is investigated along six representative magnetic field lines shown as colored dots in Figure 3. The field lines are started from positions inside the ergodic layer on a poloidal cross section of a mesh model for the three-dimensional plasma fluid code (red circles). Five magnetic field lines (No.1-5) connect to the CHD components (slanted divertor plates). One magnetic field line (No.6) is attached to an outer divertor plate, which is for a reference calculation.

Plasma parameters on the divertor legs are affected by the neutral particle density in the divertor region. Figure 4 gives the calculations of the plasma density and temperature profile along the six magnetic field lines when the neutral density in the divertor region is artificially changed. It indicates the change of the plasma parameter profiles under conditions in the range from a low neutral density to a high neutral density case. While the plasma densities rise near the divertor plate, the temperatures drop for the high neutral density. On the magnetic field line No.6, the gradient of temperature drop is moderate because the neutral density along the magnetic field line is not significantly changed outside the CHD region.

To predict impurity transport on divertor legs, a force balance for carbon ions is investigated along the six magnetic field lines. Here, a parameter R is introduced as follows:

$$R = \left(-\frac{\partial kT_Z}{\partial x} + ZeE + \alpha_Z \frac{\partial kT_e}{\partial x} + \beta_Z \frac{\partial kT_i}{\partial x} \right) \Big/ m_Z \nu_{Zi} V_{i//} \quad (4)$$

The parameter R represents the ratio of the thermal force which includes the effect of the electric field and the pressure of the impurities on the friction force. In the case where this parameter is less than zero, the thermal force works to push impurity ions toward the upstream side. When R>-1, the impurity ions are swept back to the divertor plates by the plasma flow. Figure 4 indicates the parameter profiles for all charge state carbon ions along the six magnetic field lines in various neutral density cases, showing that the friction force is dominant over the thermal force on all positions along the magnetic field lines. The value of the parameter R is more than -0.15 even in the case where a steep plasma temperature gradient is formed in high neutral density cases. The calculation of the density profiles of the impurity ions shows the density rise of the all charge state carbon ions near the divertor plates (downstream side). It indicates that carbon ions are pushed back to the divertor plates. One of the reasons for this is the presence of the relatively high density (n_e>$2\times10^{19}m^{-3}$) and low plasma temperature (T_i<30eV) in the ergodic layer in the inboard side for R_{ax}=3.60m. The collision frequency between the plasma and the carbon ions is high enough to sweep back the impurities to the divertor region.

6. Summary

For studying the performance of the closed helical divertor (CHD) configuration for retaining impurities in the divertor region, impurity transport is investigated by the neutral particle transport simulation and an impurity ion transport analysis on the divertor legs. The simulation shows that the CHD has the good performance for retaining the neutral carbon atoms in the divertor region, and most of the impurity ion source in the ergodic layer originates from sputtered carbon atoms on the vacuum vessel. It suggests that vacuum vessel conditioning is essential for reducing the impurity ion source in the ergodic layer even in the CHD configuration. The impurity ion transport analysis predicts that all charge state carbon ions on the divertor legs are pushed back to the divertor plates by the effect of the plasma flow because of the formation of the relatively high density and low temperature plasma in the ergodic layer. The analyses clearly show the effective functions of the CHD configuration and the divertor legs for retention of the impurities in the diverter region.

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Figure captions

Fig. 1. A three-dimensional model for the neutral particle transport simulation for the CHD configuration, which consists of the three components: slanted divertor plates (black), a dome structure (green) and target plates (blue), which is viewed from an outer port. A transparent red curved line indicates the position of the vacuum pumping system installed behind the dome structure.

Fig. 2. Three poloidal cross sections of the density profile of neutral carbon atoms calculated by the neutral particle transport simulation code, which are sliced at three toroidal angles (ϕ=9°, 18°, 27°) as shown in Figure 1.

Fig. 3. Six representative magnetic field lines on divertor legs in the inboard side of the tours for the CHD configuration (colored dots). The start point of the magnetic field lines inside the ergodic layer is indicated as a red circle.

Fig. 4. Plasma parameter (n_e and T_e) profiles and the parameter (R) for the force balance analysis of carbon ions along the six representative magnetic field lines (No.1-6) in various neutral density conditions in the divertor region.

Figure

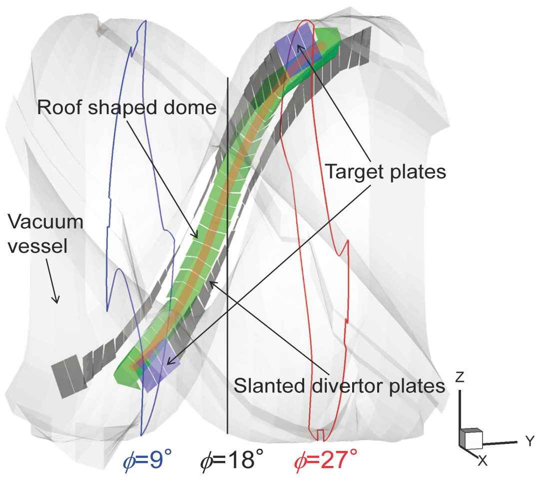
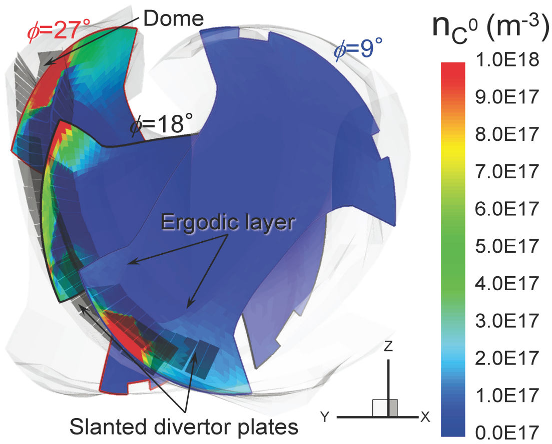


Figure 1



ϕ=27°
Dome
ϕ=9°
ϕ=18°
Ergodic layer
Slanted divertor plates
Z
Y
X
$n_C{}^0$ (m^{-3})
1.0E18
9.0E17
8.0E17
7.0E17
6.0E17
5.0E17
4.0E17
3.0E17
2.0E17
1.0E17
0.0E17

Figure 2

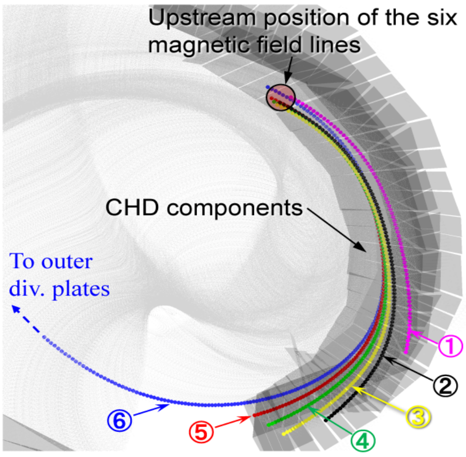
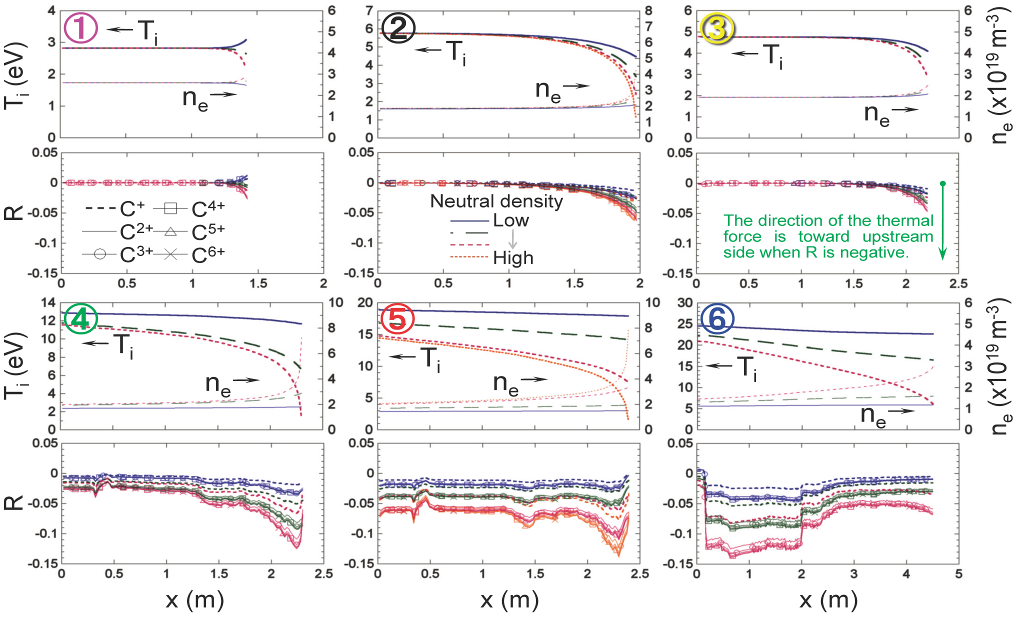

Upstream position of the six magnetic field lines
CHD components
To outer div. plates
①
②
③
④
⑤
⑥

Figure 3



①
②
③
④
⑤
⑥
T_i
n_e
T_i (eV)
n_e (x10^19 m^-3)
R
C+
C2+
C3+
C4+
C5+
C6+
Neutral density
Low
High
The direction of the thermal force is toward upstream side when R is negative.
x (m)

Figure 4