Proceedings of ITC18, 2008

A closed divertor configuration for reduction of the heat load and efficient particle control for helical fusion reactors

Mamoru Shoji, Masahiro Kobayashi, Suguru Masuzaki, Akio Sagara, Hiroshi Yamada, Akio Komori and LHD Experimental Groups

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

An innovative closed helical divertor concept is proposed for reduction of a heat load on the divertor plates and efficient particle control/pumping. The closed divertor configuration is investigated by a neutral particle transport simulation code coupled with a one-dimensional plasma fluid analysis on the divertor legs for a helical fusion reactor in which the geometry of the plasma and the magnetic field line configuration is same as that in the large helical device (LHD). The closed divertor configuration practically utilizes intrinsic three-dimensional magnetic field line configurations in the plasma periphery (an ergodic layer and divertor legs). The divertor configuration is optimized to an inward shift magnetic configuration in which the best energy confinement time has been achieved, a highly ergodized magnetic field line structure is formed in the inboard side of the torus, and the neutral density there is higher than that in the other region in the LHD vacuum vessel. It means that the divertor configuration is compatible with good main plasma confinement, effective divertor heat load reduction and efficient particle control/pumping from the inboard side. The analysis in this closed helical divertor configuration shows many advantageous over that in the other divertor concepts.

Keywords: neutral particle transport simulation, closed divertor, helical fusion reactor, plasma fluid analysis, ergodic layer, particle control, plasma periphery, LHD.

1. Introduction

The most critical issue for realizing fusion reactors is reduction of a heat load on the divertor plates with efficient particle control in the plasma periphery. For solving this issue, closed divertor configurations are designed and investigated in many plasma confinement devices. A new innovative closed helical divertor configuration which practically utilizes intrinsic magnetic field line structures in the plasma periphery (ergodic layer and divertor legs) in helical systems can solve the above critical issues.

Recent plasma experiments in the Large Helical Device (LHD) demonstrate that control of the peripheral plasma density is an important factor for achieving super dense core (SDC) plasmas [1]. The closed helical divertor configuration can contribute to sustaining the SDC plasmas by active pumping of neutral particles in the plasma periphery. An operational regime for sustaining the SDC plasma can propose a more attractive operational scenario in a helical fusion reactor with significant reduction of a heat load on the divertor plates.

In this paper, the neutral particle density profile and a heat load on the divertor plates in the optimized closed helical divertor configuration for a helical fusion reactor is investigated by a three-dimensional neutral particle transport simulation code coupled with a one-dimensional plasma fluid analysis on the divertor legs. Many advantages of the closed helical divertor configuration over the other divertor concepts are also mentioned.

2. Magnetic field line structures in the LHD plasma periphery

The LHD is the largest super-conducting helical device [2]. The magnetic configuration for plasma confinement is produced by external two twisted helical coils and three pairs of circular poloidal coils, forming helically twisted plasma (ℓ/m=2/10, where ℓ and m are the polarity and the toroidal field period). Non-axsymmetric magnetic components by the helical coils produce three-dimensionally complicated magnetic field line

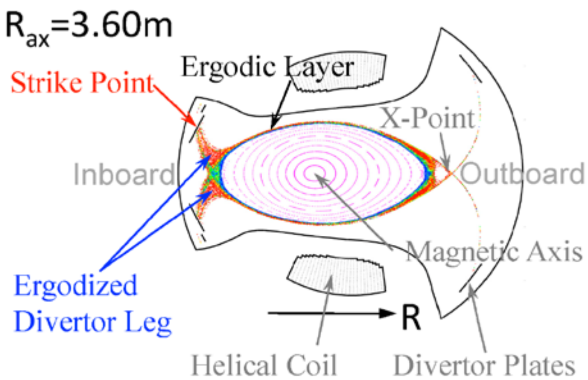

Fig.1 Poincare plots of magnetic field lines in the present open divertor case.

author's e-mail: shoji@LHD.nifs.ac.jp

structures (ergodic layer) in the plasma periphery in which the connection length of the magnetic field lines reaches to several km. These magnetic field lines are bundled and directly connected to the divertor plates at strike points along divertor legs on which the connection length is only a few meter. The radial position of the magnetic axis is flexibly controlled by changing the coil current in the poloidal coils.

Figure 1 shows the Poincare plots of magnetic field lines in the present open divertor case in an inward shift magnetic configuration (R_{ax}=3.60m) on a poloidal cross section where the plasma is horizontally elongated. The Poincare plots indicate that most of the magnetic field lines in the ergodic layer are bundled into the divertor legs in the inboard side of the torus with highly ergodized magnetic field line structure, indicating that most of the strike points (neutral gas source) locate in the inboard side in this magnetic configuration.

3. Design of an optimized closed helical divertor configuration

An optimized closed helical divertor configuration has been designed by using a fully three-dimensional neutral particle transport simulation code (EIRENE) coupled with a one-dimensional plasma fluid analysis on the divertor legs [3]. A plan of the three-dimensional geometry of the closed divertor components viewed from an outboard side of the torus is illustrated in Figure 2. The closed divertor consists of the following four main components: a V-shaped dome, slanted divertor plates, back plates and target plates. These four components contribute to concentration of the position of the strike points in the inboard side and enhancement of the neutral particle density there. Pumping ducts are placed behind the dome for particle pumping form the inboard side. An analysis by the neutral particle transport simulation predicts that enhancement of the neutral pressure by more than one order of magnitude compared to that in the present open divertor configuration [4].

Figure 3 is the Poincare plots of the magnetic field lines in the plasma periphery including a particle diffusion effect for the inward shift magnetic configuration. The particle diffusion effect (D~0.1m^2/s) is necessary for explaining the experimental results of the toroidal/poloidal distribution of the heat load on divertor plates measured with thermo-couples embedded in the divertor plates [5]. The poloidal cross section of the closed divertor components is also illustrated in this figure. The plasma wetted area on the divertor plates is enlarged in this closed divertor configuration due to the highly ergodized divertor legs in the inboard side of the torus, which contributes to

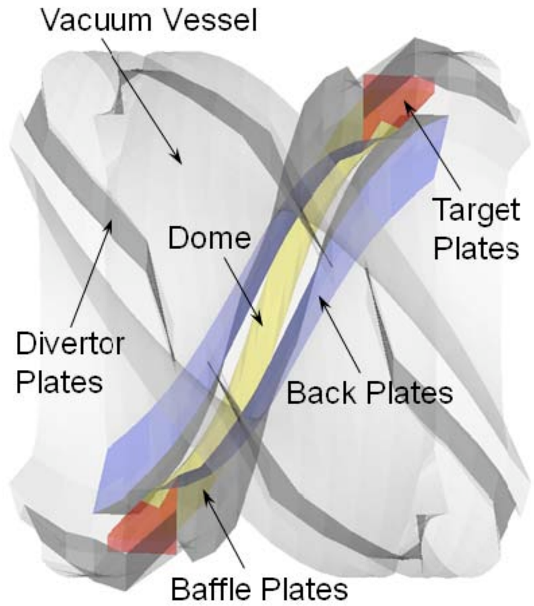

Fig.2 Three-dimensional geometry of the closed divertor configuration planned in LHD.

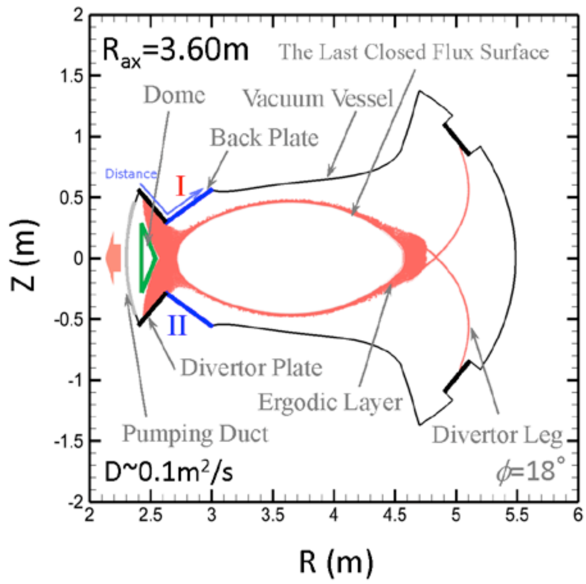

Fig.3 Poincare plots of the magnetic field lines including a particle diffusion effect in the closed divertor case.

strong reduction of the heat load on the divertor plates. This divertor configuration has the following four advantages over other closed divertor concepts [6]:

1. The highly ergodized magnetic field line structure on inner divertor legs extends the plasma wetted area on the divertor plates, which can be effective for mitigation of the heat load on the divertor components. The plasma on the divertor legs effectively prevents the outflow of the neutral particles from the divertor region to the main plasma due to ionization of neutral particles on the ergodized divertor legs.
2. The curved divertor legs toward the inboard side of the torus are also favorable for efficient particle

control/pumping from the inboard side. This is because most of neutral particles and impurities released from the slanted divertor plates directly reach to the pumping ducts through the space between the V-shaped dome and the inner vacuum vessel.

3. The ergodic layer functions as a shield against impurity penetration, which has been experimentally confirmed by comparing the measurements of carbon emission and the calculations by a three-dimensional plasma fluid code (EMC3-EIRENE) [7, 8]. The long connection length of the magnetic field lines in the ergodic layer contributes to cooling down the plasma temperature in the periphery.
4. Most of the strike points (about 80%) are directly connected to the divertor and the target plates in the inboard side for the inward shift magnetic configuration, which is favorable for efficient neutral particle control. This is because neutral particles are pumped out from the inboard side with no interference with plasma heating and diagnostic systems which have to be installed in outboard side of the torus.

4. Neutral particle transport analysis in the closed divertor configuration

The neutral particle transport simulation code has been applied to calculate the neutral density profile in the closed divertor region. In this simulation, trajectories of many test particles (representative of neutral particles) are traced in a three-dimensional grid model. We constructed a model for simulating a helical fusion reactor in which the shape of the plasma/vacuum vessel and the closed divertor components is identical to that planed in LHD. The size of the geometry is linearly extended to a Force Free Helical Reactor (FFHR) size (R_0=14.0m) from the LHD size (R_0=3.9m), where R_0 means the major radius of the device center [9]. Some closed divertor components (the V-shaped dome and the target plates) are approximated as assemblies of triangular plates in this model. Because of the arbitrary shape of the two components which crosses over toroidal sections, these components are included in the model by using a function 'additional surface' implemented in the code. The entrance of the pumping duct is set on the vacuum wall in the inboard side of the torus (behind the V-shaped dome). A special surface is introduced for simulating the entrance of the duct which absorbs test particles with a probability satisfying a predefined pumping speed there. Two surfaces at the both toroidal ends of the model are treated as a periodic one on which the position of an injected test particle are moved to another surface, and the direction of the particle is rotated at the one-toroidal pitch angle (36°) on the machine axis.

The trajectories of the test particles are determined by a Monte-Carlo method including various atomic/molecular processes in pasmas. Some parameters of neutral particles released from divertor plates are determined by using a database on plasma-wall interactions calculated by the TRIM code. We regard the surface of all vacuum components in the model as carbon. The particle reflection coefficient of the vacuum components is set to be 1.0 (no particle absorption) for modeling a steady state plasma discharge operation. The absorption probability of the special surfaces at the entrance of the duct is set to be 0.01 which provides a reasonable pumping rate (~72 m^3/s) for the helical fusion reactor.

The particle source profile on the divertor/target plates is obtained from the calculations of plasma parameters on the divertor legs. The parameter profiles are calculated by solving one-dimensional plasma fluid equations of three invariances (plasma density, momentum and energy) along the magnetic field lines on the divertor legs. The equations are solved under the boundary condition between the outer edge of the ergodic layer and the upstream of the divertor legs for satisfying the Bohm criterion on the divertor plates [10]. The parameter profiles are determined by an iteration process with the calculation of neutral particles by the neutral transport simulation.

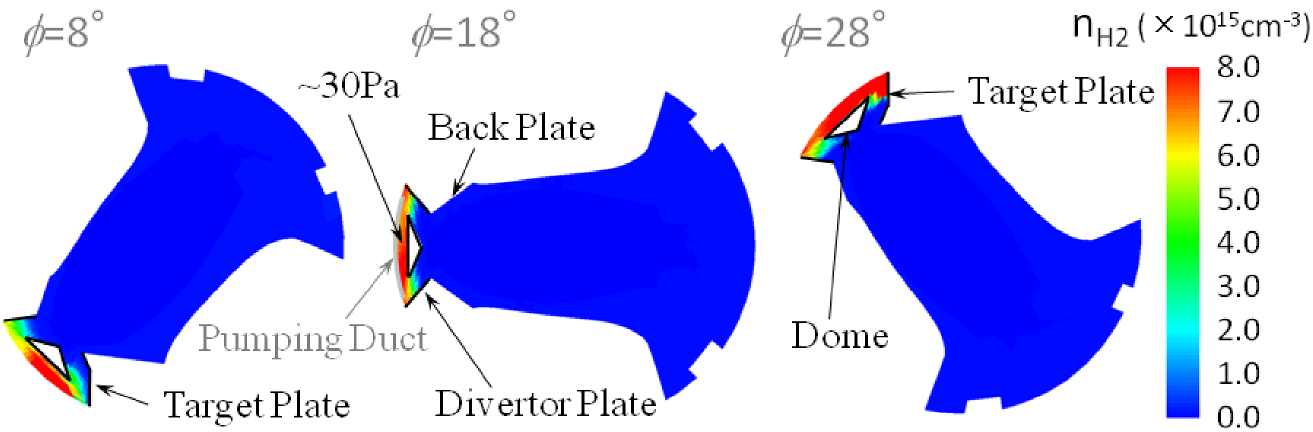

Fig.4 Calculations of the three poloidal cross sections of the density profile of neutral hydrogen molecules for the closed divertor configuration in a helical fusion reactor case.

The plasma parameter profiles inside of the ergodic layer are calculated by the EMC3-EIRENE code for the FFHR (no divertor leg version, P_{output}=284MW, T_e^{LCFS}~400eV, n_e^{LCFS}~1×10^{20}m^{-3}, Γ_{output}=1.6×10^6A), where P_{output} is the total output power from the ergodic layer, T_e^{LCFS}, n_e^{LCFS} are the electron temperature and the plasma density at the last closed flux surface, respectively, and Γ_{output} means the total current of the plasma flow at the upstream of the divertor legs [11].

When the plasma temperature at a position on magnetic field lines in the divertor legs equals to nearly zero for solving the three differential equations, we regarded that the plasma is fully dissipated and recombined by the background neutral particles at the position. It is assumed that a volume source which equals to that of the dissipated plasma is formed there. The heat load onto the divertor plates is calculated by plasma parameters at the front of the plates including the effect of the plasma sheath. Conversion of the calculations of the plasma parameter profiles along the divertor legs to the volume averaged values in the three-dimensional grid model is based on a procedure adopted in a track length estimator.

5. Calculation of the neutral density profile and a heat load distribution on the divertor plates

Figure 4 gives the calculation of the three poloidal cross sections of the density profile of neutral hydrogen molecules in the closed divertor configuration. The density of hydrogen molecules at the front of the pumping duct is about 7×10^{15}cm^{-3} (~30Pa). Local formation of the high neutral pressure there contributes to mitigation of requirements for the vacuum pumping system in the helical fusion reactor. The calculation shows that most of neutral particles are ionized in the divertor legs. Ionization in the ergodic layer near the X-points is very low (about 2% of the neutral particles released from the divertor plates). It indicates that plasmas produced by the ionization of neutral particles released from the divertor plates are almost recycled in the inner divertor region. The highly ergodized divertor legs in the inboard side contribute to effective ionization of the neutral particles in this region.

Figure 5 indicates the calculated profile of the plasma density on a poloidal cross-section where the plasma is horizontally elongated. The plasma density at the front of the divertor plates in the inboard side is significantly low. A high density and low electron temperature plasma (n_e>8×10^{13}cm^{-3}, T_e<0.1eV) is formed at the upstream on the inner divertor legs by strong interactions between the plasma and neutral particles released from the divertor plates. This low electron temperature is effective for enhancing plasma recombination processes on the divertor legs, which leads to strong reduction of head load on the divertor plates. The heat load on the divertor components is

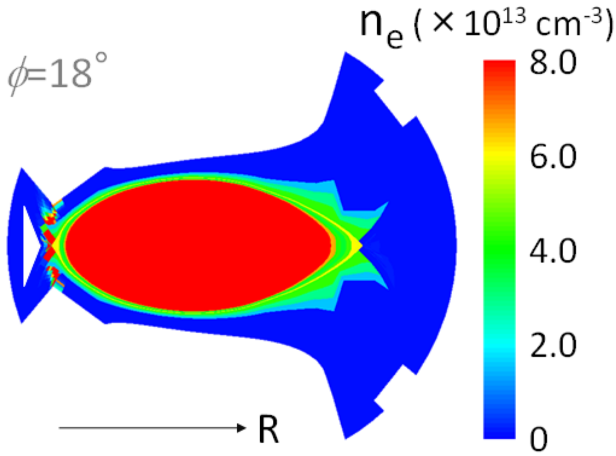

Fig.5 Poloidal cross-section of the calculated plasma density in the closed divertor case.

estimated to be less than a few MW, which is due to a combined effect of the large plasma wetted area (~600m^2), ion energy loss by ionization of high neutral particle density in the inboard side, plasma recombination process on the divertor legs, and formation of the low plasma temperature in the ergodic layer.

6. Summary

An innovative closed helical divertor concept for a helical fusion reactor is proposed for an effective particle control/pumping with reduction of the head load on the divertor plates with keeping good main plasma energy confinement in the inward shift magnetic configuration. The neutral particle transport simulation with a plasma fluid analysis of the divertor legs predicts high neutral density at the entrance of the pumping duct (behind the dome), which is enough for efficient particle pumping from the inboard side of the torus. The simulation also shows reduction of the heat load on the closed divertor components by combined effect of ion energy loss by ionization and recombination, large plasma wetted area, and low plasma temperature in the ergodic layer.

References

[1] N. Ohyabu *et al.*, Phys. Rev. Lett. **97**, 05502 (2006).
[2] O. Motojima *et al.*, Nucl. Fusion **40**, 559 (2000).
[3] D. Reiter *et al.*, Fusion Sci. Technol., **47**, 172 (2005).
[4] M. Shoji *et al.*, Plasma Fusion Res. **3**, S1038 (2008).
[5] S. Masuzaki *et al.*, Nucl. Fusion **42**, 750 (2002).
[6] R König *et al.*, Plasma Phys. Control. Fusion **44**, 2365 (2002).
[7] Y. Feng *et al.*, Plasma Phys. Control. Fusion **44**, 611 (2002).
[8] M. Kobayashi *et al.*, Plasma Fusion Res. **3**, S1005 (2008).
[9] A. Sagara *et al.*, Nucl. Fusion **45**, 258 (2005).
[10] P. C. Stangeby, *The plasma boundary of magnetic fusion devices* (Institute of Physics Publishing, Bristol and Philadelphia, 2000) p.423.
[11] M. Kobayashi *et al.*, Fusion Sci. Technol., **52**, 566 (2007).