Analysis of neutrals in helical-axis Heliotron J plasmas using the DEGAS Monte-Carlo code

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Analysis of neutral particle behavior in Heliotron J device with non-axisymmetric configuration is described based on the results of neutral transport simulation. DEGAS three-dimensional (3-D) Monte-Carlo code was applied to Heliotron J in order to investigate precisely the spatial distribution of neutral particle density in the device. A detailed three-dimensional mesh structure for the simulation has been designed in complicated helical axis plasma geometry as well as the whole volume of Heliotron J vacuum chamber. In this mesh model, a carbon target is also modeled for the simulation of the plasma-material interaction experiments. Plasma parameter dependence on neutral diffusion was investigated and a significant effect of helical geometry was clarified. Simulation results were also compared with the two-dimensional image captured with a CCD camera viewing the carbon target and the plasma-material interaction under non-axisymmetric configuration was discussed.

Keywords: neutral transport, three-dimensional Monte-Carlo simulation, DEGAS, helical system, Heliotron J, carbon target

1. Introduction

Analysis of neutral transport is an important issue for the investigation of edge plasma behavior and plasma-wall interactions. Especially in non-axisymmetric plasma confining systems, the neutral transport analysis becomes much complicated, since the structure of plasma and the vacuum vessel wall become a three-dimensional structure, which prevent us to assume a simple toroidal symmetry, such as tokamaks. In order to investigate the neutral transport in non-axisymmetric systems, three-dimensional (3-D) Monte-Carlo simulation is a powerful method. So far DEGAS Monte-Carlo code [1,2] has been applied to the GAMMA 10 tandem mirror device and the helical device LHD for neutral transport simulation in three-dimensional geometry [3-5]. Recently 3-D simulation study by using this code has started in Heliotron J device [6]. In this study, a distinctive behavior of neutrals in helically structured plasmas with localized neutral particle source is analyzed under the 3-D mesh model using the DEGAS ver.63 code. In this paper, the detailed results of 3-D Monte-Carlo simulation in order to investigate behavior of neutrals in non-axisymmetric Heliotron J plasmas are described. The effect of interactions between the limiter and the non-axisymmetric plasmas is also discussed from the viewpoint of particle source with localized in the complicated 3-D geometry.

2. Heliotron J and the simulation model

2.1 Mesh structure of Heliotron J

Heliotron J is the helical axis heliotron device with a helical winding coil of L/M = 1/4, where L and M are the pole number of the helical coil and the helical pitch, respectively [7,8]. In a standard magnetic field configuration, the average major and minor radii of the plasma are 1.2 m and 0.17 m, respectively. Figure 1(a) shows the poloidal cross-section of Heliotron J together with the line of sight in the Dα line-emission detector array and fast cameras. As shown in the figure, the line of sight is located to cover the entire surface of the carbon

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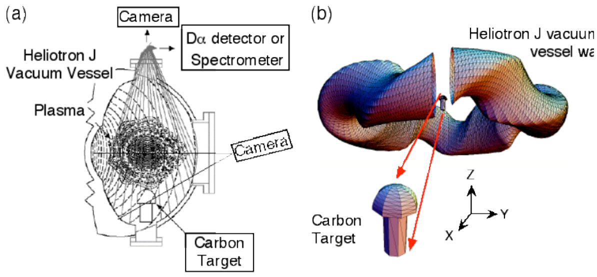

Fig.1 (a) Poloidal cross-section of the plasma and layout of the fast camera and Dα diagnostic system. (b) Mesh model of the Heliotron J vacuum vessel, plasma and carbon target for the DEGAS simulation.

target by using the multi-channel Dα array detector system [9]. In Heliotron J, two fast cameras are installed to observe the plasma and the carbon target and one is located at the top of the vacuum chamber and is looking down both the plasma and the target vertically. Another camera is set horizontally viewing the plasma and the top of the target [10].

The 3-D mesh model covering the whole area of Heliotron J for the DEGAS simulation is shown in Fig. 1(b). In this simulation, 3-D modeling of the carbon target is carried out in addition to the plasma and vacuum vessel wall in order to study the neutral particle behavior near the target. The mesh is divided into radially 15 segments and 28 segments in the poloidal cross-section, respectively. The toroidal segmentation is taken into 512 to investigate the toroidal variation of neutral density in detail especially near the target. The target head is hemispheric shape with 4 cm in radius made of carbon and a set of probes is installed on the tip. The mesh model of the target is divided into 40 segments in azimuthal direction and vertically divided into 34 segments.

2.2 Modeling of plasma parameter

Figure 2 shows the radial profiles of plasma parameters used in the DEGAS simulation. As input data for the DEGAS code, plasma parameters (N_e, T_e and T_i) are determined from the measured results with a microwave interferometer, a soft X-ray detector and a neutral particle energy analyzer, respectively. Since the obtained plasma parameters from the experiments are practically insufficient for the 3-D simulation, an appropriate assumption is required for making up an input dataset of the simulation code. A toroidal symmetry in the plasma parameters is assumed for this reason. Edge plasma parameters are determined from Langmuir probe measurements. In this simulation electron density and temperature in the SOL region are given to be 1×10^{12} cm^{-3} and 10 eV, respectively.

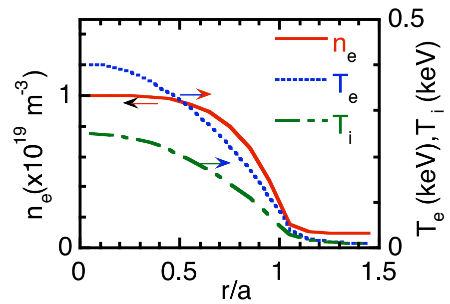

Fig.2 Radial plasma parameter profiles used in the DEGAS simulation.

3. Simulation results and Discussion

3.1 Neutral penetration and diffusion from the carbon target

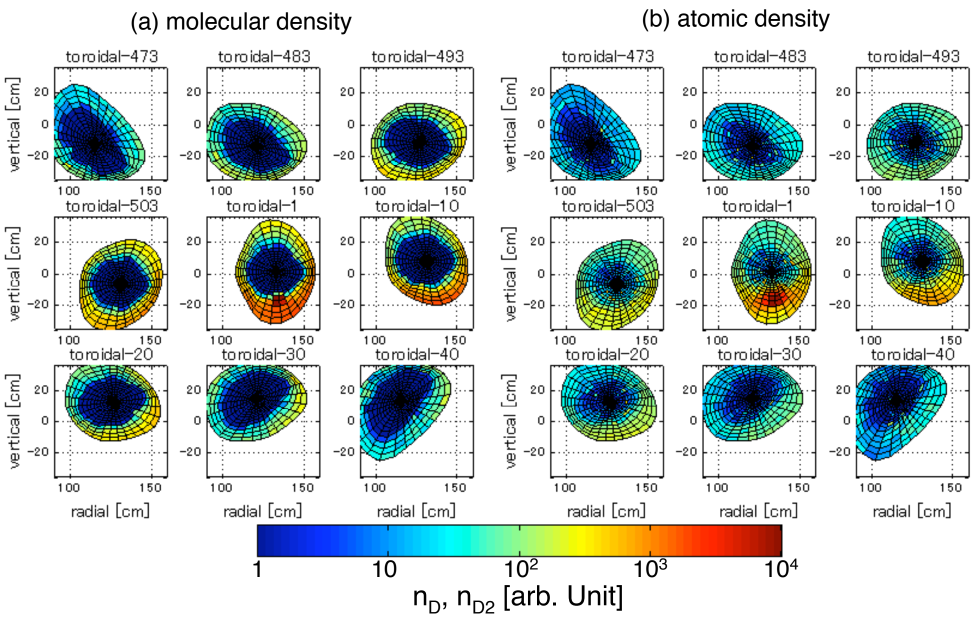

Fig. 3 3-D simulation result of deuterium neutral density profile with a point source on the target tip.

For the purpose of understanding the neutral behavior in the plasma and the vacuum chamber with helical structure, 3-D simulation was performed in the case with a point particle source on the carbon target. Figure 3 shows the simulation result of deuterium neutral density profile with a point source on the target tip. In Fig. 3(a), poloidal cross-section views of the deuterium molecule density are aligned in the toroidal direction at intervals of about 15 cm. At the location close to the poloidal plane "toroidal-1" the carbon target is installed and the test particles are launched at 10 mm inside the LCFS from the bottom of the vacuum vessel. In the simulation, deuterium molecules are injected toward the plasma center from the top of the target according to cosine distribution. As shown in the figure, deuterium molecules cannot penetrate radially toward the plasma core. Near the target position, they poloidally diffuse through the SOL region decreasing by less than two order of magnitude up to the opposite side. In the toroidal direction, on the other hand, deuterium molecules decreases by almost three order of magnitude about 60 cm distance from the target and the poloidal non-uniformity due to the local recycling induced by the target disappears. Deuterium atoms have longer penetration length toward the plasma core as shown in the Fig. 3(b). However, a strong non-uniformity in the atomic density near the target is observed compared with the molecular density.

Figure 4 shows the bird's-eye view of the Dα emission profiles determined from the simulation results. Each poloidal cross-section is toroidally aligned at intervals of about 22 cm. Compared with the atomic/molecular density profiles, the emission region is more deeply penetrated to the plasma core. From this figure it is found that in the case of the point particle source, such as the carbon target, the Dα line-emission region is localized within a quarter of the whole toroidal circumference.

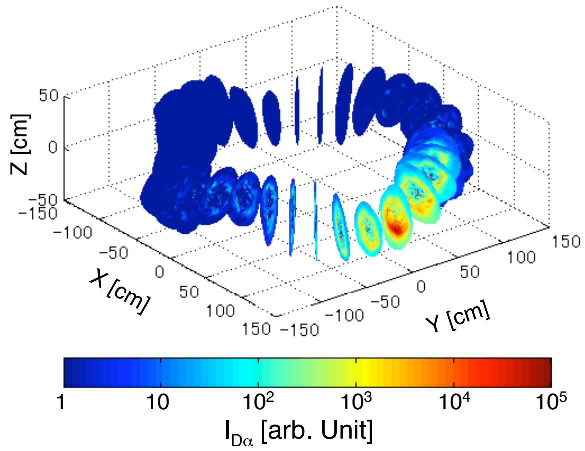

Fig. 4 Bird's-eye view of the Dα emission profiles determined from the simulation results.

3.2 Density dependence on neutral transport

In order to investigate the density dependence on the neutral transport, neutral density profile in the different density condition is calculated. Figure 5 shows the simulation result of deuterium neutral density profile in the case that the plasma density is reduced by one fourth ($N_e(0)$ = 2×10^{12} cm^{-3}) under the same condition of the other parameter as in Fig. 4. As shown in Fig. 5(a), azimuthal localization of molecules due to recycling on

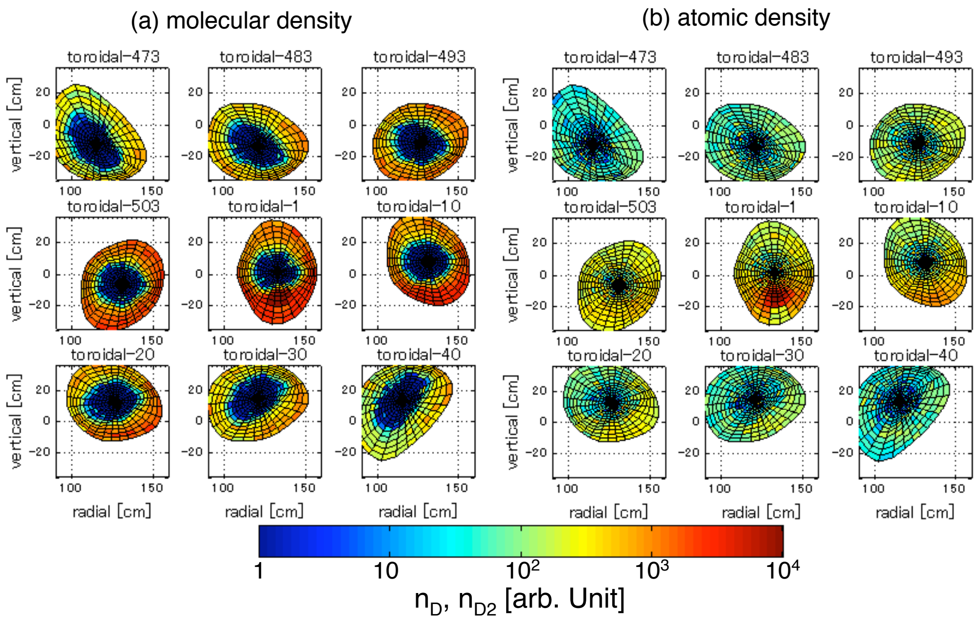

Fig. 5 The simulation result of deuterium neutral density profile in the case that the plasma density is reduced by one fourth under the same condition of the other parameter as in Fig. 4

the target is clearly reduced, which indicates that the molecules can easily diffuse through the SOL region with reduced density. On the contrary, the poloidal non-uniformity by more than one order of magnitude remains in atomic density shown in Fig. 5(b). The mechanism to explain these phenomena is not clarified. However it may affect the atomic deuterium transport that the interaction with the helically bending wall surface.

3.3 Comparison with the 2-D camera view

In order to verify the reliability of the simulation, a simulation result was compared with experimental data. Figure 6(a) shows a typical side view image of the carbon target captured with the horizontally viewing CCD camera. A strong light emission is observed on the target surface and it is found that the emission region is slightly shifted to the left side on the surface. Furthermore it is recognized that the emission cloud has a structure which is expanding along the magnetic field line.

Figure 6(b) shows the simulation results near the carbon target. In this simulation, a particle source on the top of the carbon limiter is given based on the 2-D image of Dα line intensity on the surface measured with the vertically viewing camera [11]. In the present computational circumstances, the limitation of the segmentation number in the toroidal mesh makes it

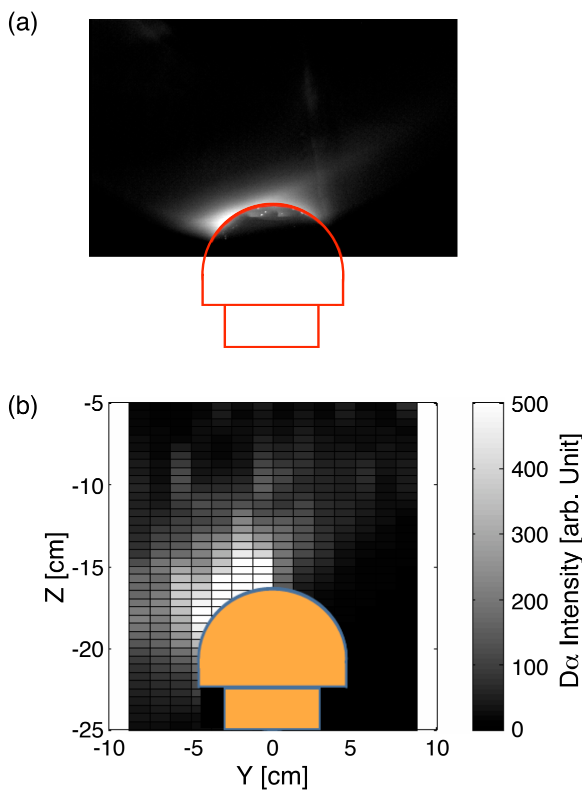

Fig.6 Comparison between 3D-DEGAS simulation and experiment. (a) 2-D image of the side view of the carbon target. (b) Predicted 2-D image of the Dα intensity near the carbon target.

difficult to perform more detailed simulation along the toroidal direction. However, the calculated 2-D image of Dα intensity also has a similar structure to the experimental results. This result indicates the validity of this analysis method applied to the helical system.

4. Summary

Using three-dimensional Monte-Carlo code DEGAS ver.63, neutral transport simulation was successfully performed in the Heliotron J with helical-axis heliotron magnetic configuration, and the behavior of neutrals this region was investigation in detail based on the simulation results. A mesh model of the carbon target was installed into the 3-D mesh structure modeling the Heliotron J vacuum vessel and plasma with non-axisymmetric configuration. The 3-D simulation with assuming a particle source due to recycling on the target showed that the shapes of the wall and plasma in the helical structure significantly influence the neutral transport. The simulation with the particle source determined from the vertically viewing Dα image of the target well reproduced the 2-D image by the horizontally viewing CCD camera. From above these results, this analysis method using 3-D simulation is demonstrated in its validity and provides the important information for understanding of the plasma transport and confinement in helical fusion devices.

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