Cover Page

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Simulation Analysis of the Carbon Deposition Profile on Directional Material Probes in the Large Helical Device using the ERO2.0 code

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The carbon deposition profile on a Directional Material Probe (DMP) installed in the inboard side in the Large Helical Device (LHD) is investigated using the ERO2.0 code. The experimental result of the carbon deposition profile with short and wide shadows (lower deposition areas) on the DMP is reasonably explained by the carbon sputtered from the carbon divertor plates installed in the inboard side. The simulation proves that short and wide shadows are formed by the carbon sputtered from the right and left divertor plate arrays, respectively. The experimental carbon deposition profile accumulated in the campaign (FY2010) was successfully reproduced by the simulation, which provides detailed understanding of material (carbon) migration in the divertor region in the LHD.

Keywords: ERO2.0, directional material probe (DMP), plasma wall interactions, material migration, EMC3-EIRENE, LHD

1. Introduction

Material migration is one of the critical issues for controlling dust particle emission, tritium inventory, and fueling retention in nuclear fusion reactors [1]. In the Large Helical Device (LHD) [2], long pulse plasma discharges have often been interrupted by the emission of large amounts of dust particles from the divertor region. After the experimental campaign, exfoliated carbon-rich mixed material deposition layers were found, which indicated that the exfoliated deposition layers induced the dust particle emission, leading to interruption of the long pulse discharges [3]. The investigation of material (carbon) migration is an essential issue for controlling the deposition in the divertor region.

Directional material probes (DMPs) have been mounted on the vacuum wall [4]. The DMP consists of a flat disk and a cylindrical pin, which guides the directionality of incoming particles onto the disk. A DMP was installed on a helical coil can in the inboard side of the torus in a previous experimental campaign (FY2010). After this campaign, short and wide shadows (lower deposition areas) were formed on the disk. The direction of the short shadow was almost perpendicular to the magnetic field line, which suggests that the deposition layer was not produced by impurity ions transported along the magnetic field lines. An analysis using energy dispersive X-ray spectroscopy (EDX) proved that carbon was the dominant material in the deposition layer. It is probable that the deposition layer was formed by the carbon atoms sputtered from carbon divertor plates near the DMP, which was explained by a simulation using the original ERO code [5] in a two-dimensional model of the LHD [6].

The original ERO code is insufficient for reproducing the deposition profile on the DMP. Therefore, the Monte-Carlo based three-dimensional plasma wall interaction code ERO2.0 was applied [7]. In the next section, the setup of a three-dimensional model for the ERO2.0 simulation is shown. In section 3, the simulation of the carbon deposition profile on the DMP is presented with a successful reproduction of the two shadows on the disk. In section 4, the experimental result carbon density profile on the disk accumulated in the campaign is reproduced by the ERO2.0 simulation.

2. Setup for the ERO2.0 simulation in the LHD

Figure 1 illustrates a three-dimensional model for the ERO2.0 simulation for an open divertor configuration in the LHD. This model is for one helical section ($0° \leq \phi \leq 36°$ in the toroidal angle) in which a periodic boundary condition is assumed at both toroidal ends. A DMP is set on a helical coil can in the inboard side. The dimension of the DMP is magnified by a factor of four for gaining

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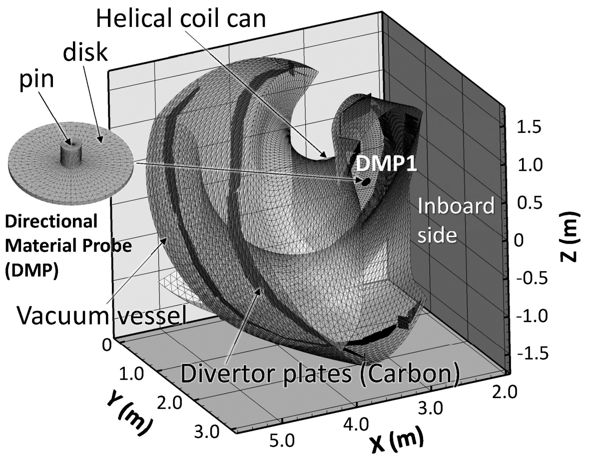

Fig.1 The three-dimensional model for the ERO2.0 simulation in the open divertor configuration in the LHD.

higher statistical results in this simulation. It is assumed that the surfaces on the vacuum vessel are covered with carbon, and the DMP is composed of tungsten. A colorimetric analysis of the surface on the vacuum vessel showed that most of the surface was covered with carbon, except for the top of the helical coil can in the inboard side [8]. In this model, the DMP consists of a pin 20 mm in diameter and 22 mm in length, and a disk 120 mm in diameter. The temperature of the divertor plates is set to be 600 K. The parameter profile of hydrogen plasmas is provided by a three-dimensional edge plasma simulation code (EMC3-EIRENE) with a fixed boundary condition of the plasma heating power (P^{LCFS}) and plasma density (n_e^{LCFS}) near the Last Closed Flux Surface (LCFS).

3. The simulation of the carbon deposition profile on the DMP

3.1 Deposition profile for low and high plasma densities

Figure 2 (a) and (b) present a simulation of the net carbon flux density profile on the vacuum vessel for a low ($n_e^{LCFS}=1\times10^{19}$ m^{-3}) and a high ($n_e^{LCFS}=4\times10^{19}$ m^{-3}) plasma density with a fixed plasma heating power ($P^{LCFS}=$ 8MW) for a typical magnetic configuration (R_{ax}=3.60 m), respectively. It indicates the high carbon flux density on the helical coil can in the inboard side. The insert illustrates the carbon flux density (deposition) profile on the DMP. For the low plasma density, a short shadow (a less carbon density area) is formed near the pin. For the high plasma density, a wide shadow is formed. The ERO2.0 simulation suggests that the experimental carbon deposition profile on the DMP, which consists of the short and wide shadows, can be explained by the superposed deposition profile for low and high plasma densities.

3.2. Investigation of the carbon source in the low plasma density

For investigating the carbon source forming the deposition profile on the DMP, the ERO2.0 simulation was performed under a hypothesized condition where the sputtering occurred only in the left or right divertor plate arrays in the inboard side. Figure 3 (a) presents the simulation of the carbon deposition profile on the vacuum vessel for the low plasma density when the sputtering occurred only on the left divertor plates. The simulation shows the high carbon flux density on a helical coil can. The carbon deposition profile on the DMP in this

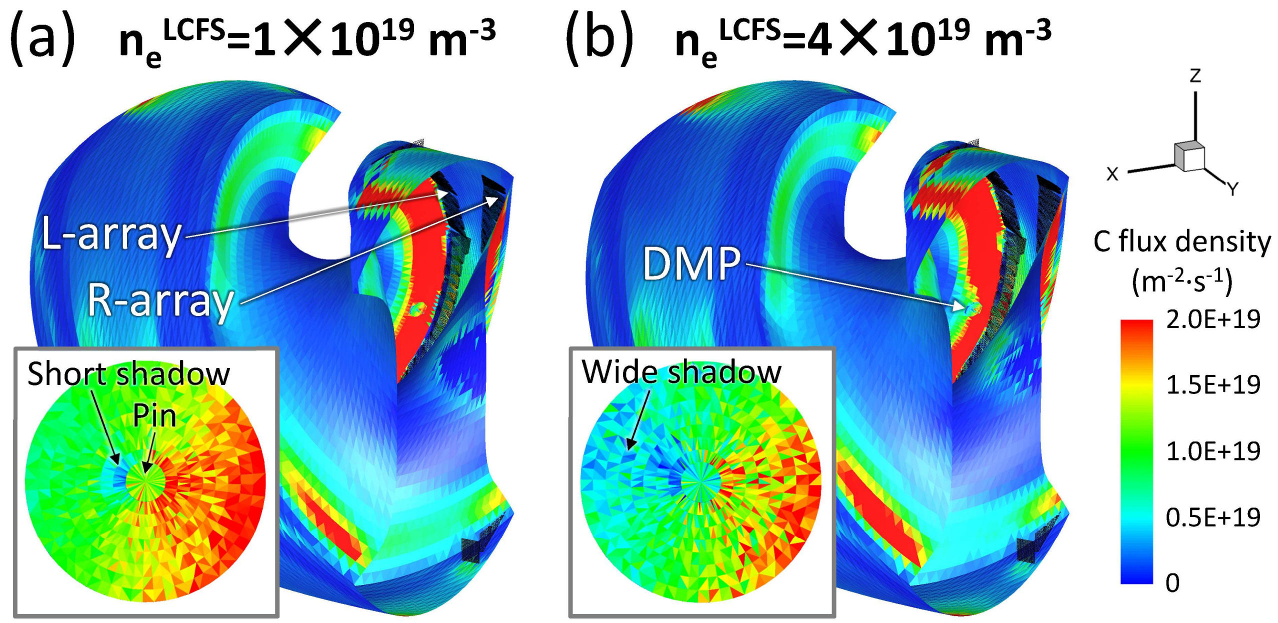

Fig.2 The ERO2.0 simulation of carbon flux density on the vacuum vessel and the DMP for the low (a) and high (b) plasma density.

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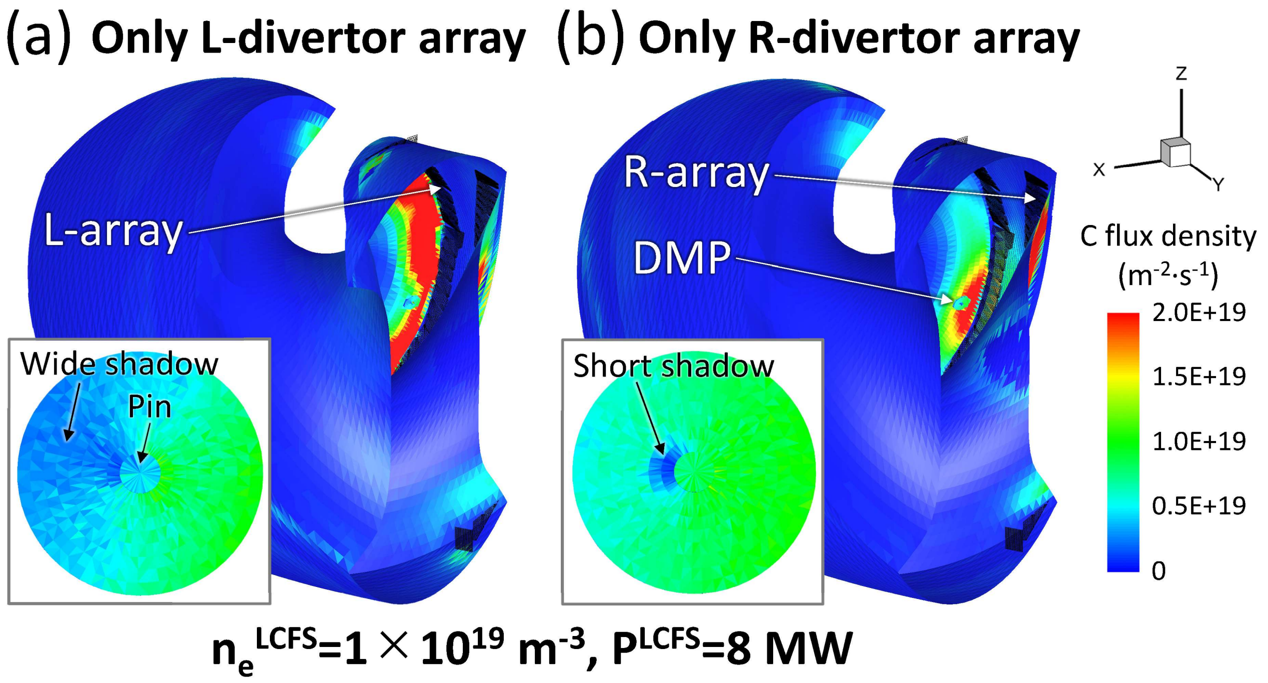

Fig.3 The simulation of carbon flux density on the vacuum vessel and the DMP for the low plasma density in which the sputtering only on the left (a) and the right (b) carbon divertor plates was included.

hypothesized condition shows a wide shadow which was formed by the carbon sputtered from the left divertor plates. Figure 3 (b) gives the simulation of the deposition profile on the vacuum vessel which included sputtering only on the right divertor plates. The carbon flux density around the DMP was higher than that in the other regions because of the short distance between the DMP and the right divertor plates near the equatorial plane. The deposition profile on the DMP presented a short shadow. The simulation reveals that the short shadow was formed by carbon sputtered from the right divertor plates.

3.3 Investigation of the carbon source in the high plasma density

Figure 4 (a) gives the simulation of the carbon flux density profile for the high plasma density in a case where sputtering only on the left divertor plates is considered. The simulation shows high carbon flux density on a helical coil can. The carbon deposition profile on the DMP shows that the wide shadow was formed by sputtering from the left divertor plates. Figure 4 (b) depicts the carbon flux density profile in a case including sputtering only on the right divertor plates. Being different from the simulation for the low plasma density, the carbon flux density on the helical coil can was low, and the carbon deposition on the DMP was negligible. The reason for the low carbon deposition was due to the ionization of carbon atoms sputtered from the right divertor plates due to the high plasma density in the divertor legs.

4. Comparison of the simulation with the experimental result on the DMP

For validating the ERO2.0 code, the simulation of the carbon deposition profile on the DMP accumulated in the experimental campaign is compared with the experimental result. The simulation was obtained by summing up the carbon flux density in various operational conditions in the experimental campaign. The plasma discharge time was classified by the plasma heating powers P^{LCFS}, plasma densities n_e^{LCFS}, and the magnetic axis configurations R_{ax}. It shows that the total plasma discharge time was 18567 sec., and the discharge times for the magnetic configurations R_{ax}~3.60, 3.75, 3.90 m, and others were 11898, 4162, 1795, and 712 sec, respectively. Using the classified discharge times and the simulation of the carbon flux density profiles in the experimental conditions, the areal carbon density profile was obtained, as shown in figure 5 (a). The simulation clearly demonstrates the directionality of the carbon deposition, which reproduces the experimental result with the short and wide shadows. Figure 5 (b) is the pie chart indicating the intensity profile of the characteristic X-ray of carbon, which is proportional to the areal carbon density along the circumference of the circle, having a radius of 7.5 mm, which is the half radius of the disk of the DMP. Figure 5 (c) is the pie chart presenting the simulation of the carbon density profile along the circumference. The simulation also presents the directionality (asymmetry) of the carbon density profile.

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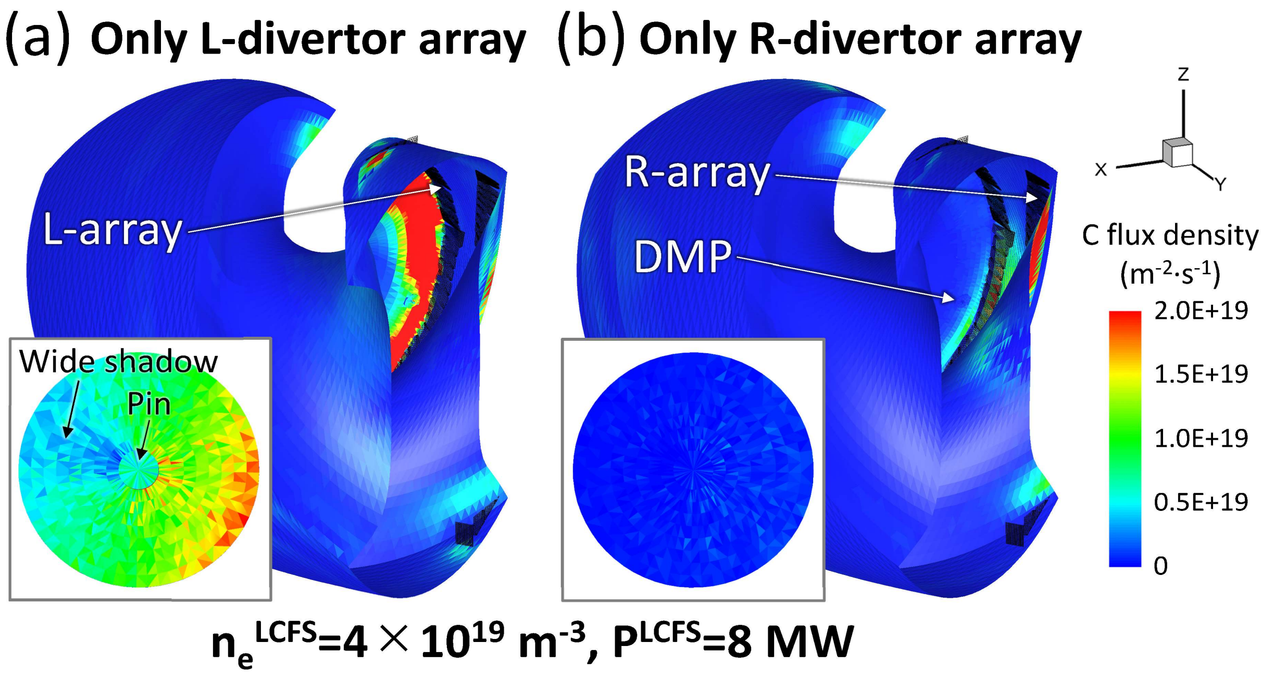

Fig.4 The simulation of carbon flux density on the vacuum vessel and the DMP for the low plasma density in which the sputtering only on the left (a) and the right (b) carbon divertor plates was included.

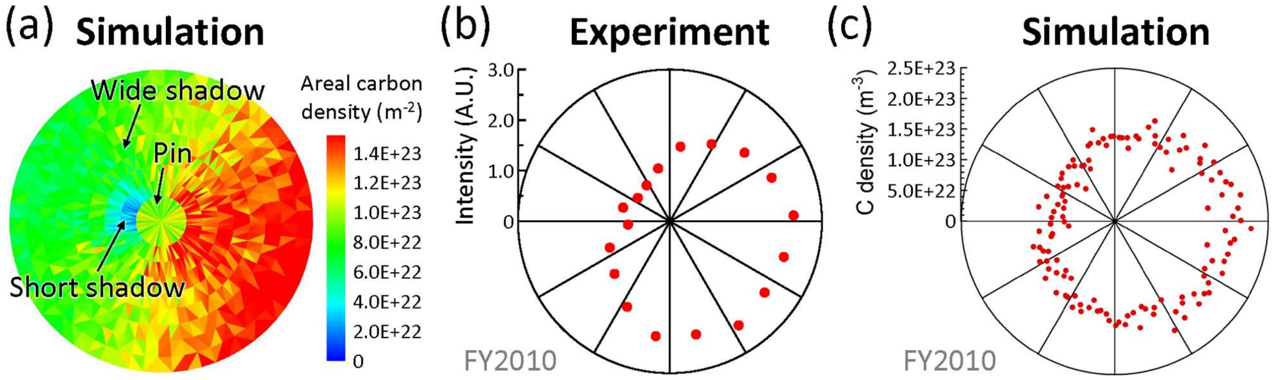

Fig.5 (a) The ERO2.0 simulation of the areal carbon density profile on the DMP accumulated in the campaign (FY2010), (b) the pie chart showing the experimental result of the characteristic X-ray intensity of carbon along a circumference on the DMP, and (c) the pie chart of the simulation of the carbon density along a circumference on the DMP in the campaign.

5. Summary

The directionality of the carbon density profile on the DMP installed in the inboard side of the torus was found in the experimental campaign (FY2010). The carbon deposition profile showed short and wide shadows (lower carbon deposition areas) on the disk. The ERO2.0 simulations revealed that the wide shadow was formed by the carbons sputtered from the left divertor plates in the inboard side, and the short shadow was made by the carbons sputtered from the right divertor plates. The experimental result on the DMP in the experimental campaign is reasonably explained by the simulation, which demonstrated the ERO2.0 applicability for detailed understanding of carbon migration in the LHD.

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References

[1] M. Shimada et al., J. Nucl. Mater. **438** S996 (2013).
[2] Y. Takeiri et al., Nucl. Fusion **57** 102023 (2017).
[3] M. Shoji et al., Nucl. Fusion **55** 053014 (2015).
[4] S. Masuzaki et al., Plasma and Fusion Res. **8** 1202110 (2013).
[5] A. Kirschner et al., Nucl. Fusion **40** 989 (2000).
[6] G. Kawamura et al., Contrib. Plasma Phys. **50** 451 (2010).
[7] J. Romazanov et al., Nucl. Mater. Energy **18** 331 (2019).
[8] G. Motojima et al., Plasma and Fusion Res. **10** 1202074 (2015).

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