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Simulation Analysis of Carbon Deposition Profile in the Closed Helical Divertor Configuration in the Large Helical Device

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Recent long pulse plasma discharges in the Large Helical Device have been interrupted by radiation collapse induced by large amounts of dusts released from a closed divertor region. Traces of exfoliation of carbon-rich mixed material deposition layers were found in the divertor region after the experimental campaigns, indicating that the thickly accumulated deposited layers were exfoliated and broken into dusts. Simulation of the density profiles of carbon deposition in the divertor region by EMC3-EIRENE reasonably explains the observation of the exfoliation of the deposition layers. It shows that the positions of the exfoliated layers correspond to the area where the density of the carbon deposition is high. It also proves that change of the configuration of target plates in the closed divertor is effective for controlling the accumulation of the carbon deposition, and carbon atoms released from the new target plates does not influence the main plasma confinement region.

1 Introduction

Steady-state plasma discharge operation is essential for future nuclear fusion reactors. The Large Helical Device (LHD) is the largest helical plasma confinement machine having superconducting helical and poloidal coils by which plasma confinement magnetic configurations are formed with no toroidal plasma current [1]. It is advantageous for sustaining steady state plasma discharges because of no instabilities and disruptions induced by the plasma current. Long pulse plasma discharges have been performed for more than one decade using ion cyclotron heating (ICH) and electron cyclotron heating (ECH) in LHD. In the experimental campaign in the fiscal year (FY) 2013, a long pulse plasma discharge with an average plasma density of ~1.2×10^{19} $m^{-3}$and a central electron temperature of ~2 keV was successfully sustained for ~48 minutes with a plasma heating power of ~1.2 MW [2]. The plasma discharge was interrupted with abrupt increase in carbon ion emission synchronized with the release of large amounts of dusts from a lower closed helical divertor region locating in the inboard side of the torus. An observation with a fast framing camera indicated the termination of the plasma discharge by radiation collapse induced by the penetration of the dusts into the main plasma. After the experimental campaign, the traces of the exfoliation of carbon-rich mixed material deposition layers were found in the divertor region. It is probable that the exfoliated mixed material deposition layers thickly accumulated in the divertor region were broken into the large amounts of dusts which induced the radiation collapse [3].

For this reason, the simulation analysis of carbon deposition in the closed helical divertor region plays a significant role for predicting the positions where dusts can be released by exfoliation of the deposition layers during long pulse discharges. It can contribute to the optimization of the closed divertor configurations in order to control release of dusts, leading to the extension of the duration time of long pulse plasma discharges. In the next section, the geometrical configuration of the closed helical divertor and diagnostics for monitoring the divertor plate temperature are presented. In section 3, the simulations of the plasma heat flux and the carbon deposition

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profiles in the closed helical divertor using a fully three-dimensional peripheral plasma simulation code (EMC3-EIRENE) are shown. In section 4, the influence of the change of the configuration of target plates in the closed divertor on the total radiation power due to carbon ions in the peripheral plasma is investigated by the simulation, which is followed by summary.

2 Configuration of closed helical divertor

For protecting the surface of the vacuum vessel from heat load due to the LHD peripheral plasma, divertor plates which consist of isotropic graphite (carbon) have been installed along the strike points. The divertor configuration has been changed from the original open divertor to closed helical divertor from the experimental campaign in FY2010 [4]. The divertor configuration was changed only in the inboard side of the tours because most of the strike points concentrate in the inboard side in the typical magnetic configuration (the radial position of the magnetic axis: R_{ax}=3.60 m) in which the highest energy confinement property has been achieved [5].

Figure 1 (a) illustrates a perspective view of the LHD vacuum vessel and the closed helical divertor which is composed of the following three components. The first one is divertor plates which are installed along the strike points in the inboard side of the torus. The front surface of the divertor plates faces to the inboard side locating on a midpoint between the two lines of the strike points. The second one is triangularly roof-shaped dome plates made of isotropic graphite installed between the divertor plates. The third one is target plates locating near the edge of lower and upper ports for intersecting one of divertor legs so as to concentrate the strike points to the inboard side for enhancing particle pumping by cryo-sorption pumps installed behind the dome plates. Since the experimental campaign in FY2014, some target plates have been replaced to new target plates as shown in Figure 1 (b). The front surface of the new target plates faces to the peripheral plasma, which was designed so as to reduce the heat load on the target plates and to control accumulation of the carbon-rich mixed material deposition layers in the closed helical divertor. By this modification, sputtered materials from the target plates can be dissipated to the LHD peripheral plasma.

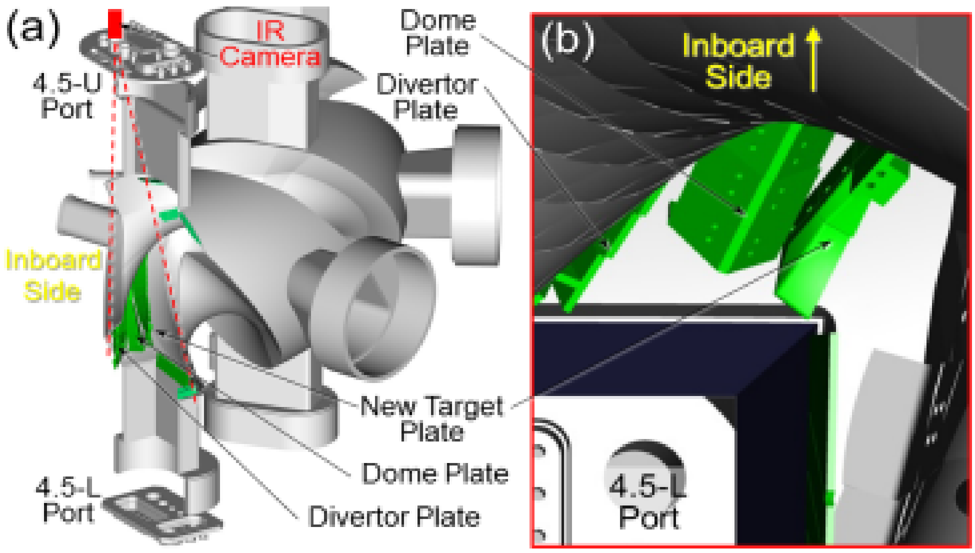

Fig. 1 A perspective view of the configuration of the LHD vacuum vessel, the closed helical divertor and an IR camera for monitoring the new target plates (a), and the field of view from the position of the IR camera (b).

The temperature profiles on the surface of the new target plates were measured with an infrared camera in stalled in an upper port (4.5-U). The infrared camera was calibrated for absolute temperature measurement in cluding the effect of the light transmission factor of the barium fluoride (BaF2) window mounted in front of the camera, etc. Figure 2 (a) gives an observed temperature profile of the new target plates near a lower port (4.5-L), which was measured in a short pulse plasma discharge in the typical magnetic configuration (R_{ax}=3.60 m). The observation shows that an area with high temperatures of more than 440 K is formed on the target plates.

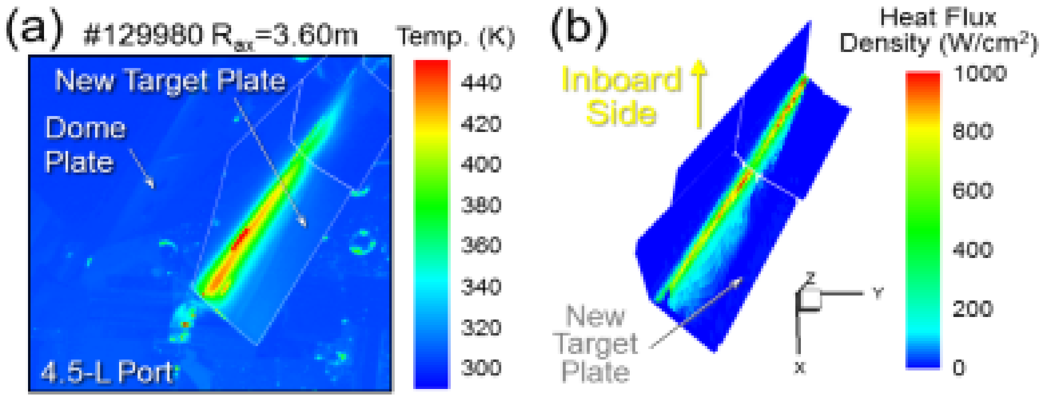

Fig. 2 Observed temperature profile of new target plates near a lower port (4.5-L) in a short pulse plasma discharge for R_{ax}=3.60 m (a), and the simulation of the heat flux density profile on the new target plates by the EMC3-EIRENE (b).

3 Simulation of density profile of carbon deposition in closed helical divertor

3.1 Set up for the simulation of the density profile of carbon deposition

The transport of carbon atoms and ions in the peripheral plasma in fully three-dimensional geometry has been investigated using the EMC3-EIRENE [6–8]. Figure 3 shows a three-dimensional grid model for the simulation, including the divertor components and the vacuum vessel for a half of one helical pitch (18°in toroidal angle). The divertor components and the vacuum vessel in the model are composed of some bodies of triangle plates. The both toroidal edges of the grid model satisfy a periodic boundary condition for simulation in the full toroidal geometry. Pure hydrogen plasma is assumed, and the three-dimensional profile of plasma parameters was deter mined by controlling the particle and heat transport coefficients in the peripheral plasma so as to fit the calculated radial profile of the electron density and temperature to measurements by Thomson scattering. In this simula tion, the electron density at the last closed flux surface (LCFS) is ~3×10^{19} $m^{-3}$and the electron temperature is ~200 eV. Figure 2 (b) gives the simulation of the heat flux density profile on the new target plates which is viewed from the position of the infrared camera. The simulation is qualitatively consistent with the measurement, which guarantees reasonable heat and particle deposition profile on the divertor plates in the simulation using the three-dimensional grid model.

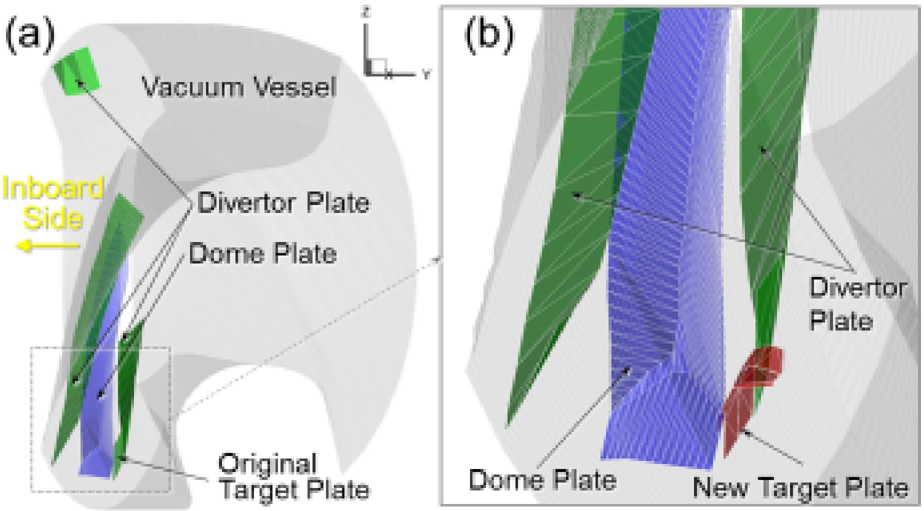

Fig. 3 3D view of the closed helical divertor for the original target plate configuration (a), and an enlarged view of the new target plate configuration (b) for a half of one helical pitch (18°in toroidal angle), which are fully three-dimensional grid models used for the simulation of carbon deposition profiles in the divertor region by the EMC3-EIRENE.

The EMC3-EIRENE is firstly applied to the fully three-dimensional simulation of the carbon deposition profile in the entire closed helical divertor region by tracking the trajectories of test particles which represent carbon atoms. The areal density profile of the carbon deposition is calculated by counting the number of test particles sticking to the surface on the divertor components per unit of area. The total number of the test particles is more than one hundred millions. In the simulation, carbon atoms are produced by sputtering at the strike points on the divertor plates and the target plates, assuming that the sputtering coefficient is 0.02 and that the sticking coefficient of the carbon atoms is 0.5 which is a typical value calculated by molecular dynamics (MD) simulation [9,10]. The energy of the sputtered carbon atoms is supposed to be 0.05 eV, which corresponds to the energy of the typical divertor plate temperature during long pulse discharges (~600 K), because the chemical sputtering is dominant over the physical sputtering on carbon surfaces in the typical divertor plasma (T^{div}_e ~20 eV and n^{div}_e ~3×10^{19} m^{-3}) [11]. It is assumed that the sputtered carbon atoms have the cosine angle distribution.

3.2 Control of carbon deposition by changing the target plate configuration

The top view of the simulations of the areal density profile of carbon deposition on the dome plates for the original and the new target plate configurations are illustrated in Figure 4 (a) and (b), respectively. It shows that the density of carbon deposition on the dome plates in front of the target plates is drastically reduced for the new target plate configuration compared to that for the original configuration.

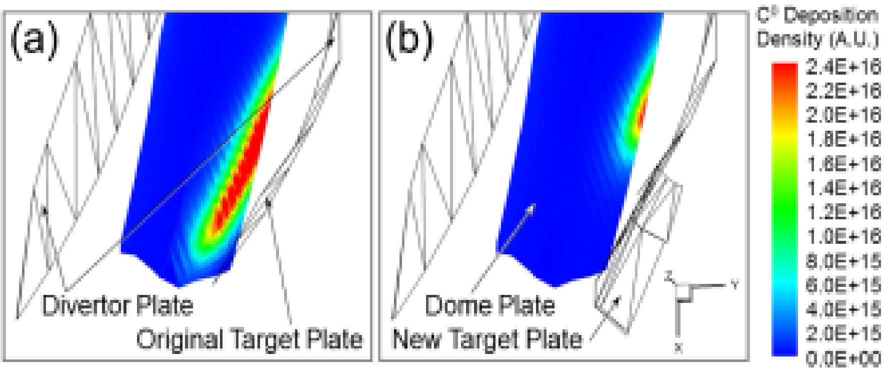

Fig. 4 Top view of the simulations of the areal density profile of carbon deposition on the dome plates for the original target plate (a) and the new target plate configurations (b).

Figure 5 (a) and (b) are photographs of the mixed-material deposition layers near the original and new target plates, which were taken after the last experimental campaign in FY2014, respectively. For the original config uration, a trace of exfoliation of the deposition layers on the dome plates in front of the target plates was found. Nano-geological diagnosis revealed that the deposition layers are composed of carbon-rich layers (98%) with small amount of iron-rich layers (2%) [12]. It is probable that thickly accumulated deposition layers produced by sputtering on the original target plates were exfoliated from the dome plates during long pulse plasma discharges which were carried out just before the end of the experimental campaign. It is experimentally supported by the fact that large amount of dusts, which were produced by broken exfoliated deposition layers, released from the divertor region have been frequently observed by CCD cameras and fast framing cameras in the long pulse plasma discharges [13].

It is proposed that the thickly accumulated layers were peeled off from the dome plates by the following two possible scenarios. The first one is the concentration of internal thermal stress in the iron-rich layers. The second one is the formation of blisters in these layers [14]. As shown in Figure 5 (b), no exfoliation of the deposition layers was found on the dome plates for the new target plate configuration, indicating that the deposition layers were thinner than that for the original target plate configuration. The simulation of the density profile of the carbon deposition in the closed helical divertor has successfully explained the observation of the control of the exfoliated deposition layers by changing the target plate configuration.

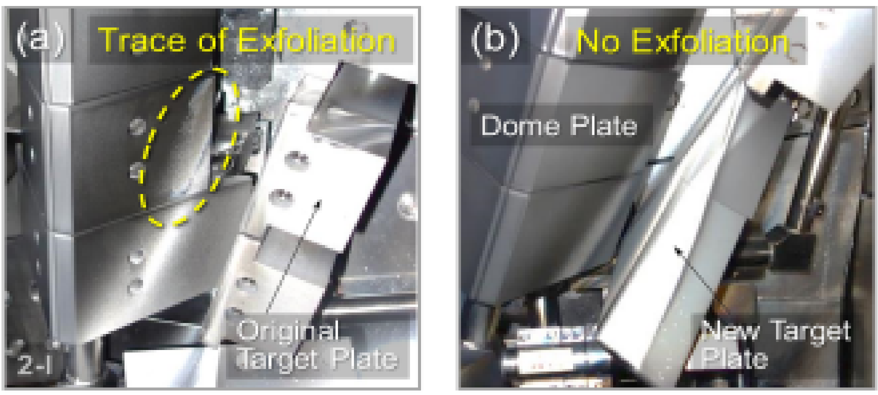

Fig. 5 Photographs of carbon-rich mixed material deposition layers near the original target plate (a) and new target plate (b) in the closed helical divertor , which were taken after the last experimental campaign in FY2014.

3.3 Density profile of carbon deposition on dome plates for new target plate configuration

In long pulse plasma discharges in the last experimental campaign in FY2014, the plasmas were often terminated by release of large amounts of dusts from a local position in the closed helical divertor in the inboard side of the torus. As shown in Figure 6 (a), traces of the exfoliation of the deposition layers were found at an edge (left side) of the dome plates installed near the equatorial plane after the experimental campaign. Similarly to the exfoliation of the deposition layers for the original target plate configuration shown in Figure 5 (a), it is probable that thickly accumulated deposition layers in this area were exfoliated and it was broken into dusts to penetrate into the main plasma, which could induce radiation collapse in the long pulse plasma discharges.

Figure 6 (b) is the simulation of the density profile of the carbon deposition on the dome plates in the inboard side for the new target plate configuration. It demonstrates that carbon is deposited with high density at an edge

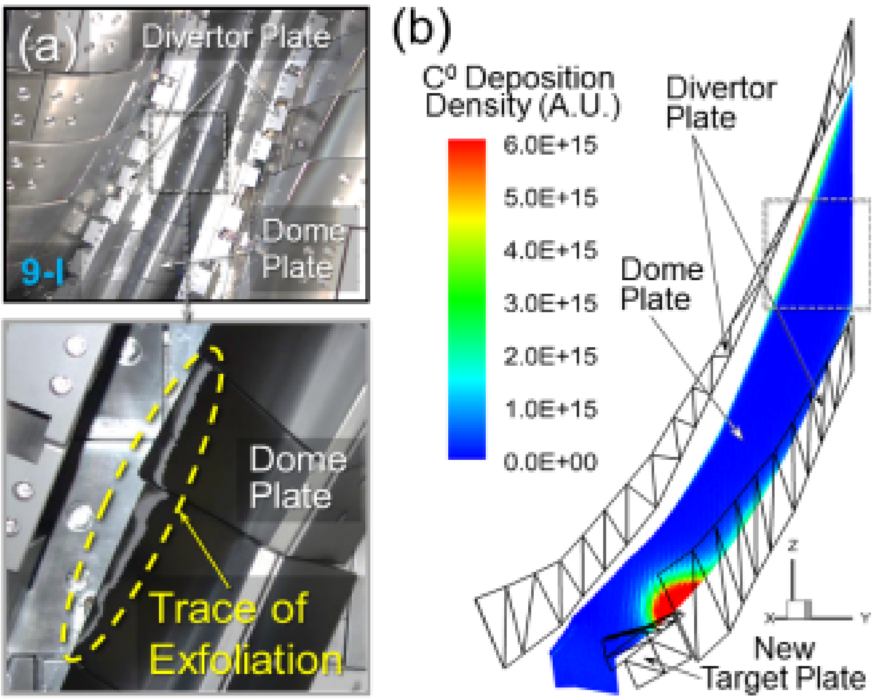

Fig. 6 Photograph of traces of the exfoliation of the deposition layers at an edge of the dome plates installed near the equatorial plane in the inboard side of the torus (a), and the simulation of the density profile of the carbon deposition on the dome plates in the inboard side for the new target plate configuration by the EMC3-EIRENE (b).

(left side) on the dome plates near the equatorial plane, which corresponds to the area where the traces of the exfoliation of the deposition layers were found. It is proved that the simulation can predict the position where the deposition layers are exfoliated in the closed divertor region. The simulation can be useful for optimizing the closed helical divertor configuration so as to reduce the accumulation of the deposition layers, which can contribute to extend the duration time of long pulse plasma discharges in LHD.

4 Radiation profile of carbon ions in the peripheral plasma

One of the possible drawbacks of the new target plate configuration is enhancement of radiation by carbon ions in the peripheral plasma near the target plates. This is because sputtered carbon atoms from the new target plates can directly penetrate into the main plasma because the front surface of the new target plates directly faces to the peripheral plasma. The simulation indicates the slight increase in the carbon ion density of a factor of 1.5 in the peripheral plasma near the target plates for the new configuration compared to that for the original one. At the positions being far from the target plates, the density profiles of the carbon ions in the both configurations are almost the same. The radiation power due to the total carbon ions (C^{+}-C^{6+}) in the grid model for the new and the original target plate configurations is figured out at 0.137 MW and 0.134 MW, respectively, indicating slight enhancement of the total carbon radiation power by change of the target plate configuration. It shows that carbon ions are localized in the outer edge of the peripheral plasma, which means that the carbon ions released from the new target plate hardly influence the main plasma confinement region.

5 Summary

The carbon deposition profile in the closed helical divertor region is investigated using a fully three-dimensional peripheral plasma simulation code (EMC3-EIRENE). By changing the configuration of the target plates, the reduction of the carbon-rich mixed material deposition layers on the dome plates near the target plates was observed in the last experimental campaign. No traces of the exfoliation of the deposition layers were found in front of the target plates. The simulations can reasonably explain the reduction of the carbon deposition layers by changing the target plate configuration. After the last experimental campaign in FY2014, the traces of the exfoliation of thickly accumulated deposition layers were found at an edge of the dome plates near the equatorial plane after the experimental campaign. The simulation demonstrates the high density carbon deposition at the area where the exfoliation was found for the new target plate configuration. The slight enhancement of radiation of carbon ions in the peripheral plasma is indicated by the simulation for the new target plate configuration, which proved that it hardly influences the LHD main plasma.

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