ELSEVIER

Journal of Nuclear Materials 313–316 (2003) 167–171

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Analysis for surface probes of third experimental campaign in the large helical device

T. Hino [a,*], Y. Nobuta [a], Y. Yamauchi [a], Y. Hirohata [a], A. Sagara [b], S. Masuzaki [b], N. Inoue [b], N. Noda [b], O. Motojima [b], LHD Experimental Group [b]

[a] *Department of Nuclear Engineering, Laboratory for Plasma Physics and Engineering, Hokkaido University, Kita-13, Nishi-8, Kita-ku, Sapporo 060-8628, Japan*

[b] *National Institute for Fusion Science, Toki-shi, Gifu-ken 509-5202, Japan*

Abstract

For the third experimental campaign of LHD, graphite tiles were installed in entire region of divertor strike region. Several material probes of SS 316L and graphite were placed along the poloidal direction at #7 toroidal sector. These probes were extracted after the campaign, and impurity deposition on the probe and retention of discharge and impurity gases were analyzed by AES and TDS, respectively. Major impurity species deposited on the probe were C, Fe and O. The iron deposition rate per one main discharge was approximately a half of that in the second campaign. The carbon deposition was significantly large, and the carbon concentration was as high as 90 at.%. These results correspond to the reduction of metal impurity level in the plasma. The retention of discharge gas and impurities doubled compared to the case of the second campaign, due to the carbonized wall. Significant retention of helium was observed, which is one of the characteristics of the LHD wall. The retention of helium is due to charge exchanged He during He main discharge shots and implantation of He ion during He glow discharges.

PACS: 52.40.H
Keywords: Large helical device; Plasma–wall interaction; Material probe; Impurity deposition; Gas retention

1. Introduction

It is quite important to know the wall conditions of fusion experimental devices and the changes arising from plasma experiments, by using plasma surface interaction (PSI) techniques. For this purpose, wall-condition data have been systematically accumulated as a database and analyzed to characterize the wall through four experimental campaigns, conducted in the large helical device (LHD) since 1998, whose baking temperature is limited below 368 K. The wall conditions for the first campaign and second campaign were reported in previous papers [1–3]. This paper presents the results obtained in the third campaign conducted in the period from July 1999 to December 2000. Some data from the fourth campaign conducted in the period from October 2000 to February 2001 are also described. In these four campaigns, helium and hydrogen gases were employed for both the main discharges and discharge cleanings.

He ECR discharge cleaning was employed in the first campaign for the initial ECH plasma production, while glow discharge cleanings was used in the second campaign for the production of NBI heated plasmas [2]. In the third campaign for ICRF heated plasmas and high-power plasma production, graphite tiles have been installed in the divertor leg region to reduce metal impurities in the plasma. Improved plasma performance

* Corresponding author. Tel.: +81-11 706 7195; fax: +81-11 709 6413.
E-mail address: tomhino@qe.eng.hokudai.ac.jp (T. Hino).

0022-3115/03/$ - see front matter © 2003 Published by Elsevier Science B.V.
PII: S0022-3115(02)01415-0

was investigated in the fourth campaign, attributed mainly to controlling the magnetic axis position. Fig. 1 shows the plasma stored energies as a function of shot number, representing the progress of LHD plasma performance. The highest values of plasma parameters achieved in these four campaigns are summarized as follows:

(1) T_e of 1.3 keV and n_e of 1.3×10^{19} m^{-3} in the first campaign,
(2) T_e of 2.3 keV, T_i of 2.0 keV, n_e of 7×10^{19} m^{-3} and averaged beta $\langle\beta\rangle$ of 1% in the second campaign,
(3) T_e of 4.4 keV, T_i of 3.5 keV, n_e of 1.1×10^{20} m^{-3} and $\langle\beta\rangle$ of 2.4% in the third campaign, and
(4) n_e of 1.5×10^{19} m^{-3} and $\langle\beta\rangle$ of 3% in the fourth campaign.

During each of four campaigns, material probes of SS 316L and isotropic graphite have been placed at several inner wall positions of the same poloidal cross-section. In order to make comparison of the wall characteristics, same probe positions were taken for each of four campaigns. After each campaign, impurity deposition, change of surface morphology and retention of discharge and impurity gases were examined, in order to clarify the PSI and degree of wall cleaning.

After the first campaign, on the entire wall surface there were deposited many sub-micron particles, which were identified as Fe–O particles. Oxygen concentration and the deposition thickness were large, 60 at.% and 200 nm, respectively. The amount of retained gas was large at the wall far from the plasma. The temperature rise during the discharge was very small in the entire wall. Thus these results suggest that the ECR discharge cleaning was effective for the wall near the plasma but not for the wall far from the plasma. After the second campaign, the deposition of Fe–O sub-micron particles disappeared at the wall except in the inner divertor leg region. In addition, both the oxygen concentration and deposition thickness became low, 40 at.% and 20 nm, respectively. The total gas retention also decreased by 30%, in particular, the decrease was largest at the wall far from the plasma. The retention of He, the gas species used for main discharges and glow discharges, was observed at the entire wall. The retained amount was comparable with the other gas species, H_2. These results suggest that both the glow discharge cleaning and the large increase of main discharge shot were quite effective for the wall conditioning.

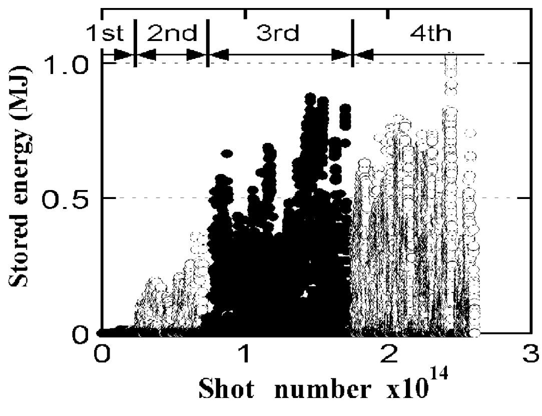

Fig. 1. Plasma stored energy of LHD to shot number.

From the third campaign, the wall surface was significantly changed by the installation of graphite tiles at the divertor leg region. In the following, the wall condition of the third campaign is presented. In addition, the plasma surface interactions analyzed for the fourth campaign are also introduced.

2. Experimental

In the third experimental campaign, the total number of main discharge shots was 10 000; 5000 shots for He fuelled discharges and 5000 for H_2 fuelled discharges. The heating powers were ECH $\leqslant$ 0.55 MW, ICRF $\leqslant$ 1.5 MW and NBI $\leqslant$ 4.5 MW. He and H_2 glow discharge cleanings were conducted. The discharge cleaning time was totally 2300 h; 1150 h for He glow discharge and 1150 h for H_2 glow discharge. Two anodes were inserted into the vacuum chamber for the glow discharge cleanings. The number of main discharge shots was increased by a factor of 2, compared to the case of the second campaign. In the fourth campaign, totally 9000 He or H_2 main discharge shots were conducted. He glow discharge cleanings was mainly employed, and the time period was 1600 h. The plasma stored energies of second, third and fourth campaigns were $\leqslant$ 430 kJ, $\leqslant$ 880 kJ and $\leqslant$ 1 MJ, respectively. Before the third campaign, graphite tiles were installed in the entire region of the divertor target. The first wall material remained the same, SS 316L. The locations of material probes are shown in Fig. 2. The toroidal position of these probes is the 7–0 port. In every poloidal position, both SS 316L

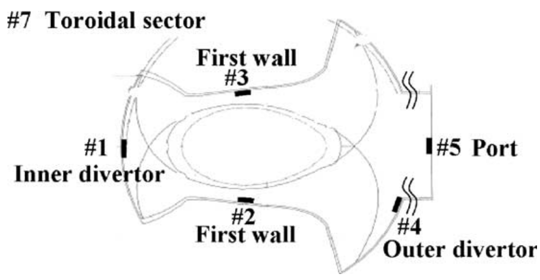

Fig. 2. Positions of material probes placed at #7 toroidal sector.

and graphite probes were placed. The graphite and SS probe clearly show the deposition of metal or carbon, respectively. The samples #1 and #4 are placed near the inner and outer divertor, respectively, #2 and #3 at the first wall, and #5 at the port far from the plasma. In addition to these probes, in the fourth campaign, samples were exposed only to the glow discharges or the main discharges by using shutters were prepared in order to examine the PSIs during the glow discharge and the main discharge.

The samples were extracted after the campaign, and then the surface morphology, depth profile of atomic composition and retained amounts of discharge gas and impurity gas were analyzed by scanning electron microscope (SEM), Auger electron spectroscopy (AES), and thermal desorption spectroscopy (TDS), respectively. In the following, the results obtained are described.

3. Results

After the third campaign, the color of every SS probe changed perhaps due to the deposition of carbon. The sub-micron particles, which were observed at the entire wall in the first campaign and at the inner wall in the second campaign, disappeared. In the graphite probe, the edge of graphite powder with a micron size, contained in the isotropic graphite, was rounded by deposition of iron oxide, Fe–O, and the erosion. The deposition of Fe–O was observed to be large at the probes placed at the first wall, #2 and #3, as shown in Fig. 3. The depth profiles of atomic composition was obtained for all probe samples. The analyses for graphite samples showed that the iron concentration was as high as 25 at.% and the deposition thickness was approximately as large as 20 nm. These values were relatively large at the probes, #2 and #3. Both the concentration and the deposition thickness were comparable to those of the second campaign. However, the number of main discharge shots in the third campaign was twice of that in the second campaign, so that the iron deposition per one main discharge shot in the third campaign becomes a half of that in the second campaign. In the main discharge plasma of the third campaign, the metal impurity concentration was largely reduced. The reduction of the iron deposition well corresponds to the reduction of metal impurity level in the plasma.

On the SS samples, the atomic composition was significantly changed by the deposition of carbon. Fig. 4 shows the depth profiles of atomic composition for the samples, #2, #4 and #5. The profiles of #3 and #1 were similar to that of #2. At the first wall, the carbon concentration became approximately 60 at.% and the deposition thickness was 5–10 nm. The oxygen concentration was 30–35 at.%, and the thickness was 5–10 nm. In the first campaign, the thickness of oxygen was as high as 200 nm. For the second campaign, the oxygen

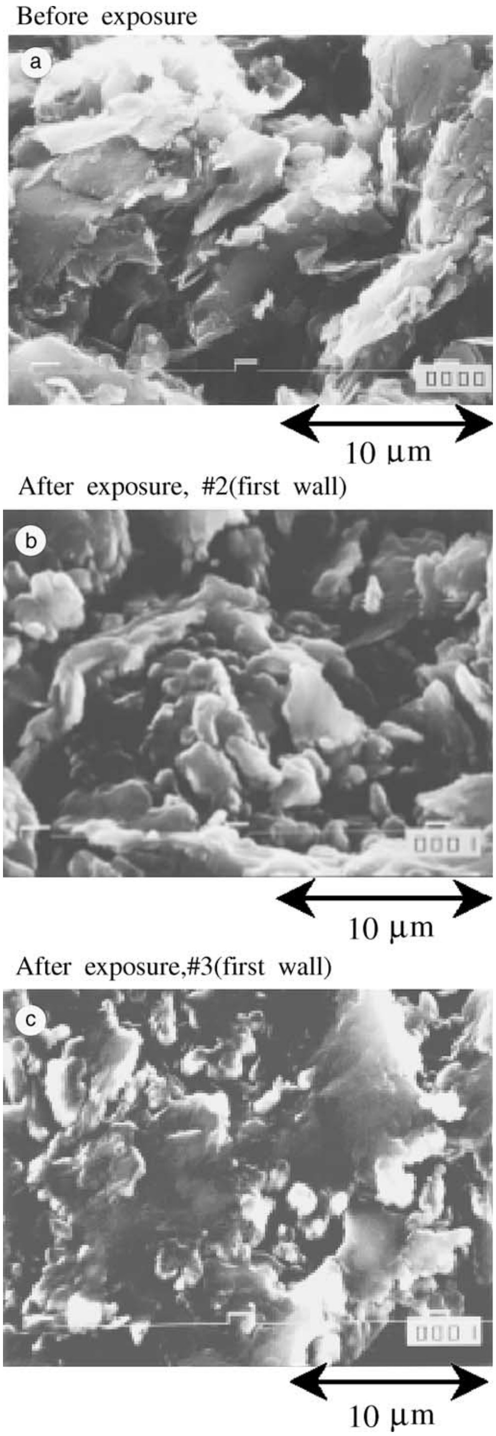

Fig. 3. SEM photographs of as-received sample, and samples placed at first walls, #2 and #3.

thickness was largely reduced. In the probes placed at the port, #5, and outer divertor, #4, the carbon concentration was as high as 90 at.%, and also the

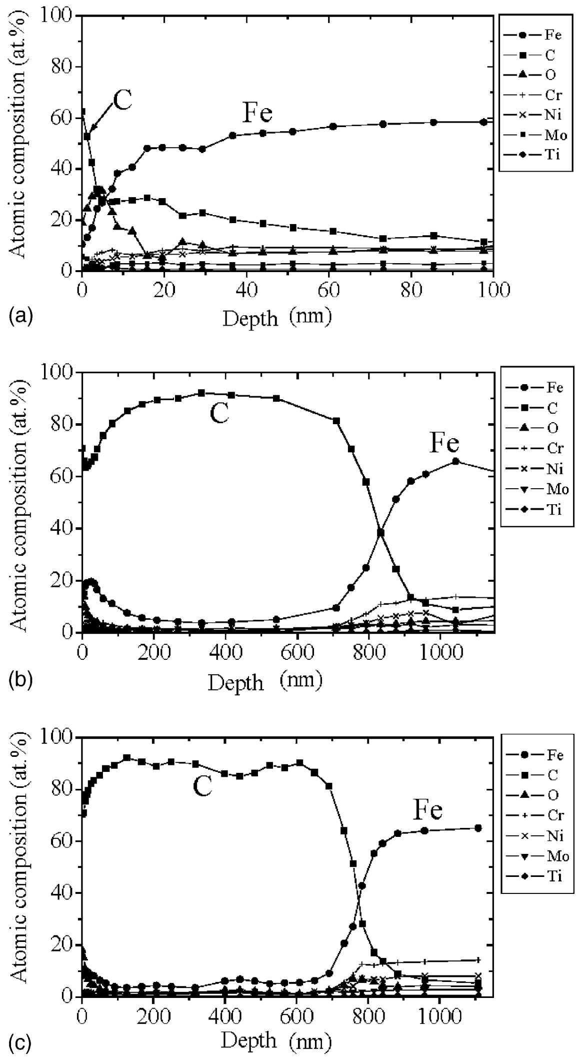

Fig. 4. Depth profiles of atomic composition for SS samples, #2, #4 and #5.

deposition thickness was 800–900 nm. The large deposition of carbon may be caused by the accumulation of eroded carbon during both the main discharge shots and glow discharge cleanings.

Fig. 5 shows gas desorption amounts of five SS samples. Major gas species were H_2O, CO_2, CO, He and H_2. The desorption of CH_4 was also observed but the amount was very small. Total gas desorption amount was roughly twice of the second campaign. In addition, the gas desorption was large at the samples far from the plasma with a large carbon deposition. In the second campaign, the gas desorption from the position far from the plasma was relatively small. The difference of the present result with that of the second campaign is presumed to be caused by the carbon deposition. One of major characteristics of the LHD wall is large helium

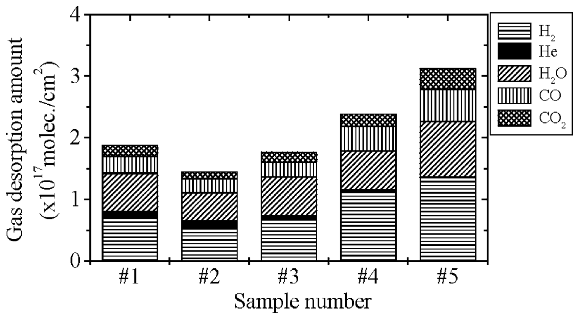

Fig. 5. Gas desorption amounts of SS samples.

retention. The retained helium amounts of five SS samples are shown in Fig. 6. The helium retention was large at the first wall and small at the wall far from the plasma. In the graphite samples, the helium retention had a similar tendency. The wall temperature of LHD is a maximum of 368 K. On the other hand, the desorption temperature of helium is a minimum of 500–700 K, so that the retained helium hardly desorbs and the helium accumulates in the wall. In addition, a half of the main discharges and a half of the glow discharges are helium discharges. These may be possible reasons for such large helium retention.

In the fourth campaign, probe samples exposed to only main discharges or only He glow discharges were prepared. These probes were placed at inside of ports, 7.5 port far from the anode and 10.5 port close to the anode. By using shutters, the samples were exposed to only main discharges or only glow discharges. Fig. 7 shows the depth profiles of atomic composition of an SS sample exposed to only main discharges and a graphite sample exposed to only glow discharges. Carbon deposition was clearly observed in the sample exposed to only main discharges. The deposition of iron was very small, and the concentration in the deposition layer was only several atomic percents. On the other hand, iron deposition was relatively large on the sample exposed to only glow discharges, compared to that of the sample exposed to only main discharges. The deposition of carbon

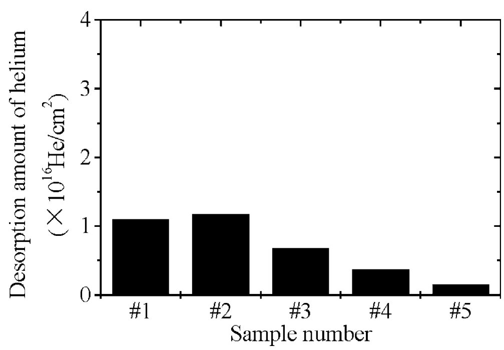

Fig. 6. Helium desorption amounts of SS samples.

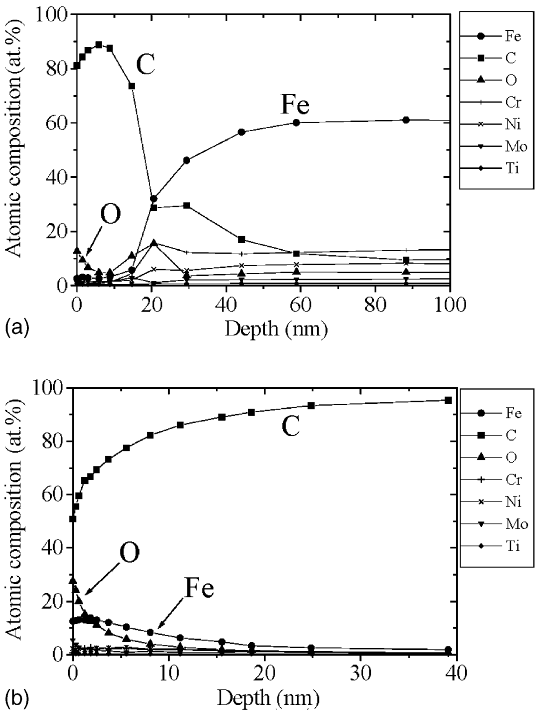

Fig. 7. Depth profiles of atomic composition for SS sample exposed to only main discharges and graphite sample exposed to only glow discharges at port of 7.5 toroidal sector.

was comparable to that of iron. Thus, it can be regarded that the main discharge erodes mainly the graphite tiles and the glow discharge mainly the first walls. The helium was retained in both the main discharge and the glow discharge. In the case of SS sample, the helium retained by charge exchanged helium during the main discharge desorbs at the temperature higher than 900 K. The helium retained during the glow discharge desorbs at the temperature lower than 900 K. In the case of the graphite sample, the retained helium desorbs at a temperature lower than 900 K in both the samples exposed to only main discharges and only glow discharges. At the position far from the anode, the helium retention due to main discharges was comparable to that due to glow discharges. However, at the position close to the anode, the helium retention of the sample exposed to only glow discharges was one order of magnitude larger than that exposed to only main discharge.

4. Conclusion

A surface probe study has been successfully carried out for the third and fourth experimental campaigns in the LHD. For the third campaign, graphite tiles were installed in the entire divertor target region. In the third campaign, the rate of iron deposition was reduced to a half of that in the second campaign. In addition, the wall has been entirely covered by the carbon. At the first wall and the wall far from the plasma, the carbon concentration was observed to be approximately 60 at.% and as high as 90 at.%, respectively. The metal impurity level in the plasma was greatly reduced during the third campaign. The wall coverage by carbon is responsible for the reduction of the metal impurity level in the plasma.

The gas retention increased to twice of that in the second campaign. This increase is again due to the deposition of the carbon. The retention of helium was observed to be significant, which is due to the low wall temperature. The helium retention is of both charge exchanged helium during the main discharge and helium ions during the glow discharge.

The plasma surface interactions during the main discharge or the glow discharge was also investigated. The graphite tiles at the divertor were eroded mainly by the main discharge. The sputtering of the first wall was caused mainly by the glow discharge. Helium retention was observed both for only main discharges and for only glow discharges. The helium retention due to glow discharges was comparable to that due to main discharges for the toroidal position far from the anode used for the glow discharge, but one order of magnitude larger than that due to main discharges for the toroidal position close to the anode.

In summary, the surface composition of the wall in LHD has been related to the progress of plasma performance with the increase of heating power and the installation of graphite tiles for the divertor. The retention of He is not negligible and is one of the characteristics of the LHD wall. One method of reducing the gas retention would be surface heating using a scanning laser flash before main discharges. For reduction of oxygen impurities, boronization has been shown to be effective in tokamaks [4]. In the near-future campaign, these conditionings are scheduled, and hence, further improvement of plasma performance is expected.

Acknowledgements

This work was supported by Collaboration Research Program of National Institute for Fusion Science.

References

[1] A. Sagara, N. Inoue, N. Noda, O. Motojima, et al., J. Plasma Fusion Res. 75 (1999) 263.
[2] T. Hino, T. Ohuchi, M. Hashiba, Y. Yamauchi, Y. Hirohata, N. Inoue, A. Sagara, N. Noda, O. Motojima, J. Nucl. Mater. 290–293 (2001) 1176.
[3] S. Masuzaki, K. Akaishi, H. Funaba, M. Goto, K. Ida, et al., J. Nucl. Mater. 290–293 (2001) 12.
[4] J. Winter, J. Nucl. Mater. 145–147 (1987) 131.