Characterization of Ion Cyclotron Wall Conditioning Using Material Probes in LHD[*]

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The ion cyclotron wall conditioning (ICWC) is one of the conditioning methods to reduce impurities and to remove tritium from the plasma facing components. Among the advantages of ICWC are the possible operation under strong magnetic field for fully torus area based on the charge exchange damage observed in thin SS samples arranged on a hexahxedron block holder with three different facings, the areas influenced by ICWC is estimated. On the plasma facing area of the material holder, high density of helium bubbles is observed by transmission electron microscope (TEM). But the other areas show no observable damage. The fact that the bubble were observed only in a sample facing the plasma implies that the effective particles, most probably charge exchange neutrals come to the wall straightly Thus, cleaning of the surfaces un-exposed to plasma directly and those in shadow area is difficult by ICWC.

Keywords: LHD, wall conditioning, RF plasma, TEM, T inventory

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1. Introduction

Future fusion devices with large superconducting coils will need long time for excitation and de-excitation of the magnetic fields. For example, the magnetic field will be kept over a week as is planned in ITER operation. Therefore, wall conditioning under strong magnetic field is highly required for those devices.

An ion cyclotron wall conditioning (ICWC) is considered as a means for cleaning hydrogen isotopes and impurities deposited on the plasma facing component [1, 2]. In particular, tritium inventory in the deposited layers and the bulk wall tiles is a serious issue in future devices. For example, ITER has an operational limitation for tritium inventory of 700 g in vacuum vessel. Thus, wall conditionings with sufficient tritium cleaning efficiency are necessary.

As a general wall conditioning method to remove impurities and retained gases, two scenarios are planned in the ITER, one is an initial conditioning before main experimental campaigns and the other is a daily or shot by shot conditioning during the campaign. Since the magnetic field will be kept over a week in the experimental campaign, the ICWC under the magnetic field will be an important cleaning method for ITER.

The first experiments on ICWC were performed in 1996 in Tore Supra [2, 3] and TEXTOR [4], and many additional devices such as HT-7, EAST, JET, AUG, W7-AS and KSTAR were operated with ICWC until now. In HT-7 and EAST, ICWC is used, in addition to conventional wall conditioning, for boronization by using a mixture of carborane ($C_2B_{10}H_{12}$) in helium or deuterium [5]. Among the advantages of ICWC are to be operated under a strong magnetic field for fully torus area which was different from local area cleanings such as a flush lump and a laser ablation. The Large Helical Device (LHD) [6, 7] is provided with superconducting coils for its confinement magnetic field and DC-glow discharge cleaning for its wall conditioning in most cases of operation [8]. As supplemental wall conditioning methods, boronization and titanium gettering are carried out for a few times during an experimental campaign.

Ion cyclotron range of frequency (ICRF) heating system has been developed for a high power and long pulse discharge plasma in LHD [6, 7]. Using the same ICRF antenna sets, an initial operation of ICWC was done successfully in 2005 [9] and additional ICWC test experiments were operated in 2006 and 2007. The advantages of ICWC

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in LHD include the durability of long-term operation and the flexibility of input power with pulse phases. However, the hydrogen removal rate by He-glow discharge cleaning (GDC) is about ten times larger than that of ICWC in LHD [9]. Two reasons are considered for the lower removal rate of the ICWC in LHD. One is the smaller effective clearing areas by ICWC than that by GDC. The other is the limited number of particles available for the cleaning during ICWC because the magnetic field, which has the same configuration as that during the main plasma operation, is maintained during the cleaning in LHD.

In Tore Supra, energetic ions and neutrals were reported as the effective accelerated particles by ICWC and, in particular, fluxes of hydrogen and deuterium neutrals with energies including tens of kiloelectronvolts were detected using charge-exchange analyzers [2]. In spite of the characterization of the effective particles, the interactions between ICRF conditioning plasma and the plasma facing materials have not been investigated yet.

In this paper, characterization of the ICWC is carried out by examining microstructures of material probes induced by the cleaning, with transmission electron spectroscopy (TEM).

2. Experimental Setup

In LHD, a surface area of vacuum vessel including the port areas and a space of superconducting areas is about 800 m^2, half of which is directly facing the plasma. The volume of the vacuum vessel and the plasma is 210 m^3 and 30 m^3, respectively. As plasma facing components, the first wall is composed of stainless steel 316 L and the divertor tiles are made of graphite.

ICWC operated using two antenna sets of RF heating system for main plasma operation in LHD. The frequency of RF generators was set at 38 MHz and 85 MHz with the magnetic field of 2.75 T and the magnetic axis, $R_{\mathrm{ax}} = 3.6$ m. Helium working gas is used and the partial pressures of helium and hydrogen were measured by quadrupole mass spectrometry (QMS) with a sampling interval of 1 sec.

A RF input phase for 3 sec and an interval phase for 2 sec are used, which is determined by the duration necessary for the data acquisition. The maximum input power of ICWC is 287 kW as the net power, and the absorption ratio is about 60%.

During ICWC experiments in 2006 and 2007, thin stainless steel (SS) 316 samples of 3 mm in diameter were set on the hexahedron block holder in LHD. The block holder has surfaces oriented to the following three directions, as shown in Fig. 1; 1) surfaces facing the plasma, 2) surfaces oriented vertical to the plasma and 3) surfaces oriented vertical to the plasma and facing a thin SS plate with a gap simulating the gap structure between the tiles. In this case, the distance between the base block holder to the thin plate is about 1.5 mm and the samples are not exposed to plasma directly. Using the specimen facing the gap structure, the cleaning effect in the deposited layer in the gap between plasma facing tiles are examined, because it was reported that hydrogen isotopes retention in the gap is not negligible [10].

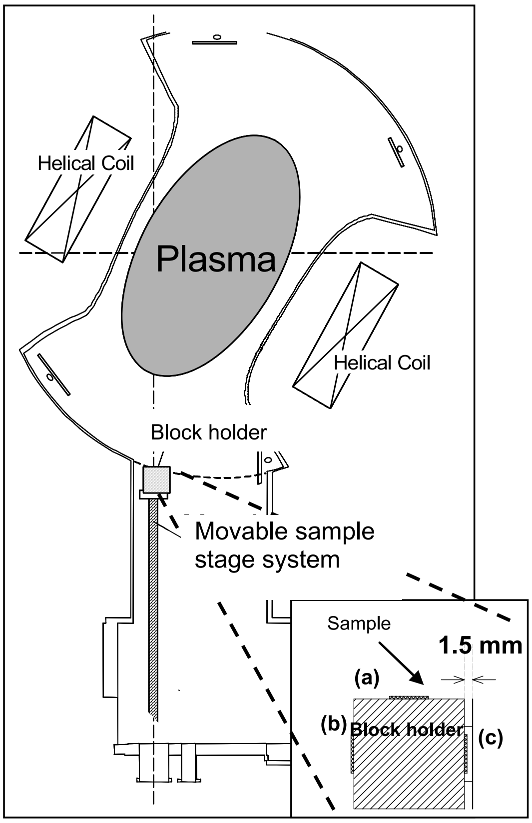

Fig. 1 The movable sample stage system at 4.5 L lower port and the hexahedron block holder. (a) surface facing the plasma (b) surface oriented vertical to the plasma and (c) surface oriented vertical to the plasma and facing a thin SS plate with the distance of 1.5 mm simulating the gap structure of the tiles.

The block holder was installed in the movable sample stage system at 4.5 L lower port in LHD which was set at the first wall position as shown in Fig. 1. The block holder was kept at the position during ICWC plasma with the integrated exposure time of about 4000 s in 2006FY. The SS samples are analyzed by transmission electron microscope (TEM), JEOL JEM-2000EXII with an accelerated voltage of 200 keV.

For comparison, microstructures of SS samples with the orientation to and vertical to the plasma are observed after exposure to He-GDC.

3. Results and Discussion

3.1 Microstructural change of material probes

The bright field images of the SS samples oriented to the three directions are shown in Figs. 2. High densities of bubbles are observed only in the sample facing the plasma (Fig. 2 (a)). For the samples directed vertical to the plasma

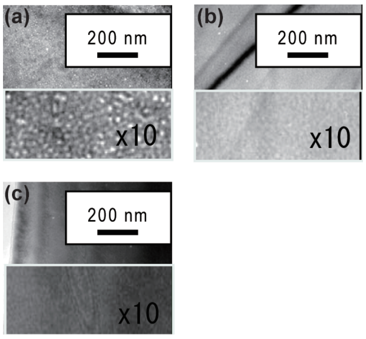

Fig. 2 TEM Bright field images of thin SS sample exposed to the He ICWC, (a) surface facing the plasma (b) surface oriented vertical to the plasma and (c) surface oriented vertical to the plasma and facing a thin SS plate with the distance of 1.5 mm simulating the gap structure of the tiles. These symbols are the same in Fig. 1.

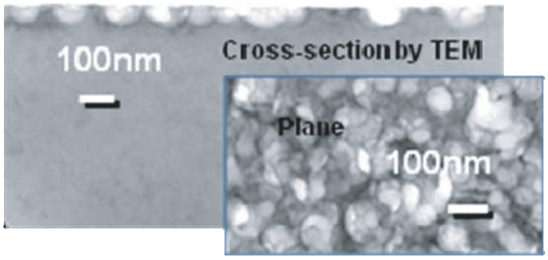

Fig. 3 Plan and cross-sectional view of TEM bright field images of thin SS sample exposed to the He ICWC.

and vertical and facing the thin plate, damage is not observed by TEM (Fig. 2 (b) and (c)). Considering that the helium bubbles are produced by an interaction between RF helium plasma and the target samples, the results imply a strong interaction of the plasma with the plasma-facing surfaces. The fact that the bubble were observed only in a sample facing the plasma implies that the effective particles, most probably charge exchange neutrals come to the wall straightly Thus, cleaning of the surfaces un-exposed to plasma directly and those in shadow area is difficult by ICWC.

A specimen mounted to the plasma-facing direction but in a different experimental campaign was cut by Focused Ion Beam (FIB) and the cross-section image is observed by TEM as shown in Fig. 3. Helium bubble images overlap with each other when observed from the surface. But a cross-section image shows that helium bubbles are located only near the surface. The depth from the top surface to the helium bubbles is about 50 nm. The reason of the large size He bubbles with diameter of about 100 nm is considered to be that this surface was heated during the exposure to ICWC plasma. However, the temperature of the samples was not measured during the ICWC.

Figure 4 shows the TEM image of samples exposed

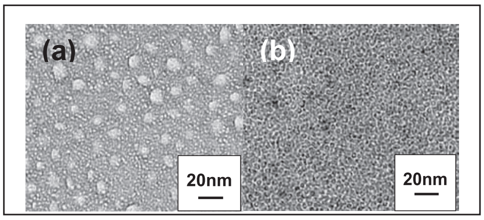

Fig. 4 TEM bright field images of thin SS sample exposed to the He GDC, (a) surface facing the plasma (b) surface oriented vertical to the plasma.

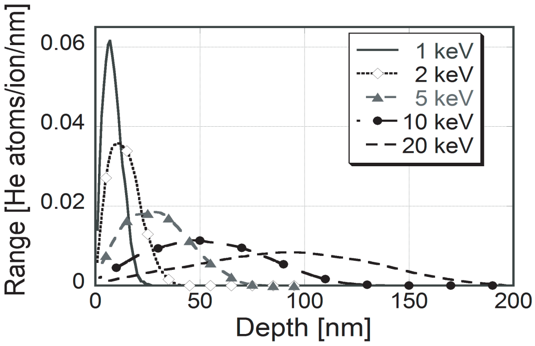

Fig. 5 Depth distribution of implanted He ions in SS316 calculated with TRIM-91 code.

to He-GDC for 65 hours in LHD. Thin SS samples were set on the hexahedron block holder which was installed to the first wall level in LHD. In this experiment, two kinds of sample sets, those directed to the plasma and vertical to the plasma, were compared. Helium bubbles were observed in the both samples. The sizes of the bubbles are larger in the plasma-facing samples than those oriented vertical to the plasma. In the case of the GDC, ions by GDC can interact with the wall with ground voltage including area un-exposed to the plasma in the vacuum vessel. The difference between TEM results by ICWC and GDC shows the characteristics of the two cleaning methods.

The depth distribution of the injected He atom in SUS316L was calculated by TRIM91-code as shown in Fig. 5. Considering that the helium bubbles are located about 50 nm from the top surface on SS targets the energies of injected He are estimated to be about 1-20 keV. From the wall conditioning viewpoint, it is favorable that the damages such as He bubbles are formed only less than 100 nm from the surface. In some tokamaks, ICWC have been operated for conventional wall conditioning to remove deposited impurities, such as carbon and oxygen [5]. Charge exchange particles by He ICWC can remove these thin layers as erosion. But the process to remove hydrogen isotopes needs further investigation.

3.2 Particle flux from ICWC plasma

Using Natural Diamond Detector (NDD) [11] charge exchange neutral particles are measured as shown in

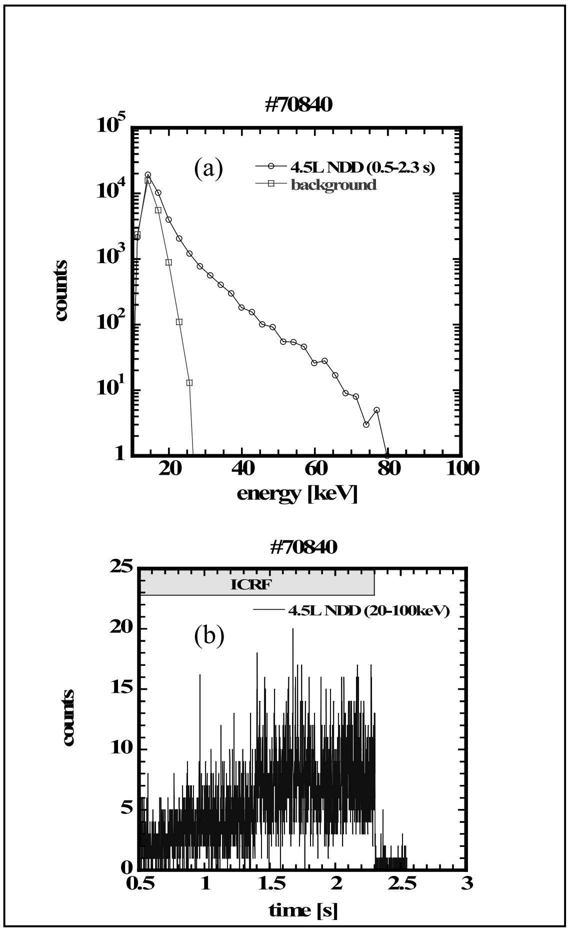

Fig. 6 The charge exchange neutrals measured by the diamond detector. (a) Energy distribution and (b) time evolution for integrated fully energy regions.

Figs. 6. This NDD is located at the 4.5 lower port which is at the same poloidal cross-section as that of the movable sample stage system This NDD system has a shutter between the plasma and the detector and this shutter was opened during plasma experiment. Background data as shown in Fig. 6 (a) was measured with shutter on the detector. Using NDD data at shot # 70840, particle flux is estimated. Particles penetrating the slit of 2 mm were detected with the integrated time of about 1.8 s. Fig. 6 (a) shows the energy distribution of the charge exchange neutral particles.

NDD data below about 30 keV are heavily influenced by the background in LHD. In this experiment, particles with energy ranging from 30 to 80 keV were measured during ICWC. However, it is expected that charge exchange particles with lower energies were also produced.

From integrated counts of full energy spectrum shown in Fig. 6 (b) a particle flux of charge exchange neutral is calculated to be about 1.6-3.2 $\times 10^5$ [s^{-1}cm^{-2}]. In this experiment, the particle flux could be measured only with RF input frequency of 38.47 MHz by NDD and not with 85 MHz due to insufficient intensity by low RF input power.

4. Summary

Based on the charge exchange damage observed in thin SS samples arranged on a hexahedron block holder with three different facings, the areas influenced by ICWC is estimated in LHD. For the thin SS samples oriented to three directions, microstructures are quite different. In the plasma facing samples high density of helium bubbles is observed, but those oriented to other directions showed no observable damage. It is suggested effective charge exchange particles come to the wall straightly and, thus, clearings of the surfaces un-exposed to the plasma and those in shadow are difficult. For example, roughly half of surface area in the vessel will not be cleaned by ICWC in LHD. This is in contrast to the damage produced by the GDC, which was observed also in the sampled directed vertical to the plasma.

The damages such as helium bubbles by ICWC were located only about 50 nm from the top surface without any visible damage in deeper area.

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