Hydrogen Retention and Carbon Deposition in Plasma Facing Wall and Shadowed Area of JT-60U

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Abstract. In JT-60U, erosion/deposition analyses of the plasma-facing wall have shown that local carbon transport to the inboard direction was appreciable in addition to long-range transports. The total deposition and erosion rates in the divertor region were $\sim 10 \times 10^{20}$ C atoms/s and $\sim -6 \times 10^{20}$ C atoms/s, respectively. About 40% of the deposition on the divertor region should be originated from the main chamber wall. The highest hydrogen concentration in (H+D)/C ratio and the retention rate were found to be ~ 0.13 and 6×10^{19} atoms/s, respectively. In the plasma-shadowed area underneath the divertor region at around 420 K, redeposited layers of ~ 2 μm-thick were found with high hydrogen concentration of ~ 0.8 in (H+D)/C, which was nearly the same level as that observed in JET. Large deuterium retention was also observed at the main chamber wall covered with boron layers. Their H+D retention and (H+D)/C were $\sim 10 \times 10^{22}$ atoms /m^2 and ~ 0.16, respectively, for the vacuum vessel temperature of 570 K. Integrating this retention over the whole main chamber wall results in significant inventory.

1. Introduction

Evaluation of fuel inventory and its retention process are critical issues for a next-step fusion device, especially with carbon-based wall. Therefore, various postmortem analyses have been performed extensively. The hydrogen retention study of tokamaks showed that a large amount of fuel particles (deuterium and tritium) was retained in carbon-deposition layers of the divertor, in particular, areas shadowed from the direct plasma impact. In JET Mk-II A, maximum D/C ratio in such area was found to be significantly high (~0.8) [1]. Such high retention would lead to unacceptably large amount of tritium accumulation.

In order to study the issues, hydrogen isotope retention and carbon deposition for the plasma facing surfaces of the JT-60U divertor tiles have been performed under a joint research between Japan Atomic Energy Agency (JAEA) and Japanese universities [2-4]. In JT-60U, tritium produced by DD nuclear reaction was distributed in the plasma-facing wall due to ripple loss of high energy tritium ion and its implantation. Hence, tritium retention is separated from carbon deposition, which is most concern in ITER. On the other hand, deuterium (D) and hydrogen (H) retention is clearly correlated with deposition of carbon and temperature of the carbon redeposited layers. The hydrogen concentration of the redeposited layers in the divertor area was smaller than that observed in other tokamaks [1,5], which is attributed to temperature rise of the deposited layers probably owing to their poor thermal contact to the substrate [6]. Carbon deposition at high temperature results in strong adhesion of the redeposited layers to the substrate. Accordingly, collected dust in the JT-60U was much smaller than that observed in other machines [7]. The smaller dust production was also helped by the precise alignment of the divertor tiles both toroidally and poloidally.

Until now, however, H and D retention analyses have been limited to the plasma facing surface of the divertor area. Hence, we have extended the analyses for the tiles of the main

chamber (first wall) and plasma shadowed areas of JT-60U. Here, we summarize the recent results and discuss the mechanism of erosion, transport and deposition of carbon impurities, and hydrogen incorporation in carbon deposited layers.

2. Experiment

2.1. JT-60U Operation and Sample History

JT-60U started operation with hydrogen discharges at March 1991. Since July 1991, deuterium experiments have been performed. The vacuum vessel has a major radius of 3 m, a height of 3.4 m and a radial width of 2.4 m. The surface area and the volume of the vacuum vessel are ~200 m^2 and ~ 170 m^3, respectively. The inside of the JT-60U vacuum vessel is fully covered with the carbon-based plasma facing tiles. The number of the tiles is roughly 12,000. In 1997, JT-60U was modified from an open divertor to a W-shaped divertor to achieve radiative divertor and high confinement plasma simultaneously. Neutral particles were pumped from the inner pumping slot in the private region through open space underneath the outer baffle plates with cryopumps installed at outside of the vacuum vessel. In 1998, the outer pumping slot was added in the private region of the W-shaped divertor as shown in FIG. 1. Carbon Fiber Composite (CFC) tiles having a high thermal conductivity of 300~400 W/mK are applied for the divertor tiles. All other areas (main chamber) are covered with isotropic graphite tiles and partially with the CFC tiles.
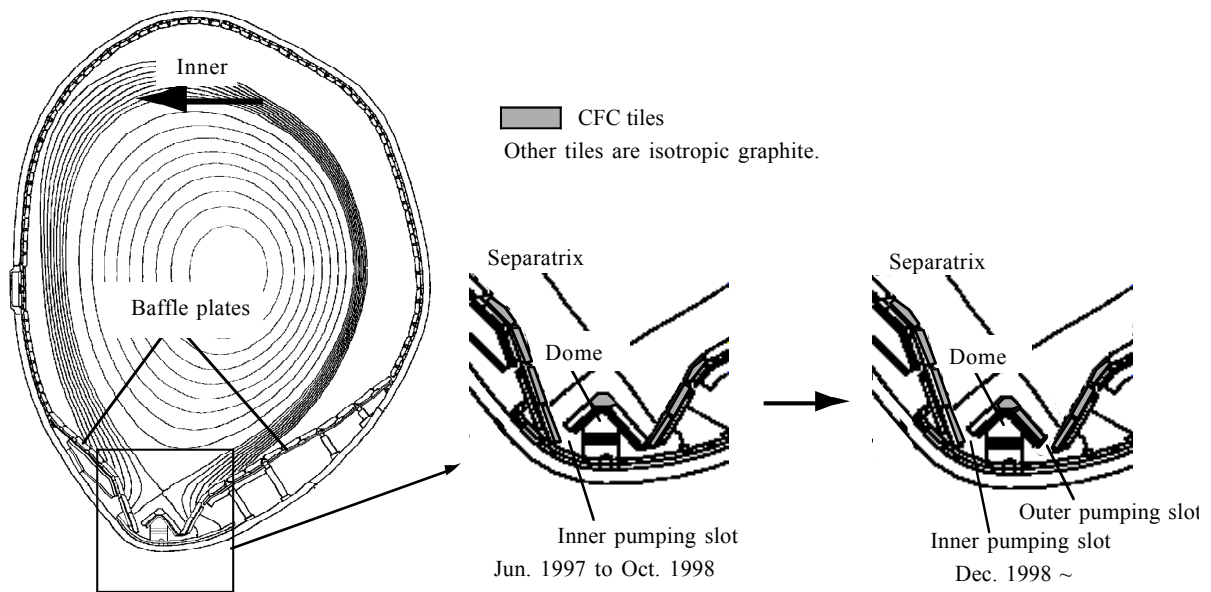

FIG. 1. Poloidal cross-sections of the JT-60U W-shaped divertor before and after the pumping slot modification.

In JT-60U, high plasma performance has been achieved using a variety of wall-conditioning methods [8]. After ventilation, the wall conditioning is conducted starting with 570 K baking, helium Taylor discharge cleaning (He-TDC), helium glow discharge cleaning (He-GDC) and tokamak discharge cleaning. Boronization using $B_{10}H_{14}+D_2$ mixture gas was occasionally made, roughly two times in one year's experimental campaign in order to reduce oxygen impurity. He-GDC is carried out at every night (~3 hours). After normal deuterium operation in the last term of a year experimental campaign, hydrogen operation is conducted to remove tritium produced by DD reaction, just before the opening of the vacuum vessel.

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005
Operation	Inner side pumping		Both sides pumping				Both sides pumping		
Sample exposure period	Tiles for D,H retention study Divertor Main chamber Tiles and dust for erosion/depositino study						Collector probes for deposition, D,H retention studies in shadowed area		
Temprature	~570 K baking (short pulse operation ~15s)						~420 K baking (long pulse operation ~60s)		

FIG. 2. Time line showing divertor operation history and the exposure periods of samples for the analyses.

FIG. 2 shows time line showing divertor operation history and exposing time of analyzed samples. Hydrogen isotope retention study was done for those tiles exposed to deuterium and hydrogen plasmas with the integrated Neutral Beam Injection (NBI) time of 2×10^4 s and the averaged power of ~9 MW, while erosion/deposition study was done for those tiles exposed to 3×10^4 sec (NBI) and ~10 MW (2×10^4 s for the outer dome wing). To study remote-area deposition, collector probes, which were made of stainless steel, had been installed during 2003-2004 experimental campaign with NBI of 8×10^3 s and ~9 MW. The integrated NBI time and the averaged power of the hydrogen plasma operation were 1/5 and 1/2 those of the deuterium operation, respectively. For the tile samples of the hydrogen isotope retention study, the maximum surface temperatures during deuterium discharges were calculated to be ~1000 K (inner divertor), ~800 K (dome) and ~1400 K (outer divertor) by using a finite element simulation code based on the tile temperatures measured by thermocouples. During the tile samples were exposed to plasma, the vacuum vessel of JT-60U has been kept at 570 K. In 2003-2004, when the collector probes were installed, long pulse operation was made and the vacuum vessel temperature was kept lower (420 K) in order to avoid the temperature escalation of neutral beam armor during the long pulse.

2.2. Analyses methods

Hydrogen isotope retention analyses were made by Thermal Desorption Spectroscopy (TDS) and ion beam analyses (Elastic Recoil Detection (ERD) and Nuclear Reaction Analysis (NRA)) to obtain the retention amounts and the depth profiles in tile samples taken from the vacuum vessel. Furthermore, Imaging Plate (IP) technique, which measure tritium retention qualitatively, was used to observe the carbon deposition pattern on the collector probes. Secondary Electron Microscopy (SEM) and a micrometer were utilized to observe the thicknesses of the redeposited layers and/or erosion depth.

3. Results and Discussion

3.1. Erosion/Deposition

3.1.1. The Divertor Region

FIG. 3 shows erosion/deposition pattern of the JT-60U W-shaped divertor (samples: 1997-2002). The erosion/deposition patterns of the divertor region were very non-uniform,

i.e., heavy deposition on the inner divertor (redeposited layer thickness: ~250 µm), in contrast to erosion dominated outer divertor region (erosion depth: ~100 µm) as commonly observed on the divertor tiles of large tokamaks [9]. This implies a carbon transport from outboard to inboard. Since the erosion at the outer divertor does not compensate the deposition at the inner divertor, the first wall has been attributed to an additional carbon source. In addition to such carbon transport through scrape-off layer, transport through private flux region was confirmed by $^{13}CH_4$ gas-puffing experiment in the JT-60U [10].

Deposition analyses of poloidal tile sides shadowed from the direct plasma impact were also made. Thick redeposited layers with the thickness of ~100 µm were observed at the outer dome wing facing to the outer divertor

FIG.3. Erosion/deposition pattern of the JT-60U W-shaped divertor (sample tiles: 1997-2002).

tile, while no deposition on the poloidal side surface of the inner dome wing. This strongly suggests direct carbon transport from the outer divertor to the outer dome wing (inboard carbon transport). Assuming full toroidal symmetry of the erosion/deposition patterns in the whole divertor area, carbon density of 0.9 g/cm^3 for the redeposited layers [6] and 1.7 g/cm^3 for the eroded substrate, net carbon erosion/deposition for 6 years (integrated NBI time: 3×10^4 s) in the divertor area were estimated to be -0.34 kg/0.55 kg, respectively [11]. As a whole, 0.21 kg (40% of the deposition on the divertor region) of carbon should be originated from the main chamber wall. Normalized by the integrated NBI time, carbon deposition and erosion rates in the divertor region were calculated to be ~10×10^{20} C atoms/s and ~-6×10^{20} C atoms/s, respectively.

3.1.2. Underneath the Divertor

FIG. 4 shows the locations of the collector probes and the intensities of tritium retained on their surface determined by IP. Similar to the tritium retention, redeposited layers of ~2 µm in thickness were found at only No.1-4 samples, and no appreciable redeposited layers were found on the other probes underneath the outer baffle plate. This indicates that carbon and hydrocarbons are transported underneath the dome, but not to far remote area. The density of the redeposited layers on the collector probes was measured to be ~1.8 g/cm^3, two times denser that those on the divertor tiles and nearly the same as that of carbon tiles. The total amount of the redeposited carbon underneath the dome region was estimated to be ~0.013 kg and the deposition rate was estimated to be ~8×10^{19} C atoms/s normalized by the integrated NBI time of 8×10^3 s. This redeposition rate is much smaller than that on the divertor tile surface, but a little larger than the calculated dust production rate of 1×10^{19} C

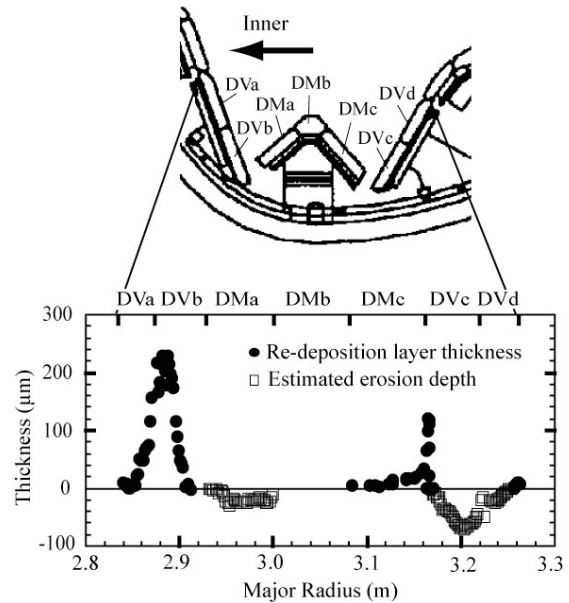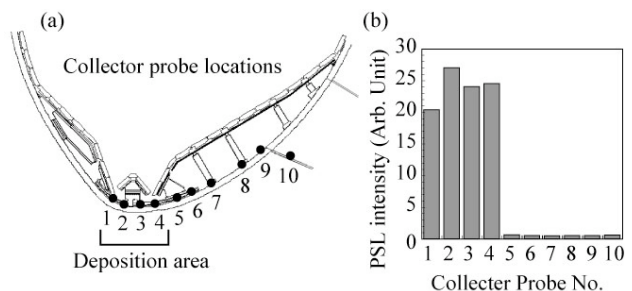FIG. 4. (a) Collector probe locations and (b) PSL intensities (tritium) measured by IP (samples: 2003-2004).

atoms/s based on the collected dust of 7 g for NBI time of 3×10^4 s [7].

3.2. Hydrogen Isotope Retention

In JT-60U, hydrogen operation followed normal deuterium operation in the last term of a year experimental campaign as described above. Hence, we focused on hydrogen as well as deuterium for the hydrogen isotope retention study. In this section, the results of the postmortem analyses of plasma facing wall tiles [12-14] and shadowed area are described, and H, D retention characteristics in deposition and erosion areas are discussed.

3.2.1. Deposition Dominant Area of the Divertor

Inner Divertor: The hydrogen retention (H+D) in atoms/m^2 and D/H ratios of the divertor region are shown in FIG.5 together with the sample locations. Although integrated NBI heating time during deuterium discharges was ~6 times larger than that of hydrogen discharges for the divertor samples (1997-1999), D/H ratio of retained hydrogen in the redeposited layers on the inner divertor tile was only ~0.4. The depth profiles of the D and H were almost constant. The H+D retention in the deposition layers on the inner divertor was ~9×10^{22} atoms/m^2 and ~0.02 in (H+D)/C, which was showing that the temperature of the redeposited layers increased to ~900 K. Since an averaged NBI power during the hydrogen operation was a half of that of the deuterium operation, the temperature increase of the inner divertor in the hydrogen operation must be less than that of the deuterium operation. Accordingly, the H retention rates in the redeposited layers formed during the H operation was larger than those formed during the D operation. In other words, the hydrogen retention characteristics of the inner divertor were strongly influenced by the H discharges performed at the last phase of a year experimental campaign.

Outer Dome Wing: The outer dome wing tile was mostly covered by the redeposited layers and the depth profiles of D and H were kept constant into deep inside with D/H of ~1. The bottom side of the tile was covered by thick redeposited layers with retained H+D of ~16×10^{22} atoms/m^2, which was the highest retention in the divertor region. This is probably because eroded carbon at the outer divertor was directly transported to the bottom side of the outer dome wing tile as described above and also its temperature was kept low without direct plasma impact. Accordingly the large amount of hydrogen was retained there. Nevertheless the hydrogen concentration in the redeposited layers on the outer dome wing tile was still very small (~0.13 in (H+D)/C ratio), reflecting rather high surface temperature of ~700 K. Owing to lower heating power of H discharges, the H concentration in the redeposited layers produced during H discharges on the redeposited layers produced during D discharges must be higher than the D concentration in the latter. Consequently, D/H in the whole redeposited layers was rather high compared with that of the inner divertor.
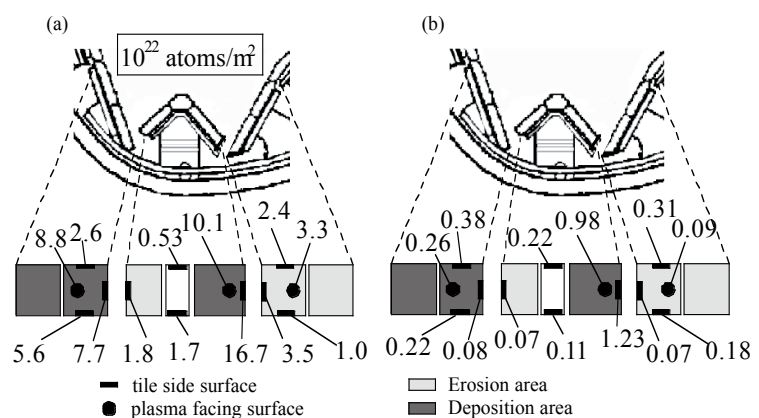

FIG. 5. (a) H+D retention amounts and (b) D/H ratios of the divertor region (sample tiles: 1997-1999).

Shadowed area underneath the divertor region: Hydrogen retention in the redeposited layers on the collector probes are summarized in FIG.6. The maximum D/H ratio of the redeposited layers underneath the dome region was ~3.6. The hydrogen (H+D) retention in the layers was ~14×10^{22} atoms/m^2, and (H+D)/C was ~0.8, which was the same level as that observed in JET [1]. The hydrogen retentions on the collector probes installed at far remote area underneath the outer baffle plate were almost background. During the period when the collector probes were installed, the temperature of vacuum vessel was kept low, ~420 K, compared with normal operation temperature of ~570 K. During the discharges, the temperature of the shadowed area was increased up to ~470 K shot by shot due to radiation from the divertor plasma in long pulse operation, which was still low compared with the temperature rise of the plasma facing surfaces. In consequence, D/H and (H+D)/C ratios were very high compared with those of the plasma facing wall tiles.
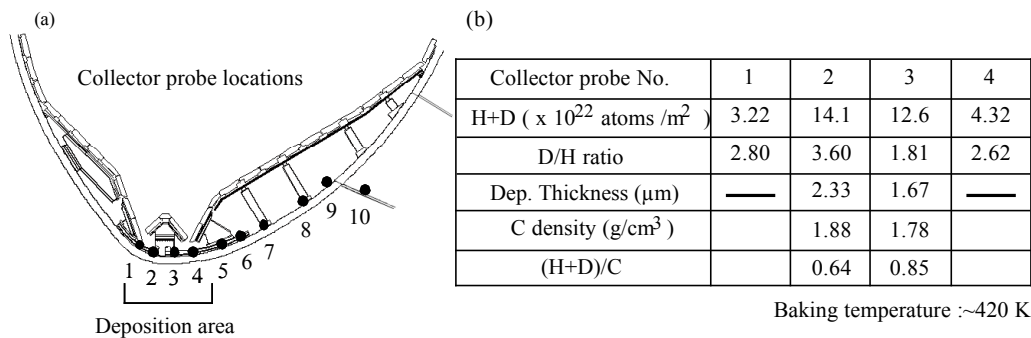

Collector probe No.	1	2	3	4
H+D (x 10^{22} atoms /m^2)	3.22	14.1	12.6	4.32
D/H ratio	2.80	3.60	1.81	2.62
Dep. Thickness (μm)	——	2.33	1.67	——
C density (g/cm^3)		1.88	1.78	
(H+D)/C		0.64	0.85	

Baking temperature :~420 K

FIG.6. (a) sample locations and (b) results of the collector probe analyses (collector probe samples: 2003-2004). The vacuum vessel was kept at ~420 K during the probes being installed. H+D retention amounts of No. 5-10 were almost background.

Table 1 summarizes the carbon deposition and hydrogen retention for the deposition dominated area in JT-60U. Here, carbon deposition rates and (H+D) retention rates were normalized by the integrated NBI heating times and (H+D)/C ratios, which were measured by TDS and ERD. The carbon deposition rate of the shadowed area was nearly one order of magnitude smaller than that of the divertor tile surface. The H+D retention rate, however, was high, because of the high hydrogen concentration.

TABLE 1 : CARBON DEPOSTION AND H+D RETENTION RATES.

	C deposition rate	H+D retention rate	(H+D)/C	D/H
Inner divertor	~6 x 10^{20} atoms/s	~1 x 10^{19} atoms/s	~0.02	~0.4
Outer dome wing	~4.5 x 10^{20} atoms/s	~6 x 10^{19} atoms/s	~0.13	~1.2
Shadowed area (underneath divertor area)	~8 x 10^{19} atoms/s	~6 x 10^{19} atoms/s	~0.75	~3.6

Baking temperature : 420 K, Others:570 K

3.2.2. Erosion Dominant Area of the Divertor

D/H ratios of the erosion dominant area were very low (~0.1) compared with those of the deposition dominant area as shown in FIG. 5. The deposition profile of the hydrogen peaked at top surface and decreased with depth. For the outer divertor, the H+D retention was ~4×10^{22} atoms/m^2. The hydrogen concentration of the outer divertor was less than 0.1 in (H+D)/C, which was measured by ERD. The depth profile of the eroded area should reflect an incident range of hydrogen ions and charge exchange neutrals. The hydrogen must be saturated easily, because of high incident flux onto the outer divertor. However, the surface of the outer divertor was eroded with the averaged erosion rate of ~1nm/s, which was estimated

from erosion depth and integrated NBI heating time. Consequently, hydrogen was retained only near surface region during hydrogen operation followed by normal deuterium operation, replacing the deuterium retained there and eroding the tile surface. This result indicates that the isotope exchange is effective for the removal of the retained deuterium at the erosion area. Table 2 shows a summary of erosion and hydrogen retention study in the erosion area of the JT-60U divertor region.

TABLE 2 : EROSION RATE AND H,D RETENTION.

	Erosion rate	H+D amount	(H+D)/C	D/H
Inner dome wing	-1.5×10^{20} atoms/s	$\sim 2 \times 10^{22}$ atoms/m^2	——	~ 0.07
Outer divertor	-4.2×10^{20} atoms/s	$\sim 3 \times 10^{22}$ atoms/m^2	~ 0.07	~ 0.31

3.2.3. Main Chamber Wall

Hydrogen retention (H+D) in 10^{22} atoms/m^2 and D/H ratios for the main chamber wall tiles are shown in FIG. 7 together with the tile locations. In the main chamber area, most area of the main chamber wall was erosion dominated or less interacted with plasmas, expect the lower and inner main chamber wall where was covered by redeposited layers of a few μm thickness. However, the hydrogen retention and D/H ratios of the main chamber wall did not show appreciable difference with the locations and were $\sim 10 \times 10^{22}$ atoms/m^2 and ~ 1 in D/H, respectively. ERD measurements showed the maximum of (H+D)/C, ~ 0.16, for the inner mid-plane tile. H was dominantly retained near surface, replacing D retained in the erosion dominated area as observed in the depth profiles of H and D for the erosion dominated divertor area. It should be noted again that most of area of the main chamber was less interacted with plasmas, and boronization using $B_{10}H_{14}+D_2$ mixture gas was performed in JT-60U. Therefore, rather high hydrogen retention with high D/H (~ 1) for the main chamber wall could be explained as follows. A part of deuterium could be remaining D in the boron layers during the boronization, and a certain amount D injected by NBI (~ 80 keV) could be escape from the main plasma without fully loosing its high energy due to ripple loss (mainly orbit loss for the main chamber) to be implanted into the main chamber wall [15]. Charge exchange neutrals could also impinge the main chamber wall. All those D retention was summing up to the significant amount. H discharges subsequently made could replace D near the surface but not those retained deep inside, which was originated from high energy and/or remaining in the boron layers. Such hydrogen isotope behavior of the main chamber wall is very important for the inventory evaluation, because of the large area. To clarify the hydrogen retention mechanism, further study is necessary.
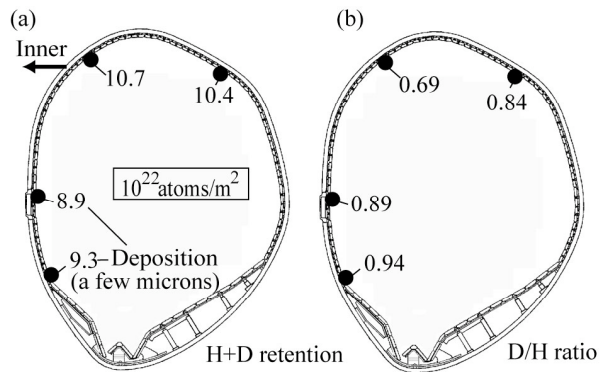

FIG. 7. (a) H+D retention amounts and (b) D/H ratios of the main chamber wall (sample tiles: 1991-1999).

4. Summary

Erosion/deposition patterns of the divertor region were very non-uniform with heavy deposition in the inner divertor and the outer dome wing, while the outer divertor and the inner dome wing were erosion dominant regions. Carbon erosion/deposition rates for whole divertor area were estimated to be $\sim 10 \times 10^{20}$ C atoms/s and $\sim -6 \times 10^{20}$ C atoms/s, respectively.

In addition to the carbon transport from the outer divertor to the inner divertor, 40% of the deposition on the divertor region should be originated from the main chamber wall. Local carbon transport to the inboard direction as well as long-range transport through scrape-off layer was clearly shown in the divertor area.

Hydrogen retention was well correlated to the carbon deposition. The highest hydrogen retention (H+D) of ~16x10^{22} atoms/m^2 was found at the redeposited layers on the outer dome wing (vacuum vessel baking: 570 K) also with the highest concentration of ~0.13 in (H+D)/C. For the erosion dominant region, hydrogen was retained only near surface region. Furthermore, D retained near surface region was appreciably replaced by H during hydrogen operation subsequently made.

In the plasma-shadowed area underneath the dome, ~2μm-thick redeposited layers were found on the collector probes, which is equivalent to the deposition rate of ~8x10^{19} C atoms/s. The hydrogen retention in the layers was very high (~0.8 in (H+D)/C), because the probe was installed in the vacuum vessel when the vessel was kept at 420 K, lower than normal operation temperature of 570 K.

The H+D retention and (H+D)/C of the main chamber wall were ~10x10^{22} atoms /m^2 and ~0.16 (vacuum vessel baking: 570 K), respectively. The isotope exchange using plasma operation seems effective for the removing the tritium retained in surface regions of main chamber wall tiles. However, the rather high D/H of ~1 observed for the main chamber wall suggests the injection of high energy D originating from NBI. Such high D retention could also be attributed to remaining D in the boron layers during the boronization. Hydrogen retention in the main chamber wall is very important because its surface area is huge, and needs more detailed examination to make realistic inventory evaluation.

Acknowledgements

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