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Hydrogen isotopes retention in JT-60U

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Abstract

Poloidal/toroidal distributions of hydrogen isotopes (H, D) retention on the plasma facing surfaces and side surfaces of carbon tiles used in JT-60U were investigated. The retention of hydrogen isotopes is nearly proportional to the thickness of carbon redeposited layers. The redeposited layers on the inner divertor area retain hydrogen isotopes uniformly with the concentration of ~0.02 in (H + D)/C, while those on the tile sides shadowed from the plasma ~0.13 in (H + D)/C. Total hydrogen isotopes retention in the whole divertor area including the baffle plates and dome unit tiles of JT-60U is estimated to be $\sim 4 \times 10^{24}$ atoms assuming that the amount of retained hydrogen isotopes is proportional to the integrated discharge time. Some of the first wall tiles are found to retain significantly large amount of deuterium, which is attributed to the injection of energetic deuterium originating from NBI.

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Keywords: 81.05.T; 28.52.C; 52.40.Hf; 52.55.Fa

1. Introduction

It is a very important issue to evaluate retention properties of tritium and deuterium in in-vessel components of current tokamak devices from a viewpoint of safety for the next fusion reactor [1–8]. We have been studying the retention of hydrogen isotopes (H, D, T) in plasma facing carbon tiles used in the W-shaped divertor of JT-60U with the inner side [7,9–11] and both sides pumping system [8,12,13]. In JT-60U, erosion is dominant in the outer divertor region and redeposition in the inner divertor region and the outer dome wing [14]. Hydrogen isotopes retention is influenced by the location of the tiles as well as the surface temperature. Nevertheless, hydrogen retention in the redeposited layers on the inner divertor tiles is very uniform with the concentration of 0.03 in (H + D)/C ratio, which is much smaller than those observed in other tokamaks [1–6,15,16]. In JET MK-IIA and MK-IIGB divertor tiles, the maximum concentration of 0.8 in D/(C + Be) ratio was

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observed in the redeposited layers on the louvers at the inner corner shadowed from the plasma while their temperature was kept low [3,6,15]. Therefore, tritium accumulation in the plasma shadowed area like pumping slot and gaps between the plasma facing tiles is of serious concern for the control of the in-vessel tritium retention because tritium retained in such area is hard to remove by discharge cleaning methods.

We have been examining plasma facing tiles used in JT-60U by various techniques to study the poloidal and toroidal distributions of hydrogen isotopes retained on plasma facing surfaces of the carbon tiles in the W-shaped divertor region. Quite recently we have extended the analysis for plasma shadowed areas and tile gaps. Here we summarize recent results on hydrogen isotopes retention and carbon deposition and evaluate the total hydrogen retention in the whole vessel of JT-60U.

2. Experimental

Fig. 1(a) shows a cross-sectional view of the JT-60U W-shaped divertor with the both sides pumping system. All tiles examined here were exposed to 6700 DD and HH discharges, except those of the outer wing and the top in the dome unit (2400 discharges), for June 1997–October 1999 experiment period. After 4300 DD and HH discharges with the inner side pumping system, 2400 DD and HH discharges were performed with the both sides pumping system. The integrated discharge time during DD discharges was 19 000 s. Before the air ventilation of the chamber, ~350 HH discharges were carried out in order to remove tritium in the tile which was produced by the DD discharges. Total 1050 HH discharges during this experimental campaign were performed. The average NBI power of the DD discharges was 8.5 MW, and that of the HH discharges was about a half compared to that for the DD discharges. Hence the temperature increase during the HH discharges was much less than that during the DD discharges. Boronization using $B_{10}H_{14} + D_2$ mixture gas was carried out three times during this experimental period. The operational temperature of the vacuum vessel and the tiles were at ~573 K. The maximum surface temperatures during the DD discharges were calculated to be ~1000 K, ~800 K and ~1400 K for the inner divertor, the dome and the outer divertor tiles, respectively. We performed a finite element modeling (FEM) analysis with inputs from the tile temperatures measured by thermocouples [17]. In general, the maximum tile temperature during a discharge appeared just before the termination of the discharge. Most of the tiles in the divertor are made with CFC (CX2002U, Toyo Tanso Co. Ltd., density = 1.7 g/cm^3, porosity = 22%). The inner dome wing tiles are made by isotropic graphite (IG-430U, Toyo Tanso Co. Ltd., density = 1.82 g/cm^3, porosity = 19.5%).

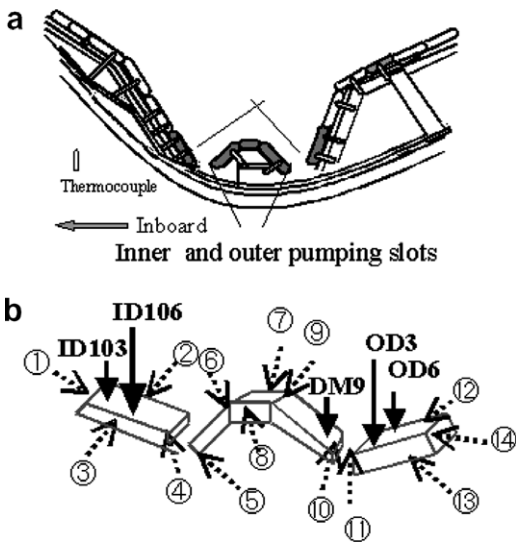

Fig. 1. Cross-sectional view of the JT-60U W-shaped divertor with the both sides pumping geometry (a) and sampling positions and sample names (b).

Fig. 1(b) shows sampling positions and sample identifications. Sample plates (8 mm × 8 mm × 0.5 mm) were cut from the tiles to include the tile surface. Five samples (ID103, ID106, DM9, OD3, OD6) were taken from the plasma facing surfaces, 14 samples (①–⑭) from tile sides, among which six samples (②, ③, ⑦, ⑧, ⑫, ⑬⑭) were from toroidal sides and eight samples (①, ④, ⑤, ⑥, ⑨, ⑩, ⑪, ⑭) from poloidal sides. For all sides, the front and rear sides were separately analyzed as shown in Figs. 3 and 4. To TDS analysis, each sample was heated from room temperature to 1273 K with a constant heating rate of 0.42 K/s and desorbed gases were analyzed by a quadrupole mass spectrometer (QMS). The dominant mass numbers observed by QMS during the heating were 2(H_2), 3(HD), 4(D_2), 15(CH_4), 19(CD_3H), 20(CD_4), 26(C_2H_4), 30(C_2H_6), 32(C_2D_4), 36(C_2D_6) and 39(C_3H_8). Here, the fragment ions of CH_4, C_2H_4 and C_3H_8 were used to evaluate the amount of retained H because the parental (main) ions of these

gases overlap with other fragment ions. Secondary ion mass spectroscopy (SIMS) was used to obtain the depth profiles of H and D within the depth of 1.7 μm [11]. In SIMS, the negative secondary ion intensities of H^- and D^- ions were normalized by that of $^{12}C^-$ for comparison. Tritium distributions were evaluated by image plating (IP) and combustion methods [18]. Erosion depth and thickness of the redeposited layers on the carbon tiles were examined by a scanning electron microscope (SEM) and a surface profile meter [14].

3. Results

3.1. Hydrogen isotopes retention in the tiles placed in divertor region

Depth profiles of $H^-/^{12}C^-$, $D^-/^{12}C^-$ and $(H^- + D^-)/^{12}C^-$ secondary ion intensity ratio within the depth of 1.7 μm for sample ID106, sample OD3 eroded by the depth of about 15 μm and the front end of sample ⑩ were evaluated by SIMS [8]. Samples ID106 and ⑩ were, respectively, covered by the redeposited layers of 85 and 32 μm in thickness. The $H^-/^{12}C^-$ secondary ion intensity ratio in near surface region was very high and exponentially decreased toward depth, while $D^-/^{12}C^-$ profiles showed its maxim just behind the H profile. This indicates that D retained near surface region had been replaced by H during the HH discharges conducted before the air ventilation. The HH discharge would also add the redeposited layers including mainly H. In addition, $(H^- + D^-)/^{12}C^-$ (or $D^-/^{12}C^-$) profiles were nearly constant throughout the thick redeposited layers.

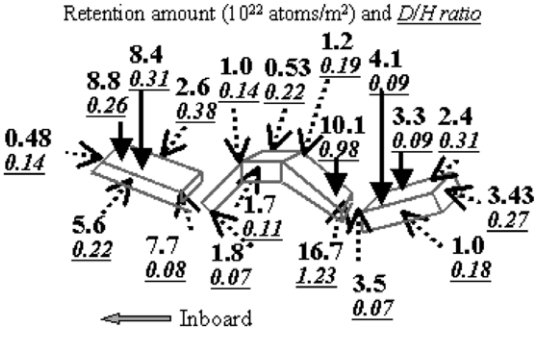

Fig. 2. The amount of retained H and D in the samples located in the divertor region and the ratio of D and H (D/H). In the retentions, contribution of hydrogen retained in the bulk was not subtracted.

The total hydrogen isotopes retention (H + D retention) was determined by integrating all desorbing species including H and D atoms in TDS analysis. Fig. 2 shows the total H + D retentions for all samples except for those of the rear side of the poloidal side surfaces. The atomic ratios of D/H were presented as underlined number in the figure. The total H + D retention given in the figure included hydrogen retention in the bulk. The present TDS results for the tiles exposed to the plasma with the both sides pumping geometry were almost the same as previously reported TDS results by Shibahara et al. [19] for a set of the divertor tiles exposed to the inner side pumping geometry.

The total amount of H + D retention of the plasma facing surface of the inner divertor increased with the thickness of the redeposited layers (sample ID103 = 104 μm, ID106 = 85 μm) and was much larger than those of the outer divertor surface where the material was mostly eroded. The sample taken near the bottom of the outer dome wing, DM9, was clearly covered by the redeposited layers with very high hydrogen concentration, since it has experienced less plasma heat load than the divertor tiles [17]. Comparing the D/H ratios of the inner and outer divertor tiles of around ~0.3 and 0.09, respectively, the D/H for DM 9 was as high as 0.98, indicating less replacement of D by H and/deep implantation of D as discussed later. The ratio of the shot numbers of the DD and HH discharges, ~5.4, was much higher than the D/H ratios of any tiles, suggesting the most of D retained during the DD discharges was replaced by H during the HH discharges.

Fig. 3 shows the sample locations viewing from the plasma (a), and the H + D retention of the toroidal side surfaces for the inner divertor, dome top and outer divertor tiles indicated by gray color (b). The H + D retentions for the toroidal sides except sample ③ were smaller compared to those for the plasma facing surfaces (see Fig. 2) and the poloidal sides (see Fig. 4). That is because only very near front surface of sample ③ was covered by the redeposited layers with a maximum of 16 μm, which retained most of H and D, while the thickness of the redeposited layer of other side surfaces were very thin. Sugiyama et al. [18] have shown that tritium retention on the ion drift side was clearly higher than that on the electron drift side. The H + D retention for the toroidal sides shows just the opposite, i.e. the electron drift side shows larger H + D retention. Carbon deposition on the electron drift

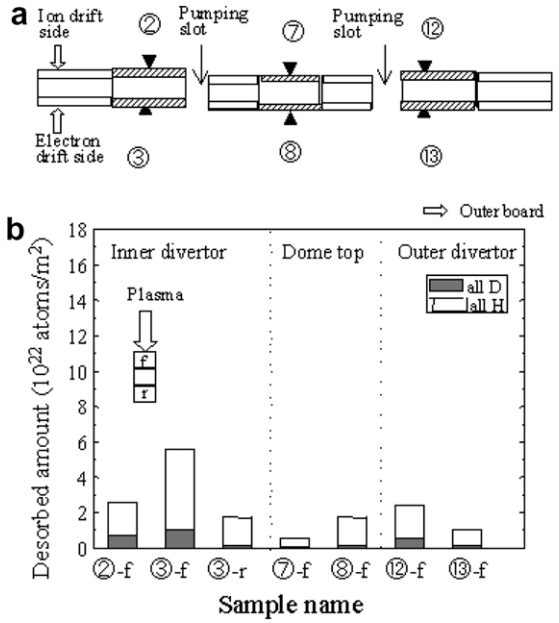

Fig. 3. Sample locations (a) and toroidal distribution of H and D retained in the side surfaces (b). X-f and -r means 'front' and 'rear' from the plasma on ion (electron) drift side.

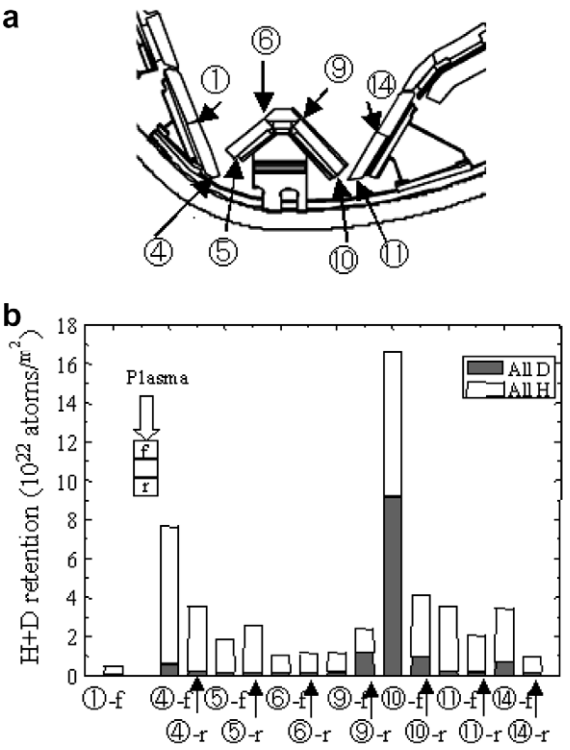

Fig. 4. Poloidal distribution of hydrogen isotopes retained in the side surfaces, facing to the pumping slot and the gaps between tiles, (a) sample locations, (b) total amount of H and D measured by TDS.

side could be larger than that on the ion drift side, because the former receives larger amount of carbon eroded at the front surface of the same tile by gyration along the magnetic filed line, compared to the latter which should receive carbon from the neighboring tile. Actually the maximum thickness of the redeposited layers was a little thicker on the electron drift side (~16 μm, sample ③) than that on the ion drift side (~13 μm, sample ②). Hence measurements of more detailed toroidal distribution are necessary. In anyway the total H + D retentions extrapolated to all the toroidal sides were $6–9 \times 10^{22}$ atoms/m^2 and would not contribute largely on the total retention.

The H and D retention in the poloidal side surfaces after exposure 6700 DD + HH discharges were compared in Fig. 4. One can see that the H + D retentions on the poloidal side except two samples of ④ and ⑩ were similar to those on the toroidal sides. In addition the difference between the front side and the rear side was small, different from the toroidal sides given in Fig. 3. The exceptional two samples, ④ and ⑩, are the bottom sides of the inner and outer divertors. Remarkable H + D and tritium retention was found on the bottom side of outer dome wing tile (sample ⑩), facing to the outer pumping slot. Tritium activities for a different set of divertor tiles which were exposed 12000 DD + HH discharges had been measured by a combustion method [18]. It is interesting to note that tritium distribution and D + H retention distribution were similar on the plasma shadowed area, where was deposition dominated and the injection of high-energy triton was inhibited. The thickness of the redeposited layers at the location of ⑩ was 32 μm and ~90 μm after the exposure to 6700 DD + HH discharges and after long-term discharges (12000 shots), respectively. This thick redeposition at the bottom sides of the outer dome wing is very likely redeposition of carbon eroded at the outer divertor and transported directly through the divertor plasma. The temperature of the bottom would be less than that for the plasma facing surface and rather high deuterium pressure (around ~1 Pa) in the divertor area and pumping slots could result in higher D/C ratio in the redeposited layers [20].

The thickness of the redeposited layers on the bottom side of the outer dome wing significantly changed through the front side to the rear side, from 32 μm to 5 μm. Although the thickness of the redeposited layers in the sample ① was a few μm after 6700 DD + HH discharges, thick redeposited layers

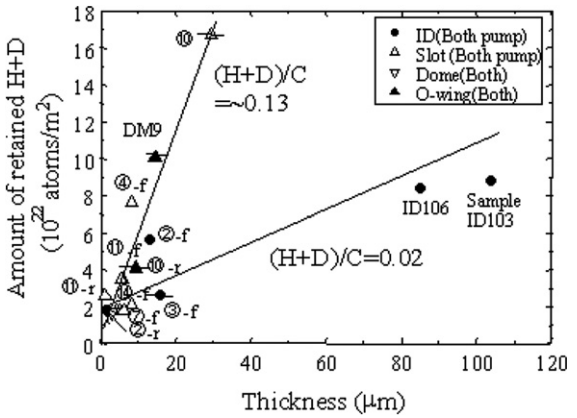

Fig. 5. Amount of retained H and D in the samples as a function of the thickness of redeposited layers.

(~80 μm) were found after exposing long-term discharges [18], resulting in higher tritium activity different from the H + D retention.

In Fig. 5, the H + D retentions for all samples except the eroded ones are plotted as a function of the thickness of the redeposited layers. Although the data are widely scattered, they can be divided into two groups as indicated by two solid lines depending on the locations of the redeposited layers i.e. the tile sides were clearly distinguished from the plasma facing surface. The linear relationships indicate that except near surface, hydrogen was retained uniformly in the redeposited layers with a constant hydrogen concentration of their thickness depending on the locations. This is quite consistent with hydrogen depth profiles by SIMS [8]. From the linear relationship with a smaller slope, i.e. 8.9×10^{20} H + D/m^2/1 μm, hydrogen isotope concentration, (H + D)/C in atomic ratio, in the redeposited layers mostly on the inner divertor tiles and on the plasma facing surfaces, was determined to be ~0.02 assuming carbon density of the redeposited layers to be 0.91 g/cm^3 [21], which is much smaller that those observed in other tokamaks [2–6,15,16]. This value agrees well with H/C of ~0.030 observed for the redeposited layers on the divertor tiles exposed to HH discharges in the JT-60 open divertor [19], and (H + D)/C of ~0.032 in the inner divertor tiles exposed to the DD discharges in the JT-60U with the inner side pumping system [10]. From the other linear relationship with a larger slope, hydrogen isotope concentration in the redeposited layers on the plasma shadowed surfaces was determined to be ~0.13 in (H + D)/C. There is no particular reason for hydrogen retention being divided into these two groups. There still could be those redeposited carbon layers including the (H + D)/C between 0.03 and 0.13 in somewhere in the JT-60U vessel. Nevertheless, the 0.13 for the plasma shadowed area observed here is actually much lower than those observed in JET and other machines.

Here, in the retentions, contribution of hydrogen retained in the bulk was not subtracted. We measured the amount of H + D retained in the sample of the inner and outer divertor tiles cut in 2 mm depth from the surface as the bulk sample. The amount of H + D retention in the bulk was almost $4–6 \times 10^{25}$ atoms/m^3 ($4–6 \times 10^{19}$ atoms/m^2/1 μm) [22], which was about one order of magnitude less than that in the redeposited layers.

3.2. Hydrogen isotope retention in the plasma facing surface of the first wall tiles

In JT-60U, the upper area of the first wall was mainly eroded, while the bottom area of the inner first wall was deposition dominated. Here, several carbon tiles of the first wall made of isotropic graphite, which were exposed to ~20 600 DD discharges including ~4300 HH discharges for July 1992–October 1999 experiment period, were analyzed. Samples were cut from two eroded tiles (samples E1 and E2) and from two deposition dominated tiles (samples D1 and D2) as shown in Fig. 6(a). D1 and D2 were covered by the redeposited carbon layers of a few μm in thickness. Behind the redeposited carbon layers, boron layers produced by the boronization clearly remained. The thicknesses of the boron layers were 1.2 μm and 0.42 μm, respectively for D1 and D2. XPS analysis showed that boron (B) content in the redeposited carbon layers was less than 14% of carbon [23]. Fig. 6(b) shows the TDS spectra of D_2 for all first wall samples. One can see that in the TDS spectra for E1 and E2, a large desorption peaks were observed at the temperature around 700 K and one shoulder at 1000 K. For D1 and D2, the desorption peaks were boarded and shifted at higher temperatures compared to those of the eroded samples. These hydrogen desorption temperatures were clearly lower that those for the plasma facing surface of the divertor tiles which showed three peaks at around 800–900 K, 1000–1050 K and 1200 K with the dominant peak at 1000–1050 K [8,22]. This is reasonable because the surface temperatures of the first wall must be lower than those for the divertor. The lower temperature is also confirmed by higher hydrogen

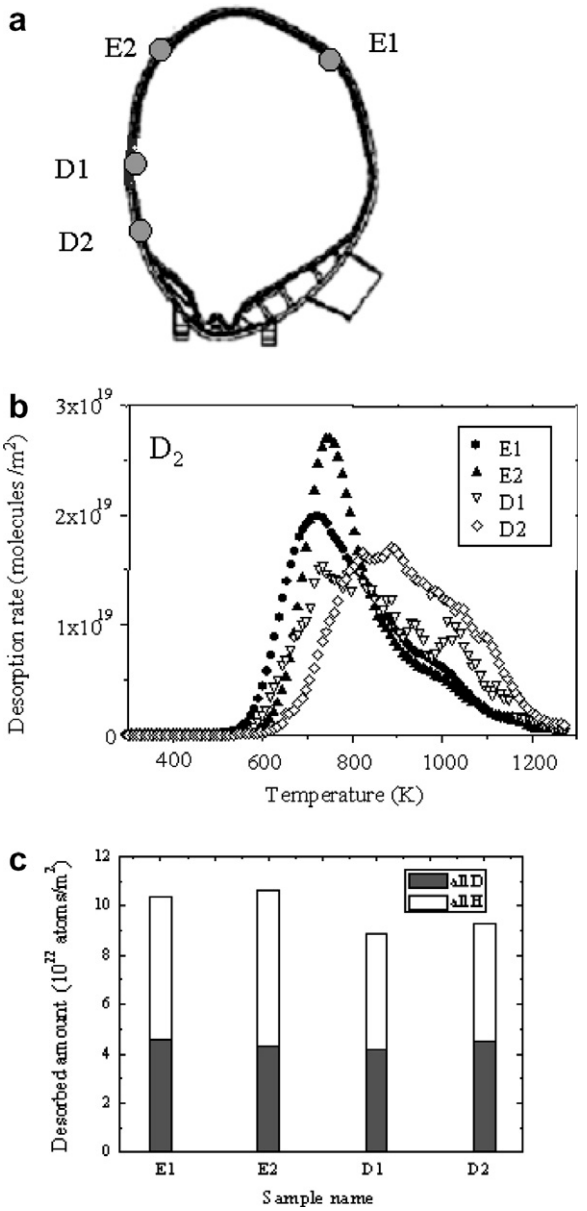

Fig. 6. Sample locations on the first wall (a), TDS spectra of D_2 gas for the first wall samples (b), retention amount of H and D atoms (c).

retention as depicted in Fig. 6(c), which shows the hydrogen retention in the redeposited layers of around 1×10^{23} atoms/m^2, one order of magnitude higher than those for the divertor. It is rather surprising to note that no clear difference appears in the hydrogen retentions for the eroded tiles and deposited ones as shown in Fig. 6(c). It was reported that the total amount of H + D in the analyzed depth of 0.5 μm by ERDA of the first wall in JET [24], is about 1.3×10^{21} atoms/m^2, and total amount of D measured by calibrated SIMS in the first wall in ASDEX-upgrade [25] is $(0.2–1) \times 10^{21}$ atoms/m^2 which was one or two orders of magnitude smaller than those of divertor tile. The total H + D retention in the first wall in JT-60 U was higher than those reported data.

Another significant difference appeared in D/H ratio. The first wall showed a much higher value of around 1.0 irrespective of the eroded tiles or deposited tiles, than those observed for the divertor tiles of around 0.08 (eroded tile) or ~0.3 (deposited tile). All these observation are very similar to those appeared at the dome area where the temperature would not be high.

In a separate measurement of tritium distribution by an IP technique, it has been shown that tritium was quite uniformly distributed on the surface of (D1, D2, E1, and E2), because tritium was directly implanted. Of course their intensities are somewhat different with each other. Taking the depth distribution of D and H [23] which shows no significant mixing, higher energy injection of D like the triton injection could have a large contribution on the hydrogen retention. JT-60U had large magnetic ripple which enhanced the ripple loss of high energy ions. And the lower temperature would not allow the replacement of H by D in wider depth, remaining significant amount of D.

4. Discussion

In the previous studies, we have found that, except near surface, in JT-60 and JT-60U, hydrogen is uniformly retained in the redeposited layers on the plasma facing surfaces of the inner divertor. Here we have confirmed the uniform retention on the redeposited layers on plasma shadowed areas, i.e. the tile sides facing the tile gap and the pumping slot, with the concentration of 0.13 in (H + D)/C, which is much larger than that for the plasma facing surfaces (0.03–0.02 in (H + D)/C). The D/H ratios of the retained hydrogen in the redeposited layers were much smaller than the ratio of shot numbers of DD and HH discharge, indicating isotopical replacement of D by H during subsequent HH discharges. The detailed mechanism of the H/D replacement and the formation of the redeposited layers in terms of temperature were already discussed by Shibahara et al. [22] and Tanabe et al. [26]. Here we briefly discuss the temperature effect on hydrogen uptake in the redeposited layers. In the present work, the

hydrogen retention in the redeposited layers was confirmed to be strongly dependent on temperature. That is because the operational temperature of JT-60U, 600 K, is near critical temperature above which hydrogen saturation concentration exponentially decreases with increasing the temperature, and below which it would stay some what constant with H/C 0.4∼1.0 [2–6,27–29]. The surface temperature of the plasma facing surface on the inner and outer divertors, easily exceed 900 K. Accordingly, (H + D)/C in the redeposited layers became 0.03 or less. Because of the poor thermal contact of the redeposited layers on the substrate, which leads to higher surface temperature and further reduces the hydrogen concentration, which is also homogeneous throughout the layers.

On the tile sides or shadowed area, hydrogen retention critically depends on the amount of carbon deposition. And the carbon deposition turns out to be depending strongly on the divertor geometry and tile alignment. In JT-60U, the W-shaped divertor seems beneficial because only the bottom of the outer dome wing was heavily deposited, most probably owing to the inwards carbon transport directly from the outer divertor. And the carbon deposition on the toroidal sides was quite small, because of very smooth alignment of the neighboring tiles in the toroidal direction. The gap distance of 1 mm, which is likely less than the gyroradius of carbon ions, would also help to reduce the carbon deposition in the gap.

Extrapolating the hydrogen retention determined here to the whole divertor area including the gap and the pumping slot, we can estimate the total hydrogen inventory. For the extrapolation, we have assumed that the amount of retained H and D is proportional to the number of the DD discharges. The plasma facing surface areas of the inner divertor, the outer divertor, the dome unit tiles and the inner and outer baffle plates are 4.4, 4.4, 5.9, 10.76 and 27.35 m^2, respectively. The total H + D and D retentions in the plasma facing surface in the tiles after exposure to 6700 DD discharges (discharge time = 19 000 s) is estimated to be $\sim 3 \times 10^{24}$ H + D atoms and 9×10^{23} D atoms, respectively. The contribution of the side surfaces was about 1×10^{24} H + D atoms, which is 30% of that for the plasma facing surfaces.

This is the first time that the hydrogen retention in the first wall of JT-60U has been measured. Because of the rather thin redeposited layers on D1 and D2, the measured thickness would include large error. Nevertheless the total H + D retention of 9×10^{22} D atoms/m^2 (see Fig. 6(c)) is comparative of the highest value for the divertor region (see Fig. 2), which is surprisingly high. One reason is the lower temperature at the first wall. Another reason is the location of the samples. They might not be representative of the first wall. Although D1 and D2 were deposition dominated tiles, they were near midplane that was nearest to the plasma. And E1 and E2 near the top of the torus were eroded and must be exposed to higher energy plasma. It is already noted that H/D for those tiles were very large, probably because of the low temperature and would not allow the isotopic exchange during HH discharges. In addition it should be mentioned that the tiles were possibly exposed to high energy deuterium originating from NBI. According to the tritium measurements by Sugiyama et al. [18], tritium retention in those areas was also the highest among the first wall tiles. Thus it is highly likely that deuteron injecting by NBI was implanted directly into those samples before fully loosing its initial energy. To confirm high hydrogen retention on the first wall samples measured here, detailed measurements for a full poloidal set of the first wall tiles are necessary.

5. Conclusion

The hydrogen isotopes retentions in the plasma facing surfaces, the side surfaces and the first wall of graphite tiles exposed to the DD and HH discharges in JT-60U W-shaped divertor with the both sides pumping system were investigated.

The total hydrogen isotope retentions in the tile surfaces depends on the tile location, and are clearly correlated to the thickness of the redeposited layers. Hydrogen is uniformly retained in the redeposited layers, except the very near surface. The hydrogen concentration in the redeposited layers shows two different values dependent on their location. The lowest concentration of ∼0.02 in (H + D)/C was found in the redeposited layers on the plasma facing surfaces, which is nearly the same as that found for redeposited layers on the same place with the inner side pumping system (∼0.03). The highest concentration of 0.13 in (H + D)/C was found in the redeposited layers on the bottom side of outer dome wing tile facing to the pumping slot. The H + D retention in the side surfaces with thin redeposited layer was quite small. From the rough estimation, hydrogen isotopes in the whole divertor area of

JT-60U is $\sim 4 \times 10^{24}$ atoms. Probably owing to the divertor geometry and tile alignment, the carbon deposition in the tile gap was very small and would not largely contribute to total D(T) retention in the vessel.

Such low H + D retention in JT-60U compared to the other tokamaks is largely owing to higher surface temperature. And divertor geometry and tile alignment also helped to reduce the carbon deposition.

Hydrogen retention in the first wall samples measured here was very high. The lower temperature of the first wall would be one reason. But the tile location might not be representative of the first wall and injection of high-energy deuteron could cause the high retention. To confirm the high retention in the first wall, more systematic studies are awaited.

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