TRITIUM RETENTION IN THE GAP BETWEEN THE PLASMA-FACING CARBON TILES USED IN D-T DISCHARGE PHASE IN JET AND TFTR

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Tritium accumulating in codeposits in the gaps between plasma facing components is a safety concern in next step fusion machines as suitable removal techniques have yet not been developed. We report on Imaging Plate measurements of the tritium areal distribution on the side surface of graphite/CFC tiles installed in the TFTR bumper limiter and JET Mk IIA divertor, both of which were exposed to D-T discharges. The tritium profiles on the four sides of TFTR tiles showed a short- and long-range decay pattern. In case of JET divertor tiles, only a small amount of tritium retention was detected on the tiles side facing the toroidal direction, while tritium retention was very large on the side facing the poloidal direction. These retention properties showed that the orientation or alignment of plasma facing component plays important role on the tritium retention in the gaps of those machines.

1. Introduction

Recently, tritium codeposition on the plasma shadowed area or in the gaps between plasma facing components of a next step tokamak has attracted much attention because of the difficulty of removal of such tritium [1,2]. The use of carbon materials as plasma facing components is minimized in ITER to reduce the associated tritium retention. However, there are still some uncertainties about carbon transport in boundary plasmas and plasma shadowed area as well as the process of carbon-hydrogen accumulation and it is important to characterize the deposition of tritium in tile gaps in existing DT machines.

Previous works for the hydrogen isotopes (H and D) retention in TFTR tiles showed that significant amount of hydrogen isotopes were retained in tile sides facing to the gaps by codeposition with the carbon sputtered from plasma-facing materials [3,4]. Our recent study for the TFTR tiles that had been exposed in the D-T discharge phase showed that a large amount of tritium was retained on the tile side-surfaces facing to the gaps between the tiles [5]. This motivated us to apply the imaging plate (IP) technique [6-8] that we have developed for tritium areal distribution measurements, to make detailed tritium retention measurements on the tile sides of the carbon tiles used in the JET divertor and the TFTR bumper limiter in D-T discharges.

2. Experimental

The Imaging Plate (IP) is a 2-D radiation detector with high sensitivity and resolution, utilizing a photostimulable phosphor (BaFBu:Eu^{2+}). The detailed descriptions about radiation detection method of IP have been given elsewhere [5-8]. Tritium activity is expressed as the Photo-Stimulated-Luminescence (PSL) intensity which is proportional to the energy deposition in the phosphor material due to radiation into the IP surface. Tritium beta ray has broad energy distribution, so that the PSL intensity is technically proportional to the convolution of the number of incident beta particles (~areal T density) and its energy distribution. Since the energy region of tritium is narrow (maximum: 18.6 keV), we can generally approximate that the PSL intensity is proportional to tritium areal density as described in Ref. [9]. In this experimental condition, the IP could detect the tritium by the range of roughly 2 μm in depth.

The measurement of the TFTR bumper limiter tiles was carried out in Princeton Plasma Physics Laboratory (PPPL). The sample carbon tiles were retrieved from lower region (tile: KC2, KC3), mid-plane (KA12, KB12, KC12) and upper region (KC21) of the bumper limiter. The gap between adjacent tiles on the limiter was approximately 3 mm but could vary from 2 ~ 5 mm. All sample tiles were used in TFTR D-T discharge phase. During a 3.5 years period, about 1000 shots of D-T discharges were carried out and 5g of tritium supplied to the vacuum vessel. Detailed description about D-T fueling history is found in Refs [10,11]. The IP surface was placed on the tile surface in a fume hood in a dark room. Two Poly-phenyl-sulfide (PPS) films with a combined thickness of 4μm were

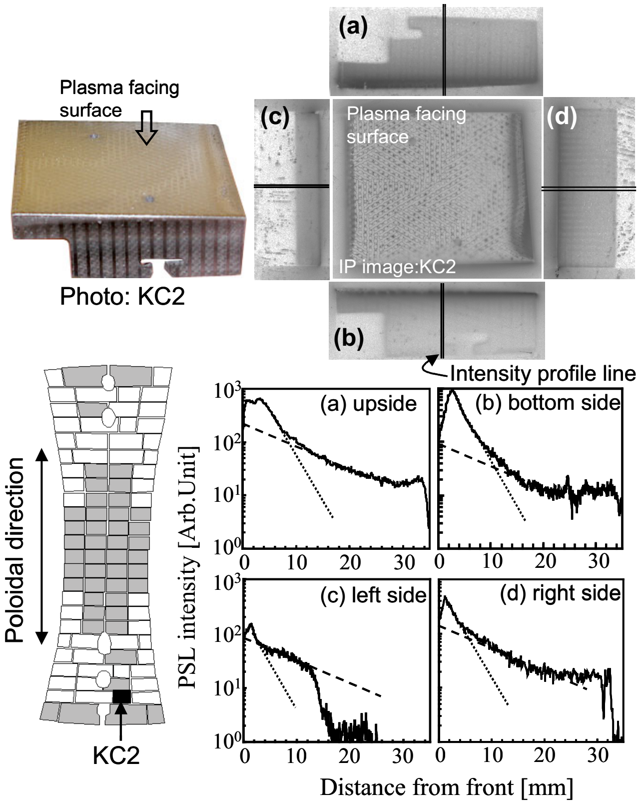

Fig.1 Upper part: the photograph and IP images of KC2 tile. The images of plasma facing and all side surfaces are shown. Lower part: the line profiles of PSL intensities as function of distance from front obtained by each side surface of KC2. (a) ~ (d) graphs show the profiles of upper, bottom, left, and right side, respectively.

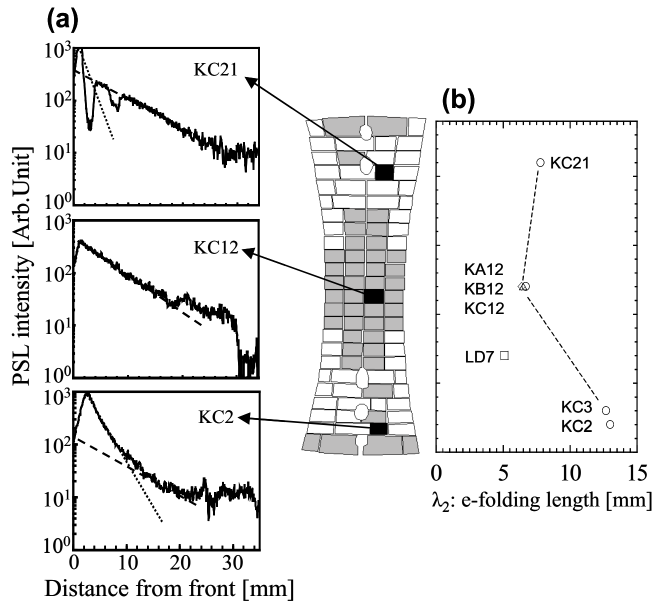

Fig.2 (a) The PSL intensity profiles obtained by KC2, 12 and 21 tiles. It is found that KC2 and 21 profiles are represented by two exponential functions as shown in dashed lines, while KC12 is fit by only one exponential line. Two dimples found at x = 2 mm and 8 mm in KC21 profile correspond to the position where the codeposited layer is partly exfoliated. (b) The comparison of the value of intensity decay length: λ_2 among the 7 tiles as function of the poloidal position. The value of λ_2 tends to be shorter at mid-part of the bumper limiter.

inserted between the IP and the sample tile in order to avoid the contamination of IP by tritium. The exposure time was about 1 hour. After the exposure, the IPs were transferred to Brookhaven National Laboratory (NBL), and processed by an IP reader, BAS-2500, to obtain the Photo-Stimulated-Luminescence (PSL) intensities for tritium profiling (tritium image).

The measurements of the JET Mk-IIA divertor tiles were carried out in the Tritium Laboratory, Forschungszentrum Karlsruhe (FZK), and the procedure is described in Ref [12].

3. Result & Discussion

3.1 TFTR

Figure 1 shows the tritium image and corresponding line profiles of the KC2 tile which was installed in the erosion-dominated region of the TFTR bumper limiter. The line profiles from the front to the rear side at the tile sides are approximately reproduced by two exponential functions:

$$PSL(x) = C_1 \exp(-\frac{x}{\lambda_1}) + C_2 \exp(-\frac{x}{\lambda_2}) \qquad (1),$$

where λ_1 and λ_2 are short- and long-range e-folding length of the PSL intensity, respectively. The first term is dominant in the region from the front to 5mm (c, d) or 1cm (a, b), that was covered by thick codeposited layers. According to the NRA analysis applied to the bumper limiter tiles employed in D-D operational phase [3], the hydrogen-rich codeposited layers (D/C ~0.2) were formed on the side surface near the plasma facing surface. Thus, the first term of the equation (1) can be attributed to the tritium retained in such hydrogen-rich ((D+T)/C ~ 0.2) deposition. λ_1 is a characteristic length relating the sticking probability of carbon particles escaping from the plasma and co-depositing with tritium on the tile sides. The value of λ_1 ~ 2mm is relatively small, and such codeposited layer was prominently observed on the sides of the tiles installed in the erosion-dominated region, which indicate that this codeposited layer was formed by prompt redeposition of the carbon/hydrocarbon species with high sticking coefficient, such as C or C_2H ions.

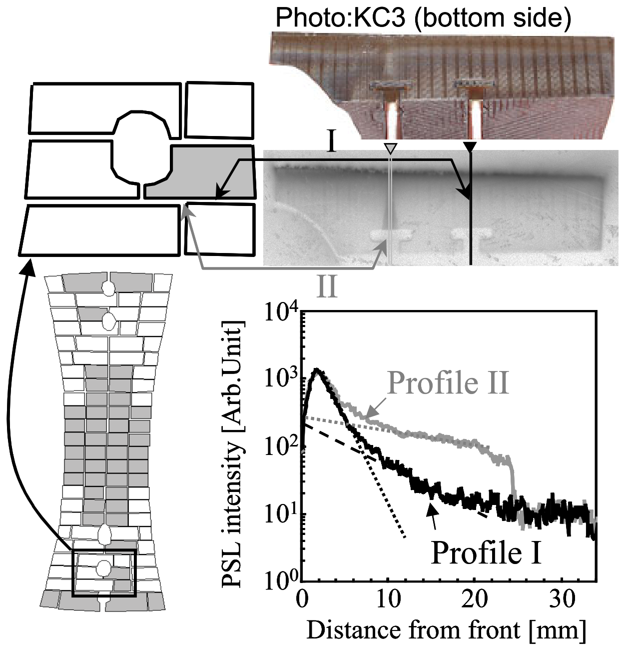

Fig.3 The IP image and the PSL intensity profile of KC3 which is adjacent to KC2. The black line shows the intensity profile at normal position. The gray profile is from the area facing to T-shaped intersection as schematically shown, where the gap width is large.

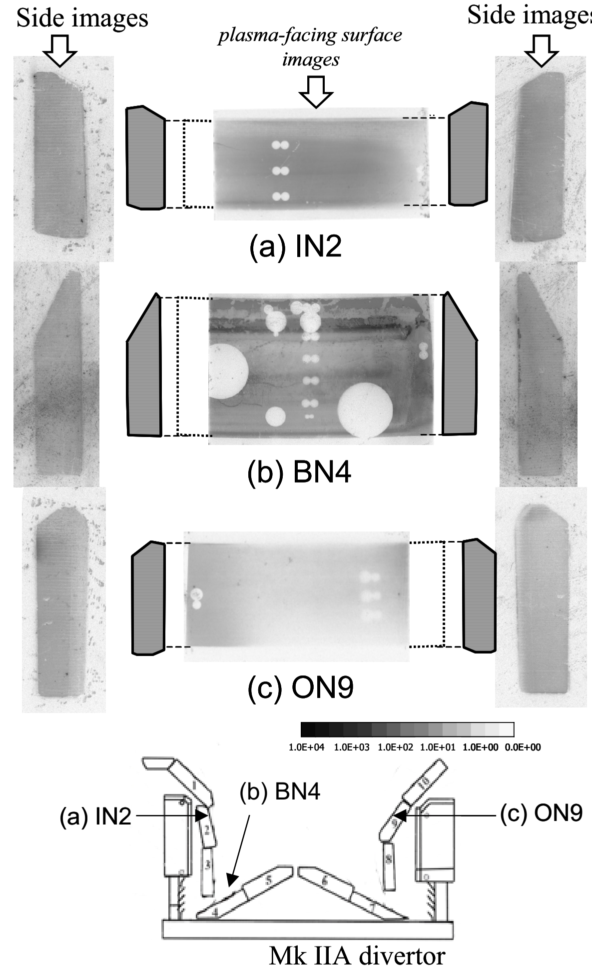

Fig.4 The side surface images of (a) inner divertor: IN2, (b) inner horizontal target: BN4 and (c) outer divertor: ON9 tiles. All side surfaces shown here are facing to the toroidal direction. Tritium distribution on the tile sides is relatively homogeneous. Other tiles not shown here also showed similar profile.

The four sides of KC2 showed different profiles. The codeposition expressed by λ_1 on the (a) upper side and (b) lower side; namely the sides facing to the poloidal direction, extends more deeply than that on the (c) right and (d) left side. This may be explained by the penetration depth of flux lines to the tile gap. The toroidal magnetic field: $\boldsymbol{B}_T$ is about 10 times larger than perpendicular component to the tile surface of the poloidal magnetic field: $\boldsymbol{B}_{P\perp}$. Hence, the pitch angle to the first wall formed by $\boldsymbol{B}_T + \boldsymbol{B}_{P\perp}$ becomes low, i.e. the flux line to the sides facing to the toroidal direction cannot penetrate deeply. In contrast, the flux line to the poloidal facing side surface can penetrate deeper. Because parallel component for the tile surface of the poloidal magnetic field: $\boldsymbol{B}_{P//}$ is almost same magnitude with $\boldsymbol{B}_{P\perp}$. In this regards, the rate $\boldsymbol{B}_{P//} / \boldsymbol{B}_{P\perp}$ also changes depending upon the limiter position. In Fig.2 (a), three profiles of bottom sides of the bumper limiter tiles from three different, i.e. upper, mid-part and lower regions, are compared. On the KC21 side, the codeposited layer was partly exfoliated around x = 2 mm and 8 mm. The profile of KC12 from mid-plane was fitted well by only one exponential, in contrast to the others.

The values of the long-range e-folding length: λ_2 obtained by the bottom side of each tile are compared in Fig.2 (b). The main process of this tritium accumulation could be the penetration of the neutral particles (as C:H molecules or radicals) into the gap. The decay length: >1.0 cm is longer than that obtained by a numerical study applied to the carbon neutrals with 0.2 of sticking coefficient [4], indicating this deep penetration to the tile gap was caused by the hydrocarbon particles with rather low sticking coefficient.

Figure.3 shows the IP image of the bottom side of KC3 which was adjacent to KC2. The plasma-facing surface was heavily eroded (as KC2), and much of the eroded material was deposited on the side surfaces. Two different types of line profiles were found on this surface. The λ_1s, which reflect the heavy codeposits, are the same between two lines, whereas the λ_2s are different. The length of λ_2 from the profile I was about 1.3cm while the one from the profile II was 3.3cm. The profile II was obtained by the area facing to the T-shaped intersection as schematically shown in Fig.3, where the gap width was locally large. This result suggests that the value of λ_2 is influenced by the gap width. In this regard, the poloidal variation of the λ_2s (: shorter at mid-plane than at the upper or lower region of the bumper limiter) might be also caused by the variation of gap width at each position.

3.2 JET

There was heavy codeposition on the sides facing to the poloidal direction, especially the side facing inner pumping slot (a detailed image is found in Ref [12]). In contrast, as shown in Fig. 4, tritium distribution on both side surfaces facing to the toroidal direction was relatively homogenous and almost no localized codeposition was observed. This is probably because of the tile shape which prevents the flux line hitting to the toroidal sides directly [13] and smaller gyro-radius of sputtered carbon compared to the step height between the neighboring tiles, namely, the eroded carbon migrating along the magnetic field line and could not land in the tile side. In addition, since B_T is relatively larger than B_P while $B_{P//}$ and $B_{P\perp}$ are almost same magnitude, particles could penetrate deeper in the gap parallel to the toroidal direction than that perpendicular one. In the divertor region, geometrical effect such as divertor structure or the position of strike point could play important role on generation of carbon impurities and impurity migration. Therefore, more analyses and comparison of the deposition distribution between different divertor structures is needed.

4. Conclusion

Tritium retention on the side surfaces of the tiles used in JET and TFTR, which strongly correlates with the carbon migration and deposition, was measured by Tritium Imaging Plate Technique. The result obtained by the TFTR bumper limiter tiles showed that the PSL intensity line profile could be fit by a two-exponential decay curve. One was the line with short-range decay, which reflected the distribution of the thick codeposition. Such codeposition was prominently observed on the sides of the tiles installed in the erosion-dominated region, which indicated the prompt redeposition of carbon/hydrocarbon particles. Another line had relatively long decay length influenced by the gap width, and extended about 30 mm into the gap between adjacent tiles. This result suggested the main process of such deep penetration was the migration of the neutral hydrocarbon with rather low sticking coefficient.

On the other hand, in the case of JET Mk IIA divertor tiles, tritium distribution on the tile sides facing the toroidal direction was relatively homogeneous. This is attributed that the eroded carbon/hydrocarbon did not accumulate locally on those sides because leading edge of a magnetic field line could not hit directly to the sides due to tile alignment. In contrast, heavy codeposition was observed on the bottom edge surface of the inner vertical target tile as pointed out in the previous studies. Its deposition showed specific pattern, which could be caused by poloidal transport of carbon/hydrocarbon in the divertor magnetic field.

These results showed that the amount of tritium retention as codeposition with carbon material is strongly influenced by divertor structure, i.e. geometry, tile alignment, gap width, pumping slot design etc., which are necessary for designing the tritium removal techniques.

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