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Tritium distribution on the surface of plasma facing carbon tiles used in JET

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Abstract

Tritium surface profiles on divertor tiles used in JET were successfully determined applying imaging plate (IP) technique. The tritium intensities measured by IP were quite consistent with the previous tritium analysis made by full combustion measurements. Present results are summarized as follows. Most of the tritium in the divertor tiles was retained in co- or re-deposited layer and did not move because of their temperature was rather low. In addition tritium produced by D–D reaction are implanted in subsurface layers rather homogeneously, which seems the main tritium source for the inner divertor tiles with some thermal modification. Still there is another but very small tritium retention observed at the back side of the tiles, of which profile reflects the 2-D CFC structure, indicating preferential absorption and migration of tritium.

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Keywords: Tritium; Tritium retention; JET; Imaging plate; Surface distribution; Divertor tiles

1. Introduction

Tritium retention in redeposited layers and dusts is a serious concern for ITER. Although hydrogen and deuterium retention implanted in graphite has been extensively studied, only limited works have been done for tritium retention in graphite tiles used in JET and TFTR. Tritium measurement in graphite tiles used in JET has successfully been done employing a combined technique of coring/full-combustion method and the first systematic results for the divertor regions are illustrated in Fig. 1, where is shown the tritium surface concentration (in MBq/cm^2) of a poloidal set of JET Mark IIA divertor tiles [1–5]. Most of the tritium was retained in the low temperature part of the divertor, particularly in shadowed regions at the inner divertor and louvers. The coring, unfortunately, could not a give detailed surface tritium distribution, because of its poor space resolution.

We have developed imaging plate technique (IP) to obtain tritium profiles on materials surface and succeeded to get detailed tritium images of graphite tiles used in TEXTOR and JT-60U [6–8]. In the present work, we have applied for the first time the imaging plate technique to obtain very detailed surface tritium distribution in CFC tiles used at JET divertor, and discussed the origin of the obtained tritium profiles.

2. Experimental

The CFC tiles measured here were the same ones in which the tritium levels were already measured by the

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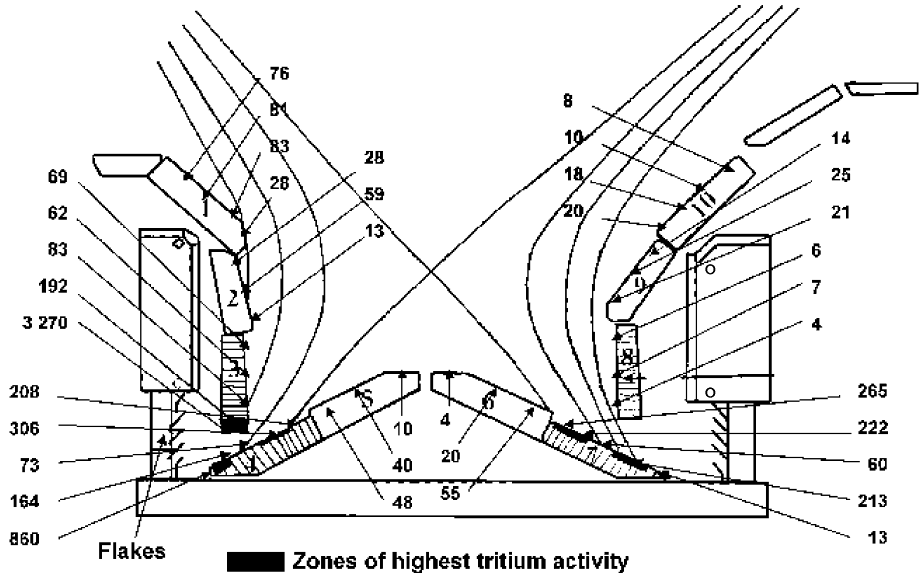

Fig. 1. Cross-section of the Mark IIA divertor in JET. All tiles except 5 and 6 were analyzed by IP. Including numbers are the tritium surface concentration within 1 mm from the surface measured by the coring/combustion technique in MBq/cm^2 [1,2].

combustion methods as given in Fig. 1. They were used in the first deuterium/tritium experimental (DTE1) campaign of JET and were taken from the divertor region. A description of the JET Mark IIA divertor arrangement existing at the time was published in [9] Except tiles 5 (BN5) and 6 (BN6), all tiles were analyzed by the imaging plate technique.

Imaging plates (IP) used here were BAS-TR2025, developed for detection of low energy β-rays such as those generated by tritium and manufactured by Fuji Photo Film Co. Ltd. The surface of the IP was in contact with the graphite tile surface for 1 h in a dark shielded room. In order to avoid the contamination of the IP with tritium, a thin (2 μm) polyimid-film was inserted between the tile and the IP. The insertion reduces the sensitivity by a factor of about 10 and tritium within the depth of about 1 μm can be analyzed. For detection of radiation sources (or higher energy sources) other than tritium, a relatively thick (12 μm) film was inserted between the IP and the tiles in order to inhibit the β-rays from tritium to reach to the IP.

After the exposure, the IP was processed by an imaging plate reader, Fuji FLA-3000/3000G or BAS-2500 to obtain digitized photo-stimulated luminescence (PSL) intensity and its 2 dimensional mapping ('tritium image'). The PSL intensity, which is a measure of absorbed energy in the IP, cannot be directly converted to absolute tritium level (Bq/cm^2) but is nearly proportional to the tritium surface concentration. Details of tritium detection by IP technique were published elsewhere [10] and applied successfully for tritium profiling on graphite tiles used in TEXTOR and JT-60U [6–8].

Unfortunately, the size of the IP is not large enough to cover the entire surface area of the JET divertor tiles. The tritium images reported covers about 3/5 of the tiles in the toroidal direction but the whole tile in the poloidal direction.

3. Results

The results for the inner divertor target tile (no. 4 tile (BN4) in Fig. 1) are shown in Fig. 2, where IP images are compared for insertion of 2 and 12 μm films (i.e., representing a tritium image and other radiation image, respectively). All the holes were from the traces of drilling to make the samples for tritium measurements by the combustion and calorimetry methods.

One can clearly see that the tile contained other (higher) energy sources. They are very likely ^{44}Sc, ^{60}Co, ^{14}C and so on, respectively, produced by neutron activation of impurities included in graphite, components of vacuum vessel (deposited on the tiles), and absorbed nitrogen, etc. Most of these other radiation sources seems to be codeposited on the shadowed area and only small on the plasma exposed area. Considering that the PSL intensities due to those other radiation sources are less than 1/10 of that due to tritium and that the higher energy radiations, particularly γ-rays are much more penetrating than β-rays from tritium are, we can conclude that the tritium images were not influenced by the other radiation sources.

One can note a quite nice correspondence of the tritium image to the photograph given at the top right of

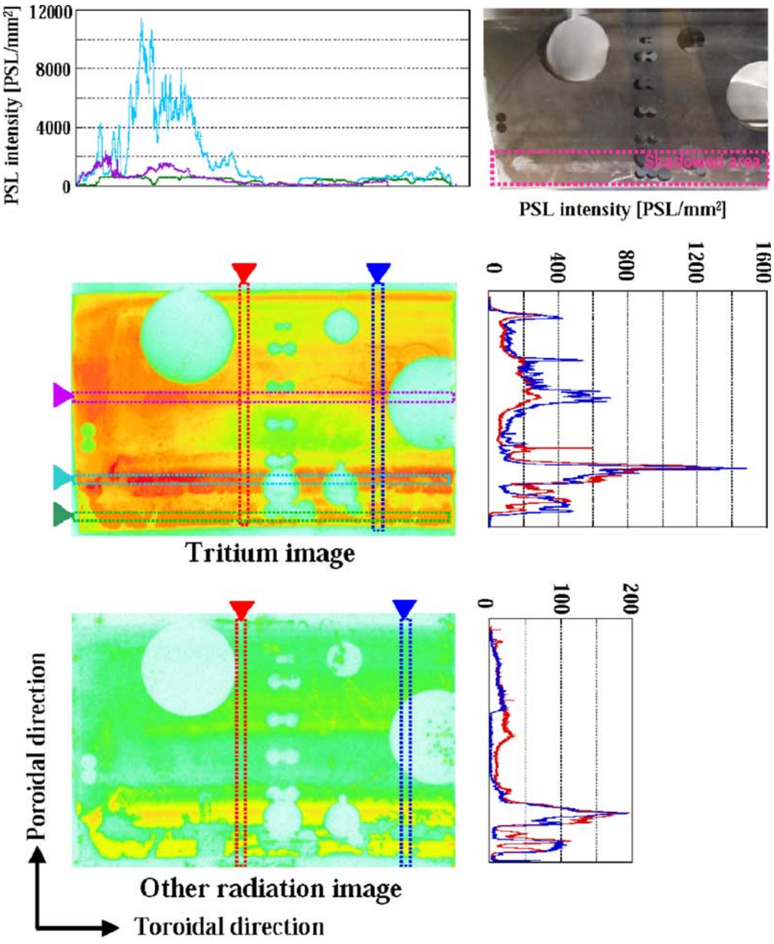

Fig. 2. Results of IP imaging and a photograph of the divertor base tile BN4. The upper IP image is for tritium and the bottom for the other radiation sources. Line profiles of PSL intensity for selected areas are also given. Numbers in tritium image are tritium levels within 1 mm from the surface in MBq/cm^2 determined by full combustion measurements after [1,2].

Fig. 2. As already indicated [1–5] and also seen in the photograph, significant redeposition was observed in the photograph as brown colored thick redeposited layers at the bottom of the no. 4 tile, where was shadowed by the inner divertor tile (IN3). Numbers written on the tritium image are retained tritium levels in MBq/cm^2 within the depth of 1 mm from the surface determined by the coring/combustion method [1], which agree generally with PSL intensities. According to the PSL intensity, the highest tritium level was found at the redeposited area with an estimated tritium level of around 3 GBq/cm^2. The combustion method showed the highest tritium level of 860 MBq/cm^2 but at a different location. It is interesting to note that the highest tritium level of 3 GBq/cm^2 was also observed at the side edge of the tile where was not exposed directly to the plasma. (see Fig. 1).

One can also see the sudden change in the PSL profile in the toroidal direction at the redeposited area, which is likely caused by the exfoliation of the redeposited layers as appears in the photographs. One can see stripes parallel to the toroidal direction originated from 2-D woven structure of CFC tiles in the redeposited (shadowed) area of the photograph in Fig. 2 (see also Fig. 5). The redeposited layers were easily exfoliated by an adhesive tape. The results of IP analysis for the exfoliated region and the backside of the exfoliated film were given in Fig. 3. From the line profile of the PSL intensity including the exfoliated layer, one can note that most of the tritium is retained in the redeposited layers. However, the tritium level of the backside of the exfoliated layer is about a half of that on the top surface. This indicates again that most of the tritium is retained in the front surface region of the redeposited layers. It should also be noted that the tritium level beneath the deposited layers was very similar to that for the plasma facing central area without the redeposited layers (eroded area).

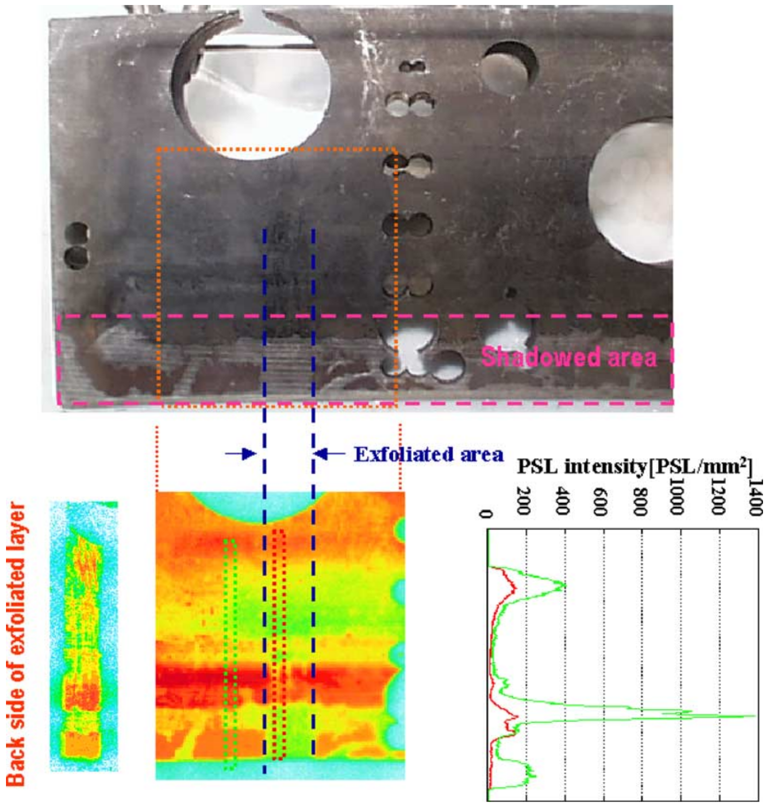

Fig. 3. Tritium profiling beneath the exfoliated area deposits and the bask side of the exfoliated layers on the inner divertor tile BN4.

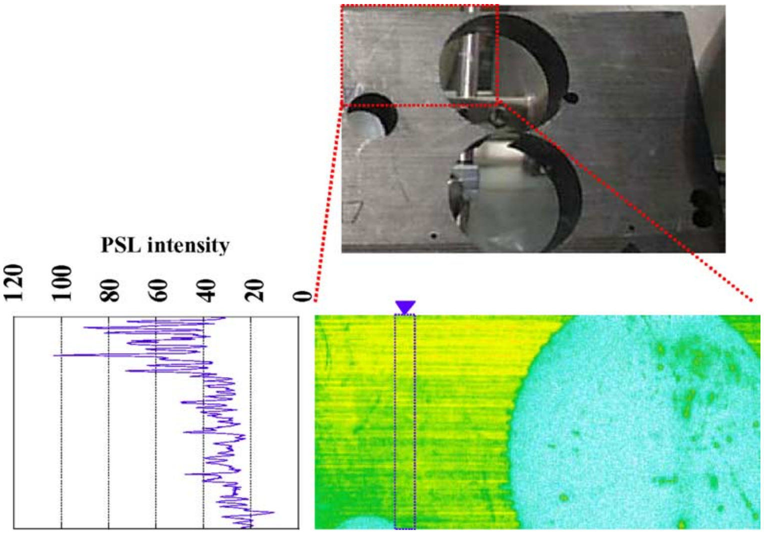

Fig. 4. Tritium image and line profile for the rear side surface of BN7. One can clearly see stripes in the tritium image and periodic intensity change in the line profile, which is just the same as woven layered structure of the 2 dimensional CFC tile used as the divertor tile.

On the plasma facing area, the tritium profile is very much inhomogeneous, and none of the tritium levels determined by the combustion method represent a typical value.

Tritium was also detected from the rear side surface of the tile, though the activity was far less than that of the front surface, as shown in Fig. 4. It is of particular interest to note that the image shows clear stripes which

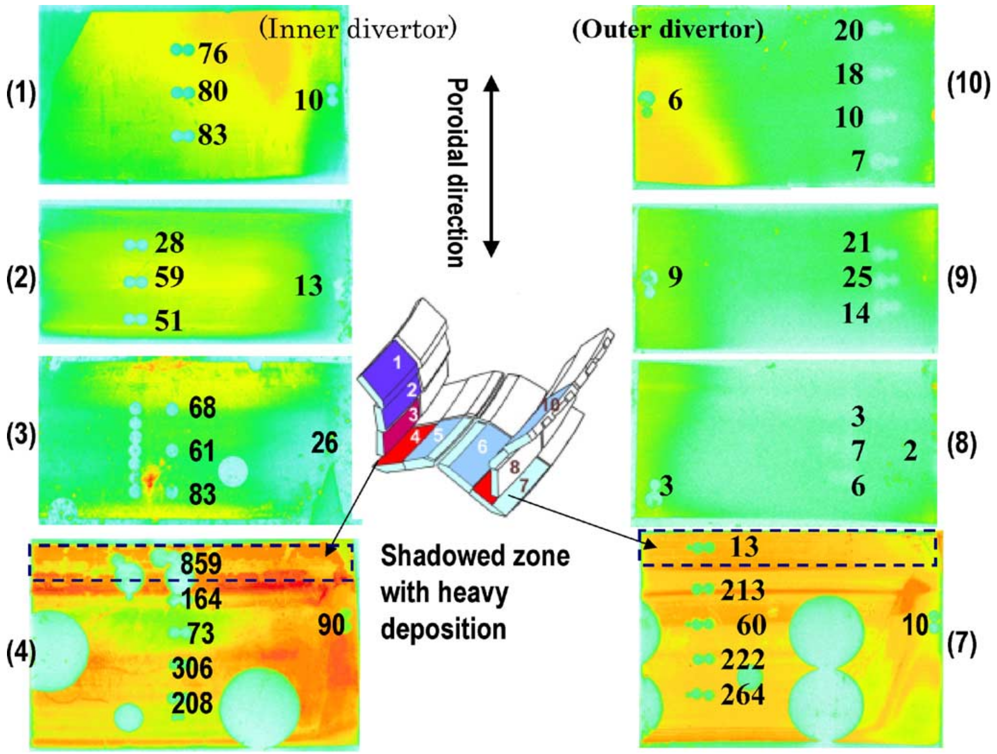

Fig. 5. Tritium image for whole divertor area. The numbers in the image are the tritium surface concentration within 1 mm from the surface measured by the coring/combustion technique in MBq/cm^2 [1,2].

is just the same as woven layered structure of the 2 dimensional CFC tile used as the divertor tile and similar images were obtained for other tiles (not shown here).

The outer divertor target tile (BN7) showed very similar tritium image as that for the inner diverter tile (BN4) but retained less tritium as shown in Fig. 5. The combustion method gave the lowest tritium activity on the shadowed area (13 MBq/cm^2) but the tritium image clearly show the highest activity there. Fig. 5 shows the results for other divertor tiles together with those for above mentioned divertor target tiles. Compared to the above mentioned tiles, the rest of the divertor tiles retained much less amount of tritium. The PSL intensities generally coincide with the previous combustion measurements as given in the numbers on the tritium images.

The tritium images for each tiles showed their own patterns, and no systematic variation was recognized within each tile. However, the images, as a whole, gave different information: (1) very similar pattern in both divertor target tiles (BN4 and BN7); (2) higher tritium activity at the inner divertor; (3) very low tritium activity in the central area of the outer divertor tiles, while the activity is higher in the central area in the inner divertor tiles.

4. Discussion

It is of great interest to compare the present JET results to JT-60U [8]. In JT-60U, tritium is produced only by D–D reaction and the divertor temperature increases during discharge, sometimes over 1300 K, because the divertor is only inertially cooled (base temperature is around 600 K). Hence, tritium retention in JT-60U tiles is not strongly correlated with the redeposition pattern and the highest tritium level was observed at the top of the dome and on the divertor baffle plates where were directly exposed to the plasma (situated very near the plasma and not shadowed). Tritium distribution was strongly modified by surface temperature showing that more or less no tritium is detected on the both separatrix, and gradual profile changes along the poloidal direction inversely correlated with the temperature profile.

Different from JT-60U, three different tritium sources were distinguished in JET depending their incident energy to the plasma facing surface: (1) high energy T, tritium ions produced by D–D reaction impinging with higher energy than the edge plasma temperature; (2) plasma T, tritium ions and neutrals impinging with energy equilibrated in the edge plasma and (3) gaseous T, gaseous tritium thermalized to the wall temperature in the torus vacuum vessel.

Because of its large gyro-radius, without fully loosing its initial energy of 1 MeV, the high energy T is implanted into plasma facing tiles with a depth in the order of micrometers as already suggested by Stan-Sion [11] for JET first wall tiles. This manifested as the uniform tritium profiles observed in the graphite tiles used in TEXTOR limiter and JT-60U divertor. [6–9] Rather homogeneous tritium distribution of the central area of the divertor tiles also confirms this.

The plasma T was retained mostly in the redeposited layers and dominated the total tritium retention in the divertor in JET. Two valleys were observed in the poloidal T profiles near the bottom regions in the divertor target tile (BN4). One appeared around the area with the tritium level of 73 MBq/cm^2 and the other between the area with 164 and 860 MBq/cm^2 in Fig. 2. The upper valley probably corresponds to the area where the separatrix or divertor leg was located and hence the high heat load desorbed tritium once retained. The lower valley is just in the middle of the redeposited layers, where one can see even the woven structure of 2-D CFC base tiles in the photograph. At the moment the reason for the existence of the lower valley is not clear. As described above, the deposited layers are easily exfoliated. Therefore some mechanical force may peel off the layers during the removal of the tile from the base plate or during the storage after the removal. This needs further investigation.

The gaseous T can be absorbed at any location in the torus as observed in the back side.

Preferential absorption and migration of gaseous tritium into the CFC tile is likely cause the stripe tritium image in 2-D CFC tiles, because the fibers and matrix are differently graphitized in 2-D CFC and characteristics to the gaseous hydrogen may be different between the successive layers [12].

In addition to these general features, significant asymmetry was observed between the outer and inner divertors in JET (see Fig. 5). The tritium patterns on each tiles and as a whole should reflect plasma character or plasma surface interaction at the divertor regions.

In JET, the divertor base (supporting structure) is water cooled. Accordingly, the base temperature of the divertor tiles was reported to be around 500 K, cooler than the ambient temperature of the of the rest of the torus (600 K) [5]. Therefore tritium from the plasma (including both the high energy T and the plasma T) was retained without significant changes in their profiles (the former was implanted into the subsurface and the latter codeposited with carbon.) As observed in Fig. 5, however, the tritium images for the outer and the inner divertor were quite different. This is mainly owing to the fact that the outer divertor area is erosion dominated, while the inner divertor deposition dominated. Accordingly the tritium on the outer divertor is dominated by the high energy tritium, whereas the co- or re-deposited tritium dominates on the inner divertor.

Another difference between the inner and outer divertor tiles appears in the toroidal patterns. Such asymmetry was not appreciable in JT-60U. The asymmetry in JET could be interpreted as the difference in the heat load between the inner divertor and the outer divertor. The toroidal length of the JET divertor tiles are so long that the plasma heat load or particle flux is not uniform but the central area in the outer divertor must experience higher flux resulting in higher temperature compared to the edge, whereas the edge region on the inner divertor must be higher heat loaded than the center. Consequently, tritium level is observed to be lower in the central area than the edge region at the outer divertor and vise versa at the inner divertor.

Because of the large gyro-radius, higher energy T can impinge the plasma facing wall deeply and homogeneously. Thus, there should be some basic low tritium level equally distributed in all the plasma facing surfaces as observed beneath the deposited layers (see Fig. 3). This is confirmed by the finding that the PSL intensity beneath the deposited layer corresponds to around 20 MBq/cm^2, which is very near the lowest tritium level observed in all tiles. We base this argument on the assumption that the implanted tritium could not be thermally released in JET. (In JT-60U, it was thermally released due to its higher temperature.) As already reported [13], thermal desorption of hydrogen implanted in carbon depends on its concentration, the lower the concentration, the higher the desorption temperature. Because the concentration of implanted T in subsurface layers should be much less than that in the redeposited layers, it is more difficult to be releases thermally. Hence, plasma heat load may not be enough to thermally desorb the implanted T even in the central area of the outer divertors. On the other hand, the retention of T together with H&D in the redeposited layers on the outer divertor target tile (BN7) is likely near the saturation level in graphite and be released thermally as observed less T retention compared to the inner divertor target plate (BN4).

5. Conclusions

Tritium surface profiles on divertor tiles used in JET were successfully determined applying imaging plate technique. The measured PSL intensities generally coincide with the previous tritium analysis made by full combustion measurements and gave more detailed information. The tritium profiles were very non-uniform particularly in the poloidal direction on the plasma facing surfaces. Most of the tritium was retained in the redeposited layers which can be easily exfoliated. According to the PSL intensities, the highest tritium level was found just at the shadowed area of the inner divertor target tile where the deposition was the highest and the estimated tritium level is as high as around 3 GBq/cm^2. The tritium retention beneath the deposited layer was very small, and the T image of the cross-section of the small specimen drilled from the tile confirmed the surface tritium retention.

All these indicate that most of tritium in the tiles is co- or re-deposited on the tile surface, particularly the redeposited layers in the shadowed region on the divertor target tiles retained a very high level of tritium

Tritium produced by D–D reaction which was implanted homogeneously into a depth in the order of micrometers, is the main tritium source for the highly heat loaded outer divertor plate. The tritium profiles in the outer and inner divertors are quite opposite in JET, i.e., tritium retention in the central area of the inner divertor is higher than the edge and vise versa in the outer divertor, probably reflecting the higher heat flux at the central area of the outer divertor tiles resulting in higher temperatures retaining less tritium and vise versa in the inner divertor.

Clear striped pattern corresponding the woven 2-D CFC structure appeared in the back side, indicating preferential absorption and migration of gaseous tritium into the tile between or along the CFC layeres.

Acknowledgements

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