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TRITIUM RETENTION IN DUST PERTICLES AND DIVERTOR TILES OF JET OPERATED WITH THE ITER-LIKE WALL

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Abstract

The Joint European Torus (JET) is operated with the ITER-Like Wall (JET-ILW): beryllium in the main chamber and tungsten in the divertor in order to replicate materials for ITER. It was present systematic and quantitative study of tritium retention in dust and divertor tiles of ILW by means of tritium imaging plate technique to assess tritium level in individual particles and, by a full combustion method to determine the total tritium amount in the tiles and dust. Using these two different techniques, it was found that the poloidal distributions of the surface and bulk trapped tritium are quite different. The total tritium activities show significant differences between the JET operation with ILW and the earlier operation with the carbon wall (JET-C) indicating that tritium retention is significantly decreased in the operation with ILW. The approximate amount of tritium in the dust and tiles was also measured.

1. INTRODUCTION

Joint European Torus (JET) has been operated since August 2011 with metallic plasma-facing components (PFC): beryllium (Be) limiter tiles in the main chamber and tungsten (W) in the divertor [1]. The success in operation with metals has had a major impact on the decision regarding materials for ITER: to eliminate carbon PFC and to start from Day 1 with Be and W components. Studies of materials, including dust particles, retrieved from JET-ILW constitute a topic of the comprehensive research on materials carried out jointly in the framework of the Procurement Agreement of the Broader Approach signed by Japan (JA) and EU. The aim is on the further developments in fusion science and technology. JA-EU Broader Approach DEMO Research and Development (BA DEMO R&D) on Tritium Technology (T2) is an agreement between the National Institutes for Quantum and Radiological Science and Technology (QST) and Fusion for Energy (F4E). This collaborative research on JET-ILW tiles and dust analysis has been conducted since 2014. Operation of JET-ILW facilitates detailed studies of fuel retention, erosion – deposition processes and dust generation under conditions relevant for a reactor-class device, i.e. ITER. Until year 2016 three JET-ILW campaigns have been fully completed: ILW-1 (2011-2012), ILW-2 (2013-2014) and ILW-3 (2015-2016) [2]. A significant number of samples from wall tiles and dust (both from ILW-1 and ILW-3) as well as dust from with the carbon wall (JET-C, campaign 2007-2009) were shipped from JET to the International Fusion Energy Research Center of QST, Rokkasho, Japan. In this study, remained tritium (T) amount in ILW-1 and ILW-3 tiles were measured. Also, remained tritium amount in ILW-1 and ILW-3 dust were measured and compared with remained amount in JET-C dust. The morphology of dust was examined.

2. EXPERIMENTAL

Tritium analyses were carried out by means of tritium imaging plate technique (TIPT) [3,4], full combustion method (FCM) [5] and liquid scintillation counter (LSC). The identification of individual dust particles was performed using scanning electron microscopy (SEM) and electron microprobe analyzer (EMPA) [6].

2.1 Specimen

2.1.1 JET dust

Dust particles collected by vacuum cleaning after three different experimental phases in JET have been studied: (i) JET-C operation in 2007-2009, (ii) the first ILW-1 operation in 2011-2012 and (iii) ILW-3 in 2015-2016. In JET-C dust particles were collected from six positions: inner divertor tiles, divertor carrier ribs, outer divertor base tiles, inner and outer louvres in the remote region of the divertor [7]. After ILW operations dust was collected from the inner (Tiles HFGC, 1, 3 and 4) and outer (Tiles 5, 6, 7 and 8) divertor tiles [2]. In total 280 g was collected in JET-C, while the amount of dust generated in the presence of metal wall was very small (around 1 g per ILW campaign) compared to that in JET-C. Dust particles at each location were stored in different glass pots.

2.1.2 JET tiles

The cross-section of the JET-ILW divertor is shown in Fig. 1. Specimens' positions (red marks) and numbers are indicated. Figure 2 (a-d) show respectively: Tile 4 as retrieved after ILW-1, the same tile after preparation of specimens by coring, the cored disk and, a triangular sample (2 mm long edges and 2 mm thickness) cut-out from that disk for tritium studies by FCM.

FIG.1. Cross-section of the JET-ILW divertor with marked position of specimen

FIG.2. Photos of ILW-1divertor Tile 4 and specimen for FCM: (a) divertor tile, (b) cored tile, (c) cored specimens and (d) cut-out specimen for tritium analysis by FCM.

2.2 Enhanced Full Combustion Method

The full combustion method is a standard technique for tritium analysis by which the total amount of T retained in materials is determined [8]. To measure effectively the tritium removal from the dust and tiles, a modified FCM approach was introduced. The experimental set-up is shown in Fig. 3. A special feature of the present work was the use tin (Sn) foil for wrapping specimens of dust particles and tiles for combustion in the flowing oxygen (a carrier gas and the oxidizing agent). Such small packages were then placed on a ceramic plate in a quartz tube inserted to a ceramic furnace. The package was heated up to 1,200 K with a heating rate of 85 K/min and kept at a temperature of 1,200 K for 30 min. At the temperature of 1100–1200 K Sn reacts chemically with oxygen and its temperature rises to about 2,100 K [9]. Consequently, the Sn foil and specimens were burned and turned into ash on the ceramic plate. The released tritium in the form of HTO was trapped in two water-filled bubblers placed in series downstream of the quartz tube. The role of a water bubbler installed before the tube oven was to humidify oxygen flowing to the heated sample. After switching-off the oven and cooling down the quartz tube, the two downstream bubblers were disconnected, and the amount of tritium released from the specimens during the heating was measured by liquid scintillation counter (LSC). In order to measure the amount of tritium remaining in the quartz tube after heating, another water-filled bubbler was connected downstream of the quartz tube in place of bubblers 1 and 2, and oxygen was passed through the reactor tube for 30 min. The third bubbler was disconnected and the amount of tritium remaining in the reactor tube was measured by LSC. The ash located on the ceramic plate was also put into the liquid scintillation cocktail vial to measure the remaining T.

FIG. 3. Experimental set-up for tritium measurement using the full combusiton method.

2.3 Tritium measurement of dusts by tritium imaging plate technique with SEM/EPMA

A tiny amount of dust was taken from the pot and gently placed on the surface of a disk made of indium (In). An advantage to using In disk is to obtain negligible intensities of background carbon because many types of adhesive tapes for analyzer include carbon [10]. The intensity of tritium retained at the surface of and/or in the dust particles was evaluated by TIPT [11,12]: emission of β-rays from tritium to the imaging plate (IP) was measured over a whole surface of the In disk for 1 h at room temperature. The spatial resolution of TIPT is 25 μm. Afterward, Electron Probe Micro Analyzer (EPMA) was conducted to determine morphology (composition and structure) of the dust particles on the same surface area where TIPT was performed. EPMA (or wavelength dispersive X-ray spectroscopy, WDS) with a 10 keV electron beam gives information on the elemental composition with around 1 μm spatial resolution. The compositional analysis of the whole In disk was performed with a resolution of 20 μm and individual dust particles were separately analyzed with a resolution of 1 μm. The obtained maps (images) of the tritium distribution and elemental compositions were super-imposed to reveal characteristic features of T retention in the individual dust particle with the aid of image analysis software FIZI [13].

3. RESULTS

3.1 Results of Full Combustion

Specific tritium activities in JET dust and tiles were measured by FCM enhanced by the heat of Sn oxidation. A histogram in Fig. 4 shows the amount of tritium captured in the two bubblers after combusting the JET-C dust collected at In/Out Louvers and Outer Divertor Base. In addition, data are shown for the remaining amount of T removed by flowing gas into the reactor tube after the FCM, and for the amount of tritium remaining in the combustion ash. The scale of the vertical axis is logarithmic. More than 99 % of tritium removed by combustion was captured in the 1st bubbler. In both samples of dust, the amount of tritium captured in the 2nd bubbler was less than 1/1,000 of that in the 1st bubbler. The amount of T remaining in a reactor tube after FCM was four orders of magnitude lower than that in the 1st bubbler. In the case of ash, the remaining amount of T was seven orders of magnitude lower than that in the 1st bubbler. The T leakage from the reactor during the combustion was monitored using an ionization chamber; no leakage was detected. It was confirmed that all T in the specimens could be effectively measured by the enhanced FCM.

FIG.4. Quantitative measurement of tritium in dusts of In/Out Louvers and Outer Divertor Base at JET-C as measured by full combustion method.

Figure 5 shows the specific tritium activities measured by the FCM for dust particles from JET-C, ILW-1 and ILW-3. The specific tritium activities are in the range 5 – 2,600 MBq/g and 6 - 750 MBq/g, respectively for JET-C and ILW. The specific tritium activities for ILW dust were within the same range for JET-C. This relatively high fuel concentration in one of the ILW samples was somewhat unexpected. Therefore, the T presence in individual particles was examined clearly showing that the high T level was associated with carbon-based grains, and not with Be and W particles [6].

FIG.5. Specific tritium activities in dust particles after operated with JET-C, ILW-1 and ILW-3 as measured by FCM.

Histograms in Figure 6 show the poloidal distribution of specific tritium activities determined by FCM in ILW-1 and ILW-3 tiles. D retention has been shown to be an order of magnitude lower on outer divertor Tiles 7 and 8 compared with inner divertor tile from nuclear reaction analysis and TDS [14,15]. However, the specific tritium activities from FCM are in a similar range for both outer and inner divertor tiles. This is also observed when the absolute T retention values from FCM are normalized to plasma facing surface area, where fuel retention is concentrated, as discussed later in Section 4. The T retention values between inner and outer divertor could indicate a difference in the retention mechanism compared with D. The specific tritium activities are in the range 3 - 25 kBq/g and 3 - 21 kBq/g, respectively for ILW-1 and ILW-3. The generated tritium amounts by DD reactions in ILW-1 and ILW-3 are approximately 15 GBq and 40 GBq, respectively [16]. There is no significant difference in the specific tritium activities in the tiles of ILW-1 and ILW-3 operation, although the amount of generated tritium of ILW-3 operation was more than twice as large in that of ILW-1 operation. However, there is an additional source of tritium off-gas in-vessel from the first deuterium-tritium experiment in JET (DTE1) in 1997 [17]. Analysis of in-vessel off-gassing has not been quantified; however, it could contribute to the for similar values between ILW1 and ILW3 results if it exceeded the production of T from DD reaction.

FIG.6. Specific tritium activities in tiles after operated with ILW-1 and ILW-3 as measured by FCM. No measurement available for ILW-1 sample 4-10.

The tiles of ILW-3 were sliced parallel to the surface, the amount of tritium in the sliced piece was measured. Figure 7 shows the results of the measurement of specific tritium activities in the sliced pieces. The horizontal axis in the figure is the thickness of the sliced tiles and the vertical axis is the specific tritium activities. Tiles 1-6, 4-10 and 6-2 were sliced about 1 mm from the surface and tile 8-8 was sliced about 0.5 mm from the surface. Most of the tritium was present in the topmost surface pieces. However, tritium was also present in the second and subsequent sample pieces. From the SRIM calculation, the maximum range of 1 MeV triton produced by the DD reaction in Wand C are about 4 µm and 12 µm, respectively. Therefore, tritium is mostly present within 0.5 mm from the surface. However, some tritium was also present at depths greater than 1 mm from the surface. Irradiated tritium diffused inside the tiles and was present at depths deeper than 1 mm.

FIG.7. Specific tritium activities in tiles after operated with ILW-3 as measured by FCM.

3.2 Tritium Imaging Plate Technique measured of ILW tiles

Investigation of remaining tritium in surface region of samples cored from the W-coated divertor tiles was done by the IP technique [4]. Figure 8 shows results of the IP for both ILW-1 and ILW-3. The colored images of cored samples show the tritium distribution on the tiles. The colors relate to the intensity of β-rays from tritium decay escaping from the depth of a few micrometers, as shown by the reference "ART-123" in the figure. Data in Table 2 also show the photo stimulated luminescence (PSL) intensity per unit time of the TIPT obtained with X-rays and β-rays. No. 6-9 at ILW-3 tile could not be measured by IP because the specimen was already used for another experiment. On vertical divertor tiles, larger amount of tritium remains near surface at the inner tiles than at the outer tiles in both the ILW-1 and the ILW-3 cases, though the area with larger remaining tritium expanded to downward in the ILW-3 case. On horizontal divertor tiles, remaining tritium increased on the outer tiles in the ILW-3 case. A drastic decrease of remaining tritium is observed at the position of 4-10, which is inside the inner pumping gap. These differences in the distribution of tritium can be attributed to the different positions of the typical divertor strike points in the two campaigns shown in Fig. 8 with green and blue lines.

FIG.8. Imaging plate results of cored samples in ILW-1 and ILW-3, and tritium reference sample. Positions of cored samples are shown in a poloidal cross-section in which left-hand side is the torus inboard side. Coloured lines show the positions of the separatrix in three typical configurations, ILW-1 predominantly green, ILW- 2 and 3 green and predominantly blue.

3.3 Composition and tritium retention of dust particles

The relationship between the compositions and tritium retentions of individual dust particles in individual summarized in Figures 9 [6]. Fig. 9(a) shows surface morphologies of dust particles on the In disk by the secondary electron detector and major compositions by WDS in EPMA. The location of C-, Be-, W-dominated dust particles (and also oxygen-rich objects) is indicated in Figure 9 (a) as small spots with superscript labels (C, Be, W, and O) across the whole surface of the In disk. Very few Be- and W-dominated dust particles were found in comparison with C-dominated and metal oxide dust particles, indicating that loose metallic dust particles were not generated in significant numbers from the ILW materials.

FIG. 8. EPMA image showing composition of dust particles (a). Small circles with superscript labels indicate the location and composition (C, O, Be and W) of dust particles. IP image showing tritium distribution on the indium disk (b) and super-

imposed image of (a) with (b) - (c).

Figure 9(b) presents IP-recorded distribution of tritium intensity on the whole surface area of the In disk. The scale indicates increasing tritium amount as the color changes from green to yellow to red on the background color of blue. A variety of different colors and sizes of green and red spots indicate different amounts of tritium retained on surfaces or in the bulk of individual dust particles and their locations on the In disk. In order to measure quantitatively which type of dust particles retain tritium or not, small spot indicated for compositions and their locations (Fig. 9(a)) and tritium distribution (Fig. 9(b)) are super-imposed together in Fig. 9(c). Two facts are immediately noticed from Fig. 9(c): (i) not all dust particles retain tritium and (ii) tritium was found at locations where the dust particles were not recognized in the EPMA image with the resolution of 20 μm. The 61% of the C-dominated and 88% of metal-rich particles did not contain tritium. The presence of particles without the T content are most likely due to debris arising from surfaces remote from the plasma, or strongly heated particles from which fuel is desorbed, either by direct plasma interaction or at the tile surface. Composition analysis also indicates possible contamination of ubiquitous dust from surroundings during maintenance, sample collection and preparation for analysis. It is important to note again that the number of Be-dominated, W-dominated, and metal oxide dust particles retaining tritium was very small. Consequently, more than 85 % of the total dust particles retaining tritium were the C-dominated ones.

4. DISCUSSION

4.1 Tritium retention of dust particles and origin of dust

The amounts of dust particles collected from divertor modules of ILW-1 and ILW-3 were shown in Table 1. The amounts of dust particle of ILW-1 and ILW-3 are over 2 orders of magnitude smaller than that from JET-C. Total tritium amount in dust at JET-C, ILW-1 and ILW-3 are also shown in Table 1. The specific tritium activities for JET-C and ILW were similar, but the total activities were quite different: 270 GBq after JET-C down to 0.2 GBq after ILW-1 and only 0.04 GBq after ILW-3. This difference is a consequence of the much lower quantities of dust generated with a metallic first wall. In addition, it has been clearly shown [5,6] that tritium in the ILW dust samples has been associated with remaining carbon particles, not with beryllium and tungsten.

TABLE 1 Remained tritium in dust particle at JET-C, ILW-1 and ILW-3 as measured by FCM

		Specific tritium activity (MBq/g)	Collected amounts(g)	Total activity of tritium(MBq)
JET-C	Inner divertor	5	110.1	550
	Inner and Outer louvers	2,633	99.4	261,720
	Outer divertor tiles and base carrier	106	51.4	5,448
	Carrier ribs	70	19.3	1,351
	Total		280.2	269,069
ILW-1	Inner Divertor tiles	748	0.27	202.0
	Outer divertor tiles	6	0.77	4.6
	Total		1.04	206.6
ILW-3	Inner Divertor tiles	55	0.50	27.5
	Outer divertor tiles	36	0.36	13.0
	Total		0.86	40.5

Comparing the specific tritium activities in the tiles and dust at ILW, the specific tritium activities in the dusts, Table 1, were 3 to 5 orders of magnitude greater than that in the ILW tiles, Fig. 6. It is difficult to understand that ILW dust with high specific tritium activities could be produced by sputtering or spalling of deposits from the ILW divertor tiles with low specific tritium activities. Therefore, since the dust captured after the ILW operation is mainly composed of carbon and the tritium concentration is the same as that of JET-C [6,18], the dust may originate from the JET-C operation. The amount of dust generated from ILW is smaller than that of JET-C; the amount of non-carbon dust in ILW dust is even smaller, and the amount of tritium present in the non-carbon dust is very small. It is possible that the amount of dust generated in ILW operations is even less than the collected dust amount [6]. By using a metallic wall instead of a carbon wall at JET, the amount of dust generated is drastically reduced, and the amount of tritium captured in the dust is also reduced. Therefore after approximately 62 hours of operation, the JET ITER-Like Wall has demonstrated a reduction in dust generation and has been effective in reducing the activity of tritiated dust in the fusion reactor.

4.2 Difference of poloidal distribution of tritium measured by FCM and TIPT

Figure 10 shows the tritium concentration per unit area (kBq/cm^2) in ILW-1 and ILW-3 tiles as measured by FCM. Figure 10 also shows the PSL intensities ($/cm^2 \cdot h$) of TIPT measurements with β-ray and X-ray. Comparing the TIPT results with the FCM results, the distribution of the tritium amounts measured by the FCM is slightly different from that measured by TIPT. In the β-ray TIPT results, the tritium amount is lower at the outer divertor Tiles 7 and 8 than the inner divertor tiles, in particular Tile 1, and the horizontal Tiles 4 and 6. The difference in the PSL intensities at X-ray TPIP between the inner and outer sides is smaller than that of β-ray TPIP. In the case of the measurement with β-ray TIPT, the amount of tritium in the outer side was shown to be very small, but the measurement with X-rays TIPT showed that tritium exists in the outer side as well as in the inner side. In the FCM results, the specific tritium activities in the inner side are not small, but the specific tritium activities in the outer side is large. The FCM measures tritium amount at 2 mm thickness.

FIG.10. Tritium concentrations as measured by FCM and PSL intensities as measured by TIPT at ILW divertor tiles. No measurement available for ILW-3 sample 6-9 as measured by X-ray TIPT and ILW-1 sample 4-10 as measured by FCM.

Figure 11 shows the particle flux attenuation with distance from the source when β-rays and bremsstrahlung X-rays from tritium penetrate tungsten or carbon, as calculated by Monte Carlo particle transport simulation code “Features of Particle and Heavy Ion Transport Code System (PHITS)” [19]. The horizontal axis of the figure shows the distance from the source of tritium, and the vertical axis shows the relative intensity of the particle flux. As shown in the figure, the range of the β-rays is very short: the range of decrease to 1% in tungsten is 0.17 μm, and even in carbon it is 1.2 μm. The range of bremsstrahlung X-ray of tritium is longer than that of β-rays, and the distance of decay to 1% in tungsten is 2 μm, and even in carbon is 64 μm. TIPT can measure tritium that is present on the surface side from these depths. Table 2 summarizes the attenuation of the particle flux and the transmission distance. TIPT(X) is superior to TIPT(b) for measuring the distribution of tritium produced by the DD reaction when irradiated to the material surface. However, the conversion efficiency from β-rays to bremsstrahlung is only 0.4% by the calclation, so the measurement efficiency of TIPT(X) is not good. The reason for the difference between the tritium distribution measured by FCM and that measured by the TIPT method is that FCM measures tritium concentration at depths ranging from 0.5 to 1 mm, while TIPT measures tritium distribution at depths ranging from a few micrometers to several tens of micrometers, so the difference in tritium distribution in the depth direction.

Torikai et al. measured the tritium depth profiles of JET Mark IIA type divertor tiles by the β-ray-induced X-ray spectrometry (BIXS) [20]. The results show that the distribution of low tritium concentration in the surface layer and high tritium concentration in the bulk. They conclude that the tritium concentration in these surface layers is low and the tritium concentration in the bulk is high due to the formation of a deposition layer on the surface or the desorption of tritium on the surface due to heating after tritium irradiation. TIPT is better for visualization of tritium distribution after irradiation, but measurement of tritium amount in tiles should be done by FCM.

FIG.11. Intensity of particle flux dependent on transmission distance of β-rays and Bremsstrahlung X-rays for tritium in tungsten and carbon calculated *by the Monte Carlo method. (a) in tungsten and (B) in Carbon.*

TABLE 2 Relation between particle transmission distance and transmittance calculated by the Monte Carlo method

Transmission distance from the source where the particle flux decreases to	β-ray in W / μm	Bremsstrahlung X-ray in W / μm	β-ray in C / μm	Bremsstrahlung X-ray in C / μm
50 %	0.0136	0.119	0.0692	1.30
10 %	0.0693	0.433	0.441	9.21

1 %	0.169	1.99	1.23	63.8
0.1 %	0.281	6.04	1.98	-*
0.01 %	0.368	-*	2.60	-*

* On the calculation, data will soon come!

4.3 Total tritium amount is ILW-1 and ILW-3 tiles

Table 3 summarizes the average tritium concentration of the ILW tiles from No. 1 to No. 8, the surface area of each tiles, the amount of tritium calculated from the surface area and tritium concentration of each tiles, the number of each tiles in the vacuum vessel, and the total amount of tritium. In this experiment, the tritium measurement of the tiles with a thickness of about 2 mm from the surface was carried out. The amount of tritium in ILW tiles were about 1 MB in most tiles, and less than 3 MBq at most. From the tritium amount in each tile and the number of each tile in the vacuum vessel, the amount of tritium in the ILW-1 and ILW-3 divertor was calculated to be 713 MBq and 646 MBq, respectively. The generated tritium amounts by DD reactions in ILW-1 and ILW-3 are approximately 15 GBq and 40 GBq, respectively [16]. These amounts were 4.8 % and 1.6 % of the amount of tritium generated in the ILW-1 and ILW-3 operations, respectively. These values are higher than the deuterium retention value of 0.2% of injected deuterium fuel for ILW-1 operating period [14]. However, if an additional off-gassing source of T from DTE1 is taken into account the T retention rate could be lower.

TABLE 3 Total tritium amount in ILW-1 and ILW-3

	Tile Number	Average T conc. (Bq/cm^2)	Surface area (cm^2)	T amount (MBq)	Total number of tiles in vessel (block)	Total T (MBq)	Total T atoms (particle)
ILW-1	1	3,395	270	0.92	96	88	4.94E+16
	3	2,671	540	1.44	48	69	3.88E+16
	4	2,803	320	0.90	96	86	4.83E+16
	6	4,809	340	1.64	96	157	8.81E+16
	7	2,373	640	1.52	48	73	4.09E+16
	8	5,140	350	1.80	96	173	9.69E+16
	Sum			8.22		646	3.62E+17
ILW-3	1	6,549	270	1.77	96	170	9.52E+16
	3	5,008	540	2.70	48	130	7.28E+16
	4	2,381	320	0.76	96	73	4.10E+16
	6	5,355	340	1.82	96	175	9.81E+16
	7	928	640	0.59	48	29	1.60E+16
	8	4,033	350	1.41	96	136	7.60E+16
	Sum			9.06		713	3.99E+17

5. CONCLUSION

Tritium amount in JET dusts and divertor tiles were measured by the TIPT and the enhanced FCM using the heat of high temperature Sn oxidation. It was found that the poloidal distributions of the surface and bulk trapped tritium are quite different. The total tritium activities show significant differences between the JET operation with ILW and the earlier operation with the carbon wall (JET-C) indicating that tritium retention has been drastically decreased in the operation with ILW. The amount of tritium in the dust and tiles was also measured.

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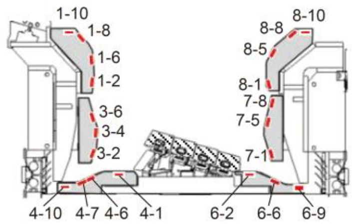

FIG.1. Cross-section of the JET-ILW divertor with marked position of specimen

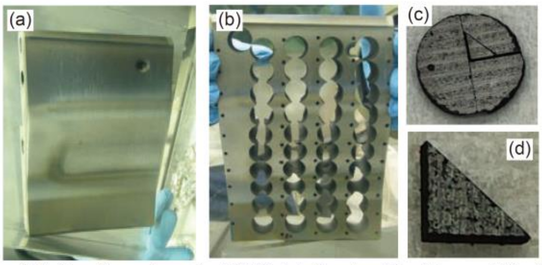

FIG.2. Photos of ILW-1divertor Tile 4 and specimen for FCM: (a) divertor tile, (b) cored tile, (c) cored specimens and (d) cut-out specimen for tritium analysis by FCM.

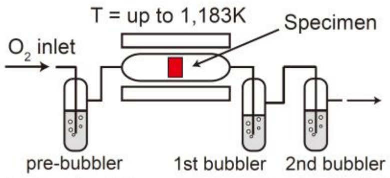

FIG. 3. Experimental set-up for tritium measurement using the full combusiton method.

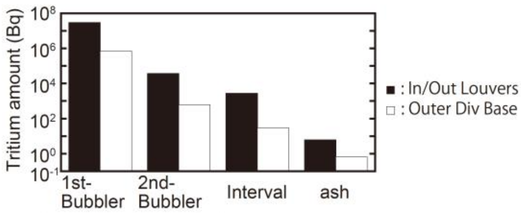

FIG.4. Quantitative measurement of tritium in dusts of In/Out Louvers and Outer Divertor Base at JET-C as measured by full combustion method.

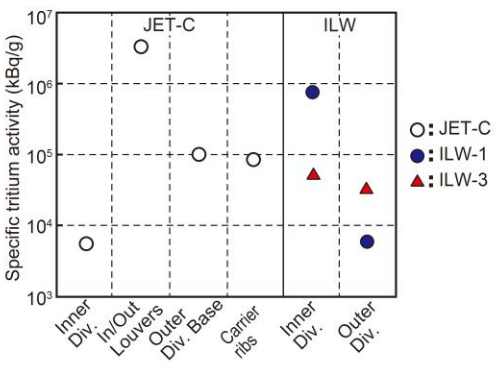

FIG.5. Specific tritium activities in dust particles after operated with JET-C, ILW-1 and ILW-3 as measured by FCM.

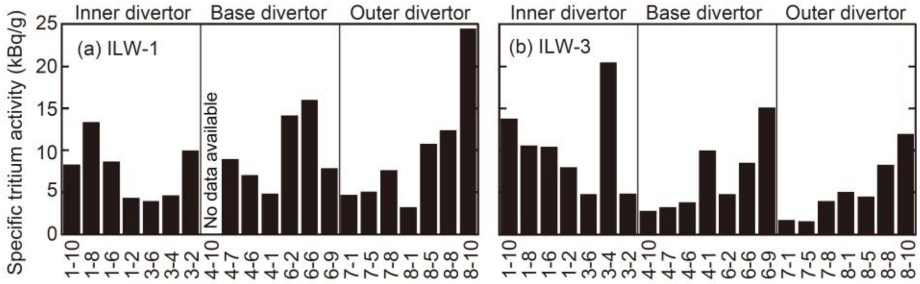

FIG.6. Specific tritium activities in tiles after operated with ILW-1 and ILW-3 as measured by FCM. No measurement available for ILW-1 sample 4-10.

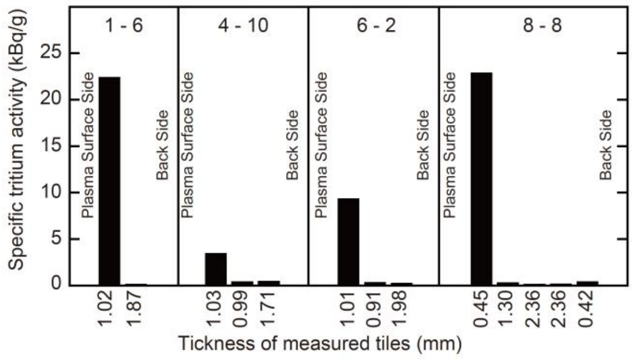

FIG.7. Depth profile of specific tritium activities in tiles after operated with ILW-3 as measured by FCM.

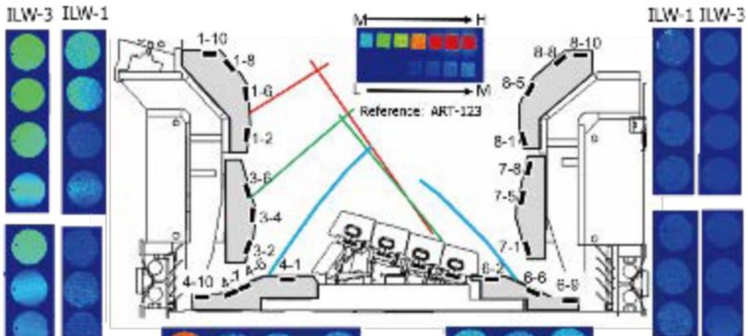

FIG.8. Imaging plate results of cored samples in ILW-1 and ILW-3, and tritium reference sample. Positions of cored samples are shown in a poloidal cross-section in which left-hand side is the torus inboard side. Coloured lines show the positions of the separatrix in three typical configurations, ILW-1 predominantly green, ILW- 2 and 3 green and predominantly blue.

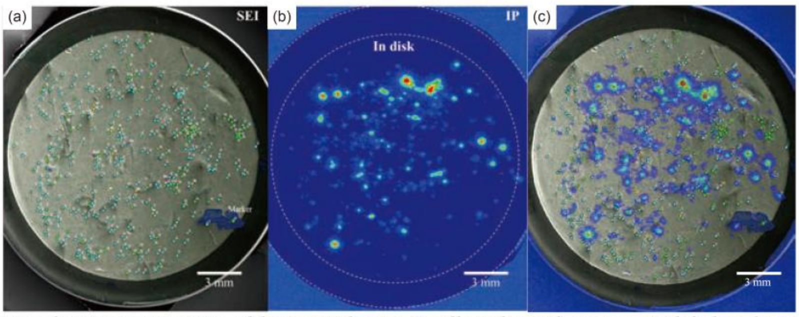

FIG. 9. EPMA image showing composition of dust particles (a). Small circles with superscript labels indicate the location and composition (C, O, Be and W) of dust particles. IP image showing tritium distribution on the indium disk (b) and super-imposed image of (a) with (b) - (c).

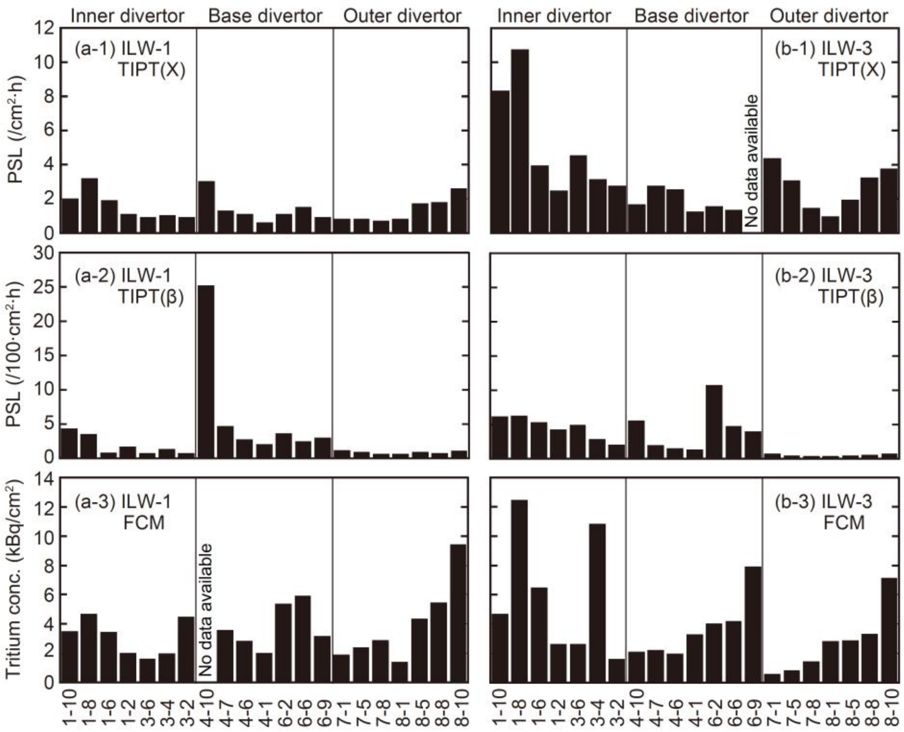

FIG.10. Tritium concentrations as measured by FCM and PSL intensities as measured by TIPT at ILW divertor tiles. No measurement available for ILW-3 sample 6-9 as measured by X-ray TIPT and ILW-1 sample 4-10 as measured by FCM.

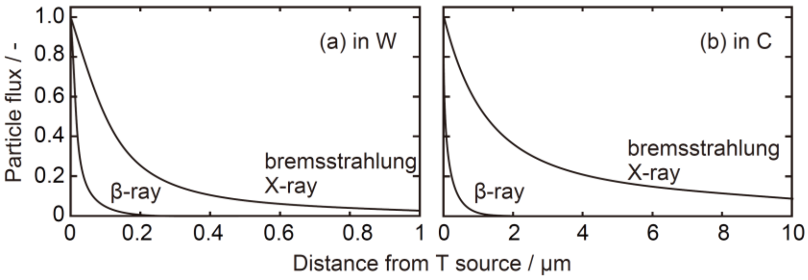

FIG.11. Intensity of particle flux dependent on transmission distance of β-rays and Bremsstrahlung X-rays for tritium in tungsten and carbon calculated by the Monte Carlo method. (a) in tungsten and (b) in Carbon.