EFDA–JET–CP(14)01/19

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** See annex of F. Romanelli et al, "Overview of JET Results", (24th IAEA Fusion Energy Conference, San Diego, USA (2012)).*

Preprint of Paper to be submitted for publication in Proceedings of the
21st International Conference on Plasma Surface Interactions, Kanazawa, Japan
26th May 2014 - 30th May 2014

ABSTRACT

Post-mortem measurements of 2-dimensional tritium (T) distribution using an imaging plate (IP) technique were performed for tungsten (W) divertor tiles (W-coated CFC) used in JETITER like wall (ILW) project. The observed T distributions were clearly inhomogeneous, and there were band-like regions with high T concentrations extended in the toroidal direction on tiles 1, 3, 4 and 6 including shadowed regions. The concentrations of T in the band-like regions were higher by an order of magnitude than the concentrations in other parts. The inhomogeneous T distributions were explained by non-uniform co-deposition with beryllium. Tritium was also detected at the edges of tiles. The concentrations of T on the outboard vertical tiles (tiles 7 and 8) were low and relatively uniform in comparison with other tiles.

1. INTRODUCTION

ITER will use tungsten (W) as a divertor material and beryllium (Be) as a main-chamber wall material in D-T operation phase because the usage of carbon (C) as a plasma-facing material is expected to result in an unacceptable level of in-vessel tritium (T) retention. To test the combination of these reference materials in a tokamak environment, ITER-like wall (ILW) project has been performed in JET [1-6]. Some of the W and Be tiles were extracted from the vacuum chamber after the first ILW experimental campaign in 2011–2012. In this study, 2-dimensional T distributions on W divertor tiles were examined using an imaging plate (IP) technique.

Imaging plates are simple and reusable radiation sensors that provide a 2-dimensional image of radiation intensity. This type of technique was applied to the T analysis for C tiles used in JET by Tanabe et al. [7-10]. However, T distributions on W divertor tiles used with Be wall tiles have not been examined. This paper gives the first report on T distribution images on the W divertor tiles used in the JET-ILW project. It should be noted that T detected in this study was one produced by DD fusion reactions and/or that remaining in the vacuum vessel since previous DT experimental campaigns with C walls. Tritium was, therefore, present as a minor isotope of hydrogen in the vessel.

2. EXPERIMENTAL PROCEDURES

The tiles analyzed were tiles 0 (HFGC), 1 (14ING1C), 3 (14ING3B), 4 (2BNG4C), 6 (2BNG6C), 7 (2ONG7A) and 8 (2ONG8B) used in the 2011–2012 JET-ILW experimental campaign. These were CFC tiles covered by W using combined magnetron sputtering and ion implantation (CMSII) [11]. The IPs used were BAS IP TR purchased from GE Healthcare Japan. This type of IP is sensitive to low energy β-rays from T (≤18.6 keV) because the phosphor layer does not have a protection coating on it. After they were cut into appropriate sizes to fit the tile surfaces, the IPs were wrapped in 1.2 or 2μm-thick polyphenylene sulphide (PPS) films to avoid contamination with T and Be. The IPs were then put on the tiles in the dark for 15–21 hours to expose IPs to β-rays from T. The intensity of the β-rays is attenuated by the PPS films to about 1/10 (1.2μm) and 1/45 (2μm). The exposures for tiles 1, 3, 7 and 8 occurred at the VTT Technical Research Center of Finland, and those for tiles 0 and 4 at the Culham Science Centre. After removing the PPS films, the 2-dimensional intensity distribution of the photo-stimulated luminescence (PSL), which is proportional to the fluence of β-rays [12], was analyzed using a laser scanner at the University of Helsinki (FLA-5100, Fujifilm) and at University of Oxford (Typhoon 9000, GE Healthcare). To examine the background radiation, similar exposures and analyses were performed with IPs wrapped in 6μm-thick polyethylene (PE) films to attenuate β-rays from T almost completely (~1/1000). A set of plastic samples labelled with known amounts of T (ART-123A, American Radiolabeled Chemicals, USA) was used as a reference for quantitative analysis.

3. RESULTS AND DISCUSSION

IPs exposed to the background radiation with 6μm-thick PE films showed uniform distributions of PSL intensity. In contrast, the exposure to β-rays with thin PPS films (1.2 or 2μm) resulted in inhomogeneous distributions. Figure 1 shows a photo of tile 6 (a) together with the 2-dimensional distribution (b) and line profile (c) of PSL intensity, as typical examples. The 2-D image (Fig.1(b)) was prepared using a linear scale mode of the Multi Gauge software (Fujifilm Co., Japan) and the colors indicate the intensity of PSL in descending order from red (highest), yellow, green and blue (lowest). The line profile given in (c) was taken along the dashed line shown in (b). There were several band-like regions with high PSL intensity (red and yellow colors) that extended in the toroidal directions. Interestingly, the location of these band-like regions corresponded to the areas with visually recognizable dark contrasts in Fig.1 (a), but not all of those regions showed a high PSL intensity. The line profile showed that the PSL intensities in the band-like regions were higher by an order of magnitude than other parts. According to the results of nuclear reaction analysis (NRA) and secondary ion mass spectrometry (SIMS) reported in [5,6], the surface of tile 6 (and that of tile 4) was covered with deposited Be, and its thickness reached to $\sim 5\times 10^{18}$ Be atoms cm−2 (~400nm for pure Be). Co-deposition of D and Be was also observed in [5,6], as shown in Fig. 2 in [6]. Therefore, it is appropriate to consider that areas with dark contrasts in Fig.1 (a) and high PSL intensity in (b) are the regions with thick D,T-Be codeposited layers.

Figure 2 shows 2-D images of PSL intensity for tiles 0–4 and 6–8 together with a photo of tile 0 and the section of the JET divertor with the tile number and the plasma configuration used predominantly during the 2011–2012 ILW operations. The numbers in the 2-D images correspond to those of the tiles, and the lowercase alphabetical letters indicate the faces of the tiles. Holes in faces a–d are due to cutting of core samples for different analyses. The IP covered roughly 1/3 of face f on tile 4 along the poloidal direction. Scales for size reduction are different from tile to tile because of the different sizes of the tiles. Circles indicated by A and B are the areas selected for quantitative analysis described below. The scale for color indication for tiles 0 and 4 differs from those for other tiles because a different laser scanner was used for analysis. The band-like regions with high PSL intensity extended in the toroidal direction were observed on tile 6 and on tiles 1, 3 and 4. The areas with high PSL intensity on tile 0 also corresponded to the region with a dark contrast. In the case of tile 1, the highest PSL intensity was observed at the apron (the flat part at the top of the tile). On tiles 4 and 6, the intensity of PSL was higher at the regions shadowed by tiles 3 and 7 than the flat parts of plasma-facing surfaces. The PSL intensity for outboard vertical tiles, i.e. tiles 7 and 8, was significantly lower than those for other tiles. Tritium was also detected at the edges of the tiles (faces e, i and j).

Quantitative analysis was performed by taking into account the escape depth of β-rays from T for the high PSL intensity regions on tiles 1 and 6 indicated by circles A and B in Fig.2. The PSL intensities in regions A and B were 25,000 and 14,000 PSL cm^{-2}, respectively. In this analysis, T was assumed to be trapped in the D,T-Be co-deposited layer. The intensity of PSL (PSL cm^{-2}) is expressed by the following equation:

$$I_{\mathrm{PSL}} = Et \int_0^d C(x) \exp(-\mu_{\mathrm{Be}} x) \exp(-\mu_{\mathrm{PPS}} L)\, dx \quad (1)$$

where E is a dimensionless factor determined by the detection efficiency of the IP, geometrical configurations (for example, roughly a half of β-rays are emitted in the direction to IP in the case of a flat sample) and other conditions; t is the exposure time (s); d is the thickness of co-deposited layer (cm); C(x) is the volume concentration of T in the co-deposited layer (Bq cm^{-3}) and L is the thickness of the PPS film (cm); μ_{Be} and μ_{PPS} are the apparent absorption coefficients (cm^{-1}) of the co-deposited layer and the PPS film, respectively. The absorption coefficient μ_{Be} was calculated from the density of pure Be and the range of β-rays recommended by Katz and Penfold [13]. The attenuation factor k in Eq. (17) in [13] was set to 10^{-3}. The value of μ_{PPS} was experimentally evaluated with the standard plastic samples labelled with T. The thickness of the co-deposited layer in region B was assumed to be 400 nm because of the NRA result reported in [5], as mentioned above. In the case of region A, the thickness of the co-deposited layer was assumed to be sufficiently larger than the escape depth of β-rays (~3μm in Be) because the thickness at the apron of tile 1 was reported to be ~9×10^{19} Be atoms cm^{-2} (~7μm for pure Be) in [5]. For simplicity, the depth profiles of T were assumed to be uniform throughout the thickness of the co-deposited layer. The comparison of the I_{PSL} for regions A and B with that of the standard samples and the evaluation under the above-mentioned assumptions showed that the T concentration in the co-deposited layer was ~10^{-20} MBq cm^{-3} for both regions A and B. This value of T concentration corresponds to ~5–10×10^{15} T atoms cm^{-3} or [T]/[Be] = ~5–10×10^{-8}. The D concentration in the co-deposited layer formed on tile 1 was reported to be ~10% of Be concentration [5,6]. The fraction of T to D was calculated to be [T]/[D] = ~5–10×10^{-7}. The concentration of T was significantly smaller than that of D, as expected. The coincidence in the volume concentration of T on tiles 1 and 6 indicates that the difference in the PSL intensity from region to region shown in Figs.1 and 2 is mainly caused by the difference in the thickness of the co-deposited layer. The areal concentration of T is given as a product of volume concentration and thickness of the co-deposited layer, and it is ~1–2 kBq cm^{-2} or ~5–10×10^{11} T atoms cm^{-2} if the thickness of the co-deposited layer is ~1μm. Note that IPSL increases with increase in the thickness of the co-deposited layer up to the escape depth of β-rays (~3μm, as mentioned above) and becomes independent if the thickness exceeds the escape depth. The co-deposited layers contain not only hydrogen isotopes but also C, N and O [14]. Careful comparison of T profiles with those of C, N and O is necessary to understand the influence of these impurities on T retention.

Tanabe et al. examined T distributions on C tiles extracted from a Mark II Septum Replacement Plate (Mk II SRP) divertor used during the 2001–2004 operational period of JET (see Fig.1 in [10]). As observed in this study, the T concentrations on the outboard vertical tiles (tiles 7 and 8) were lower than those on other tiles. They also reported that the shadowed regions on tiles 4 and 6 showed higher T concentrations than the plasma-facing surfaces of the tiles [10]. However, in their case, the T concentration on tile 1 was not necessarily high in comparison with other tiles, whereas the highest PSL intensity was observed in this study. In the 2001–2004 operational period, not only the tile material but also the magnetic configuration in the divertor region were different from that in the 2011–2012 experimental campaign. The strike points were mainly located on tiles 4 and 6 in 2001–2004, whereas they were predominantly on tiles 3 and 5 in 2011–2012, as shown in Fig.2. Operation with C tiles under the current Mk II High Delta divertor configuration was performed in JET in 2005–2009 [15]. The influence of material difference (C versus W & Be) on T retention can be directly evaluated by measuring T distributions on C tiles used in 2005–2009 experimental campaign and comparing the results with those obtained in this study. According to Brezinsek et al. [16], a global gas balance showed that the long-term D retention with ILW was lower than that with C walls by more than a factor of 10. The comparison of T distributions on the ILW tiles with that on the C tiles will provide important information on the mechanisms underlying the reduced long-term D retention with the ILW.

CONCLUSIONS

Tritium distributions on W-coated CFC tiles used in JET in the 2011–2012 ILW experimental campaign were clearly inhomogeneous. The band-like regions with high T areal concentrations extended in a toroidal direction were observed on tiles 1, 3, 4 and 6. The T areal concentrations in the band-like regions were higher by an order of magnitude than the concentrations in other parts of the tiles. The location of the band-like regions corresponded to the areas covered by dark films, and, therefore, the formation of the band-like regions was explained by the formation of thick co-deposited layers of D,T with Be. The volume concentrations of T in the co-deposited layers, which were evaluated on the several assumptions for the selected areas on tiles 1 and 6, were comparable with each other. It appeared that inhomogeneous T areal concentrations were mainly due to variation in the thickness of the codeposited layer. The T areal concentrations on outboard vertical tiles (tiles 7 and 8) were low and uniform in comparison with those on other tiles.

ACKNOWLEDGEMENTS

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was also supported by JSPS KAKENHI Grant Number 26289353, the Japan Atomic Energy Agency under the Joint Work contract 26K140325, as a part of Broader Approach activities, and the National Institute for Fusion Research as a part of

TEXTOR Collaboration. The authors would like to express their sincere thanks to Dr Margarida Ruas (University of Oxford) for the use of the image scanner, and to Professors Y. Nakamura and S. Masuzaki (the National Institute for Fusion Science), Dr. N. Asakura (the Japan Atomic Energy Agency) and Dr. P. Coad (Association EURATOM-Tekes) for their kind advice and encouragement.

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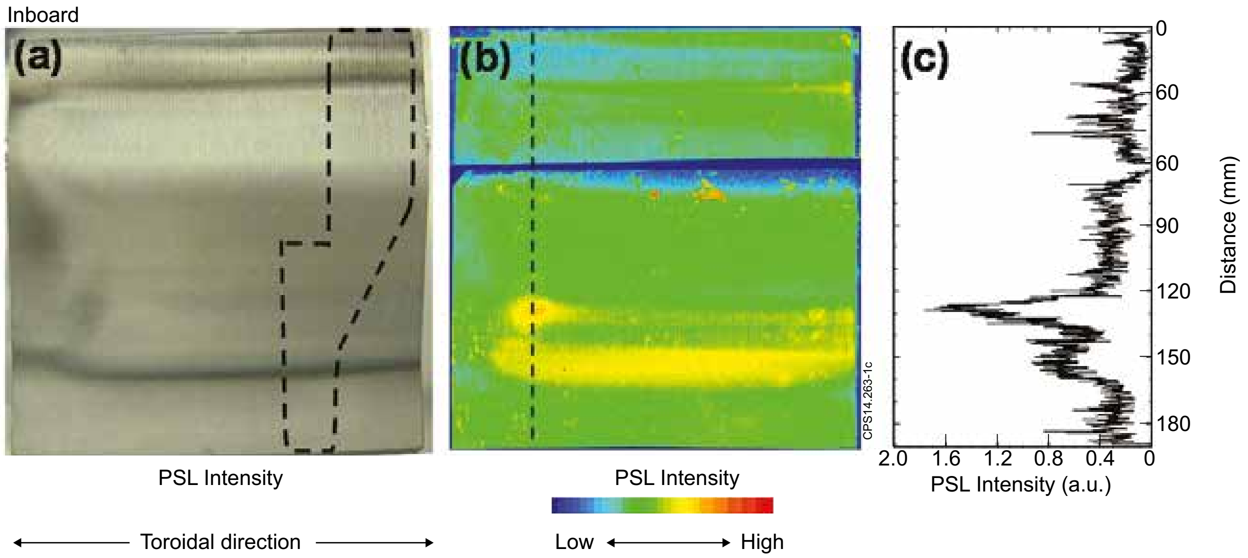

Figure 1: Photo (a), 2-D image (b) and line profile (c) of the PSL intensity of tile 6 (2BNG6C). Dashed line in (a) shows cross-section of the tile. The line profile was taken along the dashed line shown in (b). The upper and lower sides of this figure correspond to the inboard and outboard sides in JET, respectively. Colors in (b) indicate the intensity of PSL in descending order from red (highest), yellow, green and blue (lowest).

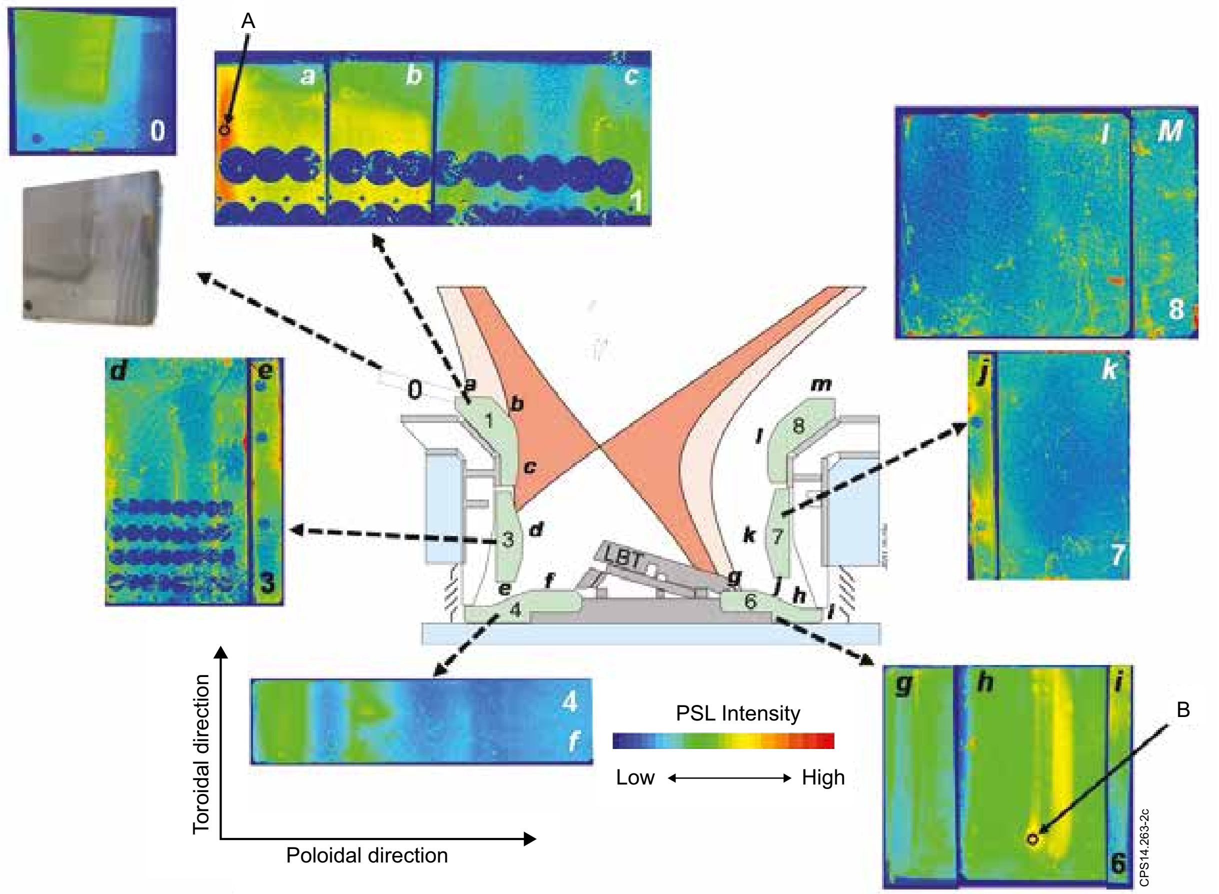

Figure 2: 2-D images of PSL intensity for tiles 0–4 and 6–8 together with a photo of tile 0 and section of the JET divertor region. Numbers in the 2-D images correspond to those of tiles, and the lowercase alphabetical letters indicate the faces of the tiles. Holes in faces a–d are due to core sample cutting for different analyses. IP covered roughly 1/3 of face f of tile 4 along the poloidal direction. Scales for size reduction are different from tile to tile because of the different sizes of the tiles. Circles indicated by A and B are the areas selected for quantitative analysis. The scale for color indication for tiles 0 and 4 differs from that for other tiles because a different laser scanner was used for analysis.