

Tritium distribution in JET Mark IIA type divertor tiles analysed by BIXS

Y. Torikai ^{a,*}, M. Matsuyama ^a, N. Bekris ^b, M. Glugla ^b, P. Coad ^c,
W. Naegele ^d, A. Erbe ^d, N. Noda ^e, V. Philipps ^f, K. Watanabe ^a

^a Hydrogen Isotope Research Center, Toyama University, Gofuku 3190, Toyama 930-8555, Japan

^b EURATOM Association, Forschungszentrum Karlsruhe, Tritium Laboratory, D-76021 Karlsruhe, Germany

^c EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OXON OX14 3DB, UK

^d EURATOM Association, Forschungszentrum Karlsruhe, Institute for Material Research II, D-76021 Karlsruhe, Germany

^e National Institute for Fusion Science, Oroshi-cho, Toki-shi, Gifu 509-5292, Japan

^f EURATOM Association, Forschungszentrum Jülich, Institute for Plasma Physics, TEC, 52425 Jülich, Germany

Abstract

Distribution of tritium concentrations on the surface and in the bulk (up to 1 mm in depth) in a complete poloidal set of divertor tiles exposed to D–T plasma shots in JET was measured by β -ray-induced X-ray spectrometry (BIXS). The observed X-ray spectra showed that tritium distribution was different not only from tile to tile but also highly non-uniform in each individual tile. The peaks of bulk tritium concentration obtained by BIXS are correlated with the corresponding one obtained previously by other methods. For the first time, tritium depth profiles in the plasma-facing surface of complete divertor tiles were obtained by BIXS and they can be classified by four types of a tritium depth profile.

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PACS: 81.05.T

Keywords: Divertor; JET; Tritium

1. Introduction

During the operation of fusion machines with D–T plasma, tritium is accumulated in plasma-facing components (PFCs). To improve the understanding of tritium accumulation in PFCs under plasma–wall interactions, various techniques were used to measure the tritium inventory and distribution in these components. For

example, a ‘coring’/full combustion method [1], β -ray-induced X-ray spectrometry (BIXS) [2], a nuclear reaction analysis [3], an β -ray analysis by pin diode [4], an accelerator mass spectrometry [5,6], an imaging method [7], and so on were used for this purpose. In those method, ‘coring’/full combustion method was used by Penzhorn et al. to determine tritium depth profiles. The results revealed that much tritium was concentrated in the co-deposition layers on tiles and a large fraction up to 61% of tritium migrated into the bulk of the tiles [8]. Though quantitative data are obtained by full combustion the method has two main drawbacks. Firstly, it

* Corresponding author. Tel.: +81 76 445 6932; fax: +81 76 445 6931.

E-mail address: torikai@hrc.toyama-u.ac.jp (Y. Torikai).

requires a complete destruction of the analysed sample. Secondly, it can be only used *ex situ*.

Recently, Matsuyama et al. [2,9,10] have proposed a new tritium measuring method, which is based on measurements of X-rays produced by the interactions between β -rays and constituent atoms. This is named β -ray-induced X-ray spectrometry (BIXS). BIXS can non-destructively determine the amounts of tritium on the surface and in the bulk, and the depth profiles of the tritium in bulk. The BIXS offers the opportunity of non-destructive measurements. The BIXS determine surface and bulk tritium amount and its distribution. In a previous study [11], coring samples of JET divertor tiles were measured by BIXS and obtained spots data of tritium inventory and surface contamination by metals. In this paper, a complete poloidal set of 10 divertor tiles (Mark IIA configuration) retrieved from JET after the first Deuterium–Tritium Experimental campaign (DTE1) [12,13] was analysed using BIXS. We report the results of BIXS measurement of tritium distribution in the divertor tiles. The results give the tritium distribution on the surface and in the bulk of each tile. Tritium distributions in the poloidal direction are measured for three toroidal coordinates on the tile. Additionally tritium depth profiles are discussed.

2. Experimental

2.1. Specimens

A complete poloidal set of 10 divertor tiles numbered from IN1 to ON10 was investigated by BIXS. The size of the smallest tile was $285 \times 105 \text{ mm}^2$ and that of the largest one was $379 \times 129 \text{ mm}^2$. The previous study showed that a large amount of tritium was trapped in the co-deposition areas on the tiles IN3, BN4 and BN7 [1], while small amount of tritium was found in the erosion areas of the same tiles. Fig. 1 shows a schematic view (A) of the JET divertor tiles and a photo (B) of the inner base divertor tile BN4 as an example. This tile contained both the eroded and co-deposited areas. Nine

spots numbered, from 'a' to 'i', which are shown in Fig. 1(B) as an example, were measured for each divertor tile.

2.2. Measurements by BIXS

X-ray spectra from the tiles were measured at Tritium Laboratory of Forschungszentrum Karlsruhe (TLK) by using a portable germanium X-ray detector. The details of the measurements and analysis of an X-ray spectrum have been already reported [2]. The BIXS measurements were carried out in a glove box located at the TLK, since all the tiles were highly tritiated. The X-ray detector was attached through a glove hole in the glove box. To estimate tritium amount on the surface, BIXS measurements were performed in an argon atmosphere. For this purpose, a specially designed adapter for argon supply was attached to the top of the X-ray detector. Fig. 2 shows the schematic view (A) of the X-ray detector and the photo (B) of the argon gas supply adapter. The tile was close to the head of the adapter for all the measurements. The flow rate of argon was controlled at about $1000 \text{ cm}^3 \text{ min}^{-1}$ during the measurements. The X-rays from the tiles were measured for at least 15 min per one spot.

3. Results and discussions

3.1. Tritium distribution in the poloidal and toroidal directions

Fig. 3 shows an example of the X-ray spectra observed for the tile numbered IN1. Six major X-ray peaks were observed. Five sharp peaks of 1.03 keV, 2.96 keV, 5.38 keV, 6.37 keV, and 7.48 keV were assigned to characteristic X-rays of Na(K α), Ar(K α), Cr(K α), Fe(K α), and Ni(K α), while the broad peak was the bremsstrahlung X-rays. The intensity of Ar(K α) informs about the amount of surface tritium in the range of up to about $0.5 \mu\text{m}$ beneath the surface and that of the bremsstrahlung X-rays gives the bulk tritium concentration in the depth range of up to about 1 mm. The peaks of Cr(K α),

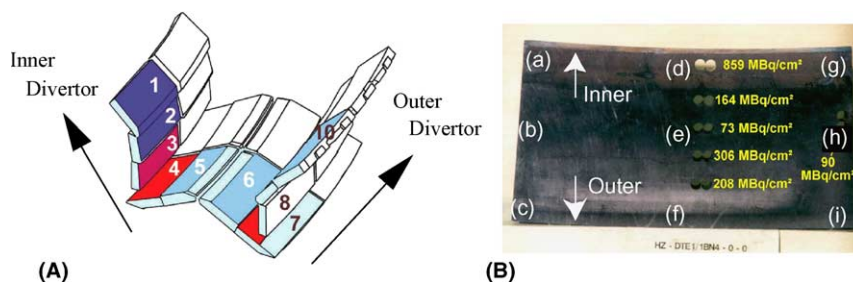


Fig. 1. Schematic view of the JET divertor tiles (A) and photo of the BN4 tile (B). Points of (a)–(i) in photo (B) are the measurement spots by BIXS.

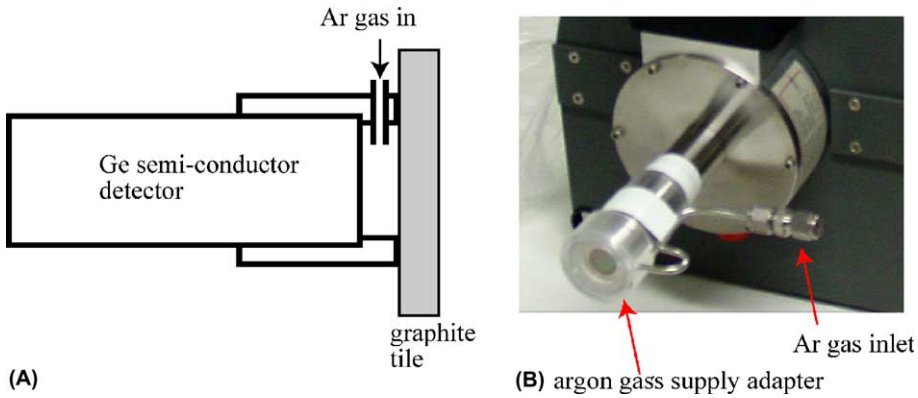


Fig. 2. Schematic view (A) and photo (B) of Ge semi-conductor detector.

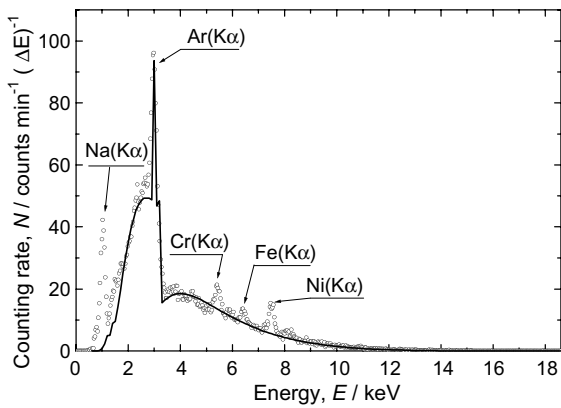


Fig. 3. Example of the X-ray spectra observed for IN1: open circles and the solid line represent the observed and simulation spectra, respectively.

Fe(K α), and Ni(K α) X-ray are due to deposition of stainless steel components sputtered from other parts of the tokamak.

Fig. 4 shows the result of BIXS measurements for a series of the central spots from IN1 to ON10 tiles. This figure gives information about the tritium distribution in poloidal direction from the inner to the outer part of the divertor. Fig. 4(A) and (B) show the characteristic and bremsstrahlung X-ray intensities, respectively. Fig. 4(C) shows the tritium amount within the layers of 1 mm beneath the surface measured by the combustion method [1].

The advantage of the BIXS method is that it gives an opportunity of distinction between tritium in a thin (0.5 μm) near-surface layer (co-deposited layer, for example) and tritium in the bulk of the tile (up to 1000 μm). Fig. 4 demonstrates that the tritium distribution in poloidal direction is highly non-uniform. The important observation is that the profiles of the surface and the bulk concentrations mainly correlate. At least

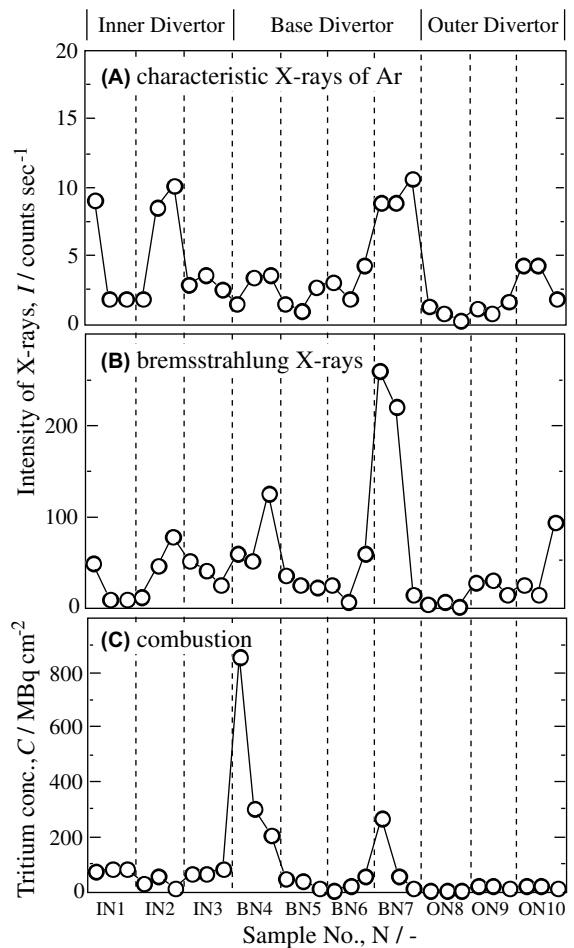


Fig. 4. Comparison between X-ray intensities and the full combustion method.

the position of the peaks can be correlated. At the same time there are differences in some details, for example,

the ratio of the surface/bulk concentrations is not constant.

From comparison of results obtained from bremsstrahlung X-ray intensity and combustion method, two intense peaks appeared in the almost same spots (tiles BN4 and BN7), indicating that BIXS method is able to evaluate the amount of tritium retained in a deep region. Amplitude of the peaks and some other details were different. This can be due to very high non-uniformity of tritium content on the tile surface, such as the results in two spots close to each other can be different.

Poloidal measurements were made also in two other toroidal coordinates on the 10-tiles band through the edge dots 'a, b, c' (see Fig. 1), called 'left' and dots 'g, h, i' called 'right'. The results are shown in Fig. 5. Fig. 5 is 'a map' of tritium distribution over the surface of 10 tiles. One can see that the concentrations both in the near-surface layer and in the bulk are highly non-uniform in the toroidal as well as poloidal directions. The maximum Ar(K) intensity (BN6 point 'c') are about 120 times higher than the minimum intensity (ON8 point 'h'), similarly, the maximum bremsstrahlung X-ray intensity (BN6 point 'c') was about 350 times higher than that of minimum value (ON8 point 'f').

3.2. Tritium depth profiles

The depth profiles of tritium were obtained from analyzing of the X-ray spectra by computer simulation. For this purpose, simulation spectra were determined using various promising profiles and compared with the observed spectra. The best fit gives the tritium depth

profile. An example of such a comparison is given in Fig. 3. At least four types of the depth profile were obtained by BIXS analysis over the divertor surface. Fig. 6 shows, as an example, four depth profiles from 'A' to 'D', which are obtained from the tiles IN1 (spot 'i'), IN3 (spot 'g'), BN6 (spot 'c') and BN7 (spot 'a').

One can roughly classify the depth profiles into two classes. The first one corresponds to a type of the profile 'A', where tritium is retained in a near-surface region with an approximately uniform concentration. Such depth profile appeared in the inner tiles IN1 and IN2. These tiles have neither serious deposition nor serious erosion because the magnetic lines guided plasma towards internal part of the divertor and it went past these tiles. The thickness of the tritium containing layers in these tiles varied from 15–30 μm in IN1 to 25–30 μm in IN2.

Three profiles in Fig. 6, namely 'B', 'C' and 'D' are characterized by a distribution of the concentration over the depth. The profile 'B' has the maximum concentration on the surface. This indicates that a diffusion of tritium from the surface into bulk took place. This type of the profiles was observed mainly in tiles IN3 and BN4. These tiles (as well as BN7) are heavily loaded by plasma particles and seems accept the main power coming to the divertor. It is suggested that the concentration 'tail' in the depth profile is due to thermal diffusion of tritium at the elevated temperatures by plasma impact. The range of high tritium concentration in the bulk varied from 20–40 μm for IN3 to 30–100 μm for BN4.

The depth profiles of 'C' and 'D' have the maximum concentration in the depth. They are typical for the tiles

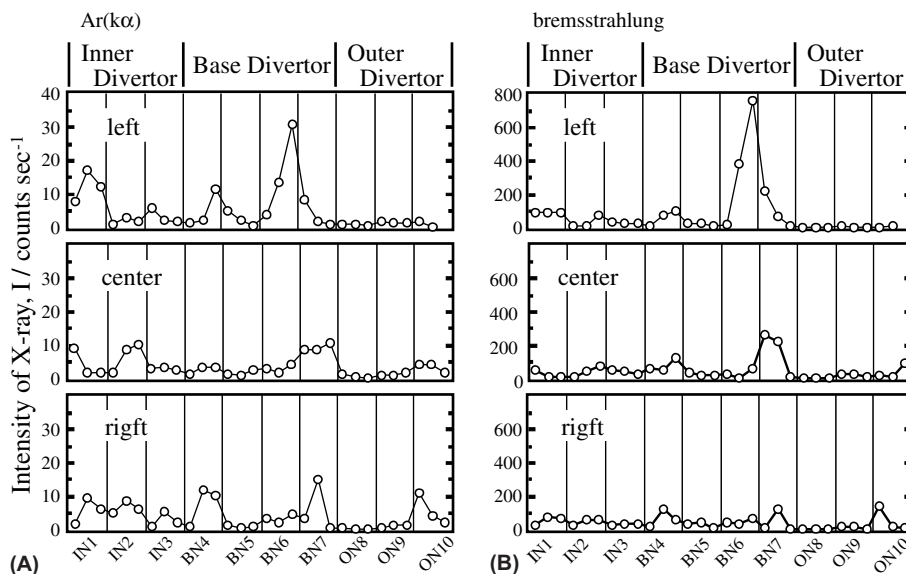


Fig. 5. Intensities of Ar(K α) and bremsstrahlung X-rays measured by BIXS in the poloidal direction.

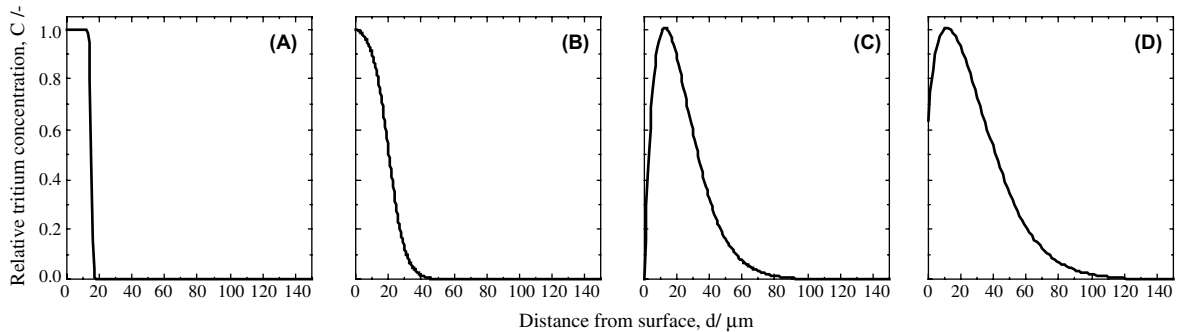


Fig. 6. Tritium depth profiles determined by computer simulation. Depth profiles of (A), (B), (C) and (D) are obtained from the tiles IN1 (spot 'i'), BN3 (spot 'g'), BN6 (spot 'c') and BN7 (spot 'a'), respectively.

(BN5, BN6) and BN7, respectively. The range of high tritium concentration varied from 40 μm for BN6 to 120 μm for BN7.

There are many factors that influence a tritium depth profile and the amount of tritium. Tritium can be co-deposited in the co-deposition layers on the surface, and this depends on the rate of co-deposition, rate of erosion, flux of tritium particles, power loads and so on. Tritium can be implanted from plasma to the co-deposition, and this depends on the plasma flux, tritium ion energy, tile temperature, and properties of the tile in the near-surface region. Tritium can desorb from the surface and at the same time migrate into the bulk. The competition between these two processes determines the accumulation and the depth profile. Particularly, increase of temperature may, in principle, cause both to adsorb on the surface and desorb from surface of the tritium accumulation.

4. Conclusions

Tritium distribution and depth profiles in a complete poloidal set of 10 divertor tiles retrieved from JET after DTE1 were systematically examined by β -ray-induced X-ray spectrometry (BIXS). As a result, main results obtained in the present study are as follows:

- (1) Tritium distribution in the near-surface layers and the bulk, which were evaluated from the intensities of $\text{Ar}(K\alpha)$ and bremsstrahlung X-rays, was highly non-uniform even in one tile. Such non-uniform tritium distributions were also obtained in the poloidal and toroidal direction. Intense peaks for both

X-rays were observed for BN4 and BN7 tiles, and this agrees with the result obtained by full combustion method. In addition, this highest intensity appeared in BN6 tile, which was newly found in the present method.

- (2) Tritium depth profiles for all the observed X-ray spectra were estimated by a numerical calculation. Although the depth profiles were different from spot to spot, it was seen that shape of all the depth profiles could be divided at least into four types. Formations of four depth profiles were correlated with the cooperative effects of deposition, erosion, temperature, tritium flux, and so on.

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