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論　文

β線誘起X線計測法およびモンテカルロシミュレーションによる大型ヘリカル装置LHDで使用された黒鉛タイル中のトリチウム深さ方向分布の非破壊測定

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Non-destructive depth profiling of tritium in graphite tiles from Large Helical Device using β-ray induced X-ray spectrometry and Monte Carlo simulation

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Abstract

A special experimental setup was designed and constructed to perform simultaneous multipoint measurements of β-ray induced X-ray spectra for non-destructive depth profiling of tritium in plasma-facing tiles retrieved from fusion devices. The setup consists of compact silicon drift detector and an airtight acrylic chamber. The plasma-facing graphite tiles used in the deuterium experiment of Large Helical Device (LHD) in National Institute for Fusion Science (NIFS) were examined. The obtained X-ray spectra were simulated using Monte Carlo simulation tool kit Geant4. It has been found that tritium penetrated beyond the carbon deposition layer.

1. Introduction

Accurate evaluation of tritium (T) retention in plasma-facing materials (PFMs) of fusion reactors is required for evaluation of T inventory in a vacuum system, and safe and economical disposal of PFMs after services in reactors. However, the escape depth of β - rays emitted by T is small (several μm or less) due to low kinetic energy (≤18.6 keV), and hence measurement of T retention in the bulk of materials is difficult. To solve this problem, β-ray induced X-ray spectrometry (BIXS) was developed [1,2]; far larger escape depths of X-rays than β-rays allow to get the information about T located in deeper region by detecting bremsstrahlung and characteristic X-rays induced by β-rays. Analysis of X-ray spectra by taking account of generation and attenuation of X-rays in materials provides a depth profile of T non-destructively.

Tritium distributions in plasma-facing tiles in fusion devices are strongly inhomogeneous, and the variation of the T concentration can be significant even in a single tile [3,4]. Therefore, it is preferable to perform simultaneous measurements of several different points even for a single tile because BIXS analysis takes relatively long time (e.g., several days) in most cases. However, simultaneous multipoint analyses are difficult with a germanium (Ge) detector commonly used for BIXS analysis. This is because Ge detector must be cooled to liquid nitrogen temperature during measurements to minimize noise and the size of liquid nitrogen tank is larger than that of the tiles.

In this study, a special setup for multipoint analyses was constructed using a compact silicon drift detector (SDD) cooled by a Peltier element. The main component of the setup is an airtight acrylic chamber capable of accommodating a whole plasma-facing tile and installation of three SDDs. By using this set up, the plasma-facing graphite tiles used in deuterium (D) experiment of Large Helical Device (LHD) [5,6] in National Institute for Fusion Science (NIFS) were examined. The obtained spectra were compared with the results of simulation using Monte Carlo simulation tool kit Geant4 [7-9] for evaluation of depth profile of T.

2. Experimental procedures

Two graphite tiles, 9RD16-1 and 9RD16-2, retrieved from LHD divertor [10] after the 1st deuterium experimental campaign were analyzed. These tiles were from the inner side divertor at the center level. The position of sample tiles can be seen in Fig. 1. LHD is heliotron-type plasma machine and, because of its superconducting coils in heliotron configuration, LHD has an advantage of steady-state plasma operation [5,6]. The divertor tiles of LHD are composed of isotropic graphite (IG-430U, Toyo Tanso Co., Japan), while the inner surface of vacuum chamber is covered by type 316 stainless steel. Because these tiles were used in the D experiment, they were exposed to a small amount of T produced by DD fusion reactions: ${}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{1}T + {}^{1}_{1}H + 1.01$ MeV.

The detector used was the SDD with 8 μm (0.3 mil) thick Be window (X-123SDD, AMPTEK Inc., USA [11]). This detector is cooled by Peltier element installed in the casing, and no coolant tank is necessary.

Fig.1 Photo of inner divertor region of Large Helical Device (LHD) in National Institute of Fusion Science (NIFS). The circled tiles are those analyzed in this study; the tile in right side is 9RD16-1, and one in left side is 9RD16-2.

Fig. 2 shows schematic diagram of the BIXS measurement setup (a) and its photo (b). In most cases, BIXS measurements are performed under Ar gas atmosphere to evaluate the surface T concentration from the intensity of Ar(Kα) X-rays. As mentioned above, an acrylic airtight chamber which is the main component of this setup is sufficiently large to accommodate a whole divertor tile; the inner diameter is 305 mm

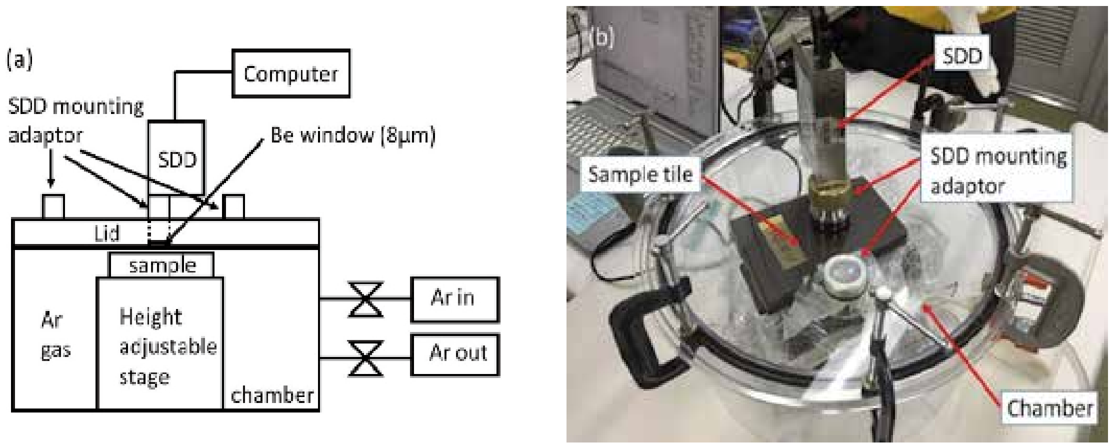

Fig. 2 (a) Schematic diagram of experimental set up and (b) photo of chamber with sample tile and silicon drift detector (SDD).

and height is 160 mm. The chamber is equipped with two valves to replace air inside the chamber with Ar gas. The top of the chamber is covered with an acrylic lid having three o-ring-sealed adaptors for mounting SDDs. A divertor tile is place on a height adjustable stage, and the distance between tile surface and detector window is adjusted to be typically 5 mm.

The measurements of the divertor tiles were performed in a radiation-controlled area in NIFS. After installing the tile at the proper height, the measurements were performed under Ar gas atmosphere for 5 days for the tile 9RD16-1 and 3 days for the tile 9RD16-2, respectively.

Prior to the BIXS measurements, 2-dimensional distributions of T at the tile surfaces were examined by β-ray measurements using an imaging plate (IP) technique. Fig. 3 shows 2-dimensional distributions of photo-stimulated luminescence (PSL) from IPs. Blue-square contrasts in Fig. 3 (a) and (b) are areas covered by tile identification labels. The T distribution at the surface of the tile 9RD16-1 was almost uniform, and the X-ray spectrum was acquired from the central part of the tile. On the other hand, the distribution of T at the surface of the tile 9RD16-2 was not uniform. Therefore, the SDD was placed at the position with the highest T surface concentration. The black circles in Fig. 3 indicate the places where SDDs were located for BIXS measurement.

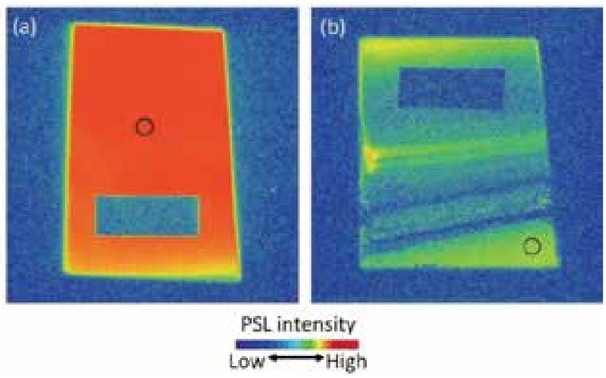

Fig. 3 Two-dimensional images of photo-stimulated luminescence (PSL) intensity of sample tiles 9RD16-1 (a) and 9RD16-2 (b). Blue-square contrasts observed in the tiles are regions covered by tile identification labels. The silicon drift detector was placed at the position indicated by a black circle on each sample.

Penetration depth of T was evaluated from BIXS spectra using Monte Carlo simulation toolkit Geant4 [12, 13]. Röllig et al. [14] simulated BIXS spectra with four different physics packages of Geant4 and reported PENELOPE physics [15] provided the best agreement with observed X-ray spectra. Therefore, Geant4 with PENELOPE physics model was used in this study.

3. Results and discussion

The X-ray spectra of the LHD tiles are shown in Fig. 4. The peak at 2.96 keV is Ar(Kα) characteristic X-rays. The transmittance of X-rays below 0.6 keV is negligible for the SDD Be window [11]. Therefore, the characteristic X-rays of carbon (0.277 keV) induced in the sample tiles is not visible. There are broad spectra of bremsstrahlung in the energy range of 1–9 keV, and strong absorption of bremsstrahlung by Ar is observed at 3.2 keV. These characteristics are similar to those observed in X-ray spectra of carbon tiles retrieved from Joint European Torus (JET) examined using a Ge detector (see Fig. 3 in [2]). Therefore, it was concluded that the present setup provides accurate BIXS spectra.

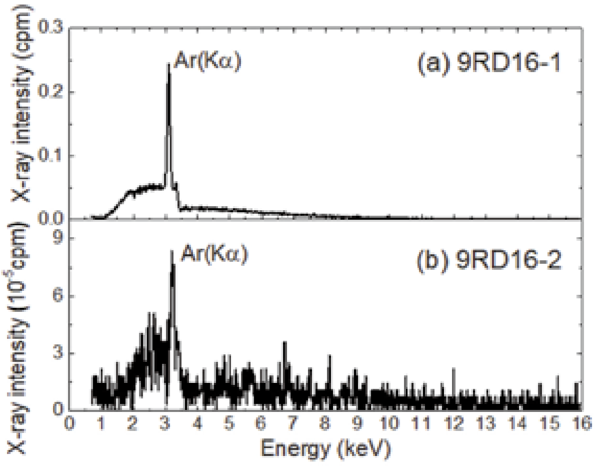

Fig. 4 X-ray spectra of (a) 9RD16-1 and (b) 9RD16-2 obtained by BIXS measurements.

The intensity of Ar(Kα) characteristic X-rays shows the information on the amount of T at/near surface (< 0.5 μm), whereas the intensity of bremsstrahlung gives the T content in the bulk up to 1 mm [16]. The Ar(Kα) X-ray intensity of the tile 9RD16-1 was orders-of-magnitude higher than that of the tile 9RD16-2, though these two tiles were located in adjacent positions in LHD. These spectra indicate 9RD16-1 contained more T on the surface than 9RD16-2 tile and it is consistent with the IP result shown in Fig. 3.

As previously explained, T is produced by the DD fusion reactions in LHD. There are two mechanisms of an accumulation of T in the divertor tiles. A part of T produced by the DD reactions is thermalized in the LHD plasma and deposited onto tile surfaces with carbon accommodated in plasma by sputtering erosion of carbon tiles. The thickness of the deposition layer at the measured region on the tile 9RD16-1 was around 1 μm. Other part of T is implanted to bulk with high energy (~1.01 MeV). The range of 1.01 MeV T in carbon was evaluated to be 8 μm at normal incidence using SRIM program [17].

The detailed analysis of the spectrum for the tile 9RD16-2 was impossible due to poor signal to noise ratio caused by low T retention. Nevertheless, the depth profile of T in the tile 9RD16-1 was evaluated by simulating the X-ray spectrum using Geant4 on the assumption that T was distributed up to depth of 1, 4, 6 and 8 μm from the surface. Because the range of 1.01 MeV T in carbon was evaluated to be 8 μm at normal incidence, deeper penetration of T than 8 μm was not considered in the simulations. Fig. 5 shows the comparison of the X-ray spectrum observed for the tile 9RD16-1 and that obtained by Geant4 simulations. The X-ray peaks at 1.74 keV shown in simulated X-ray spectra are characteristic X-rays of silicon induced in the SDD itself. The main characteristic points of observed spectrum, i.e. intense Ar(Kα) X-rays and absorption of bremsstrahlung by Ar, were well reproduced in the simulated spectra. The relative intensity of bremsstrahlung to Ar(Kα) X-rays was low in the simulations in which penetration depth of T was assumed to be 1 and 4 μm, as shown in Fig. 5 (a) and (b). Nevertheless, good agreement between observed and simulated spectra was obtained by assuming deeper penetration depth (6 μm in Fig 5 (c)). In the case of penetration depth of 8 μm, the intensity of bremsstrahlung in a high energy region (> 6 keV) in

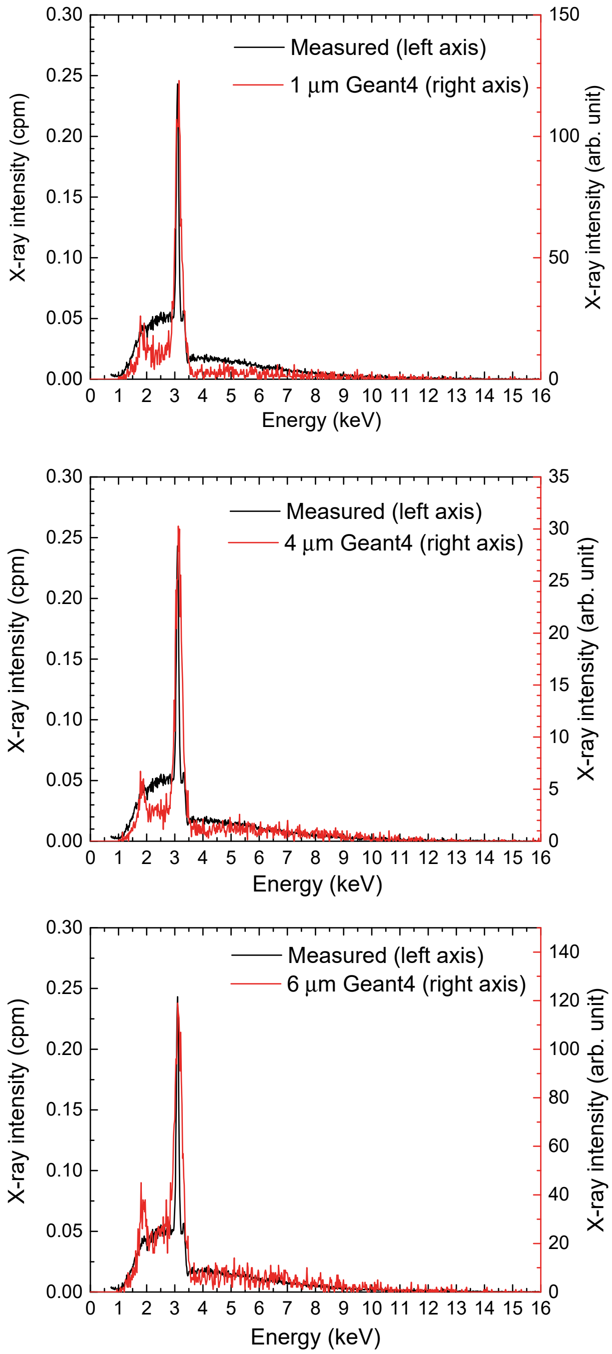

Fig. 5 Comparison of measured X-ray spectra for the tile 9RD16-1 with spectra simulated using Geant4 by assuming penetration depth of T is 1 μm (a), 4 μm (b), 6 μm (c) and 8 μm (d).

simulated spectrum was higher than that in observed spectra, as shown in Fig. 5 (d). These observations suggest that the penetration depth of T was around 6 μm. This value of penetration depth was larger than the above-mentioned thickness of deposition layer. It appears that a significant part of T retained in the tile 9RD16-1 was implanted in the tile at high energy (~MeV).

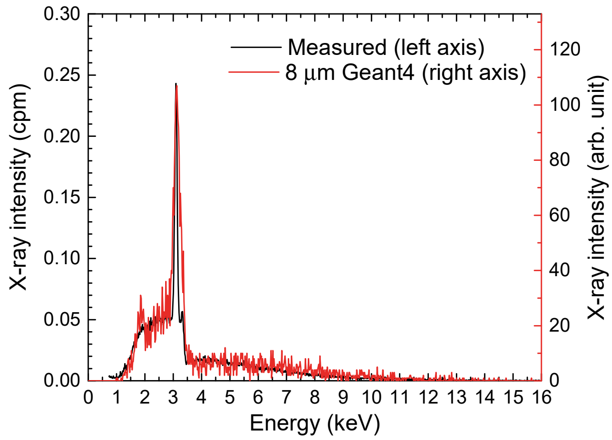

Fig. 5 (cont'd) Comparison of measured X-ray spectra for the tile 9RD16-1 with spectra simulated using Geant4 by assuming penetration depth of T is 1 μm (a), 4 μm (b), 6 μm (c) and 8 μm (d).

4. Conclusions

The measurements of β-ray induced X-ray spectra for divertor tiles retrieved from LHD were successfully performed using a newly-designed compact setup capable of multipoint analysis. The BIXS measurements showed that the T concentration in the tile 9RD16-1 was orders-of-magnitude higher than that in the tile 9RD16-2, though these tiles were in adjacent positions in LHD. The X-ray spectrum provided by Geant4 simulation based on the assumption that T penetrated up to the depth of 6 μm showed good agreement with measured BIXS spectrum. This value of penetration depth was larger than the thickness of carbon deposition layers formed at this position during operation of LHD. These observations suggested that a significant amount of T was distributed beyond the deposition layer due to implantation with high energy.

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