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Tritium depth profile in matter using an imaging plate

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ABSTRACT

A method to detect tritium non-destructively in regions deeper than the escape depth of beta rays is being developed using bremsstrahlung induced by beta rays with an imaging plate (IP). An IP made of europium-doped BaFBr(I), a photostimulated luminescence (PSL) material, is a two-dimensional radiation sensor. The bremsstrahlung energy spectrum is a continuum with photon energies, varying based on the atomic number and thickness of the target (or absorbing) material. When tritium migrates into matter, the bremsstrahlung energy spectrum distribution would change. The PSL intensity of the IP is affected by this energy spectrum variation. In order to quantify the amount of tritium in deeper regions with the IP technique, a tritium depth profile is required.

In this study, a new method of obtaining a tritium depth profileusing the combined technique of the IP and thin absorbers is presented.

1. Introduction

Non-destructive and quantitative measurement of the amount of tritium retained on/in plasma-facing materials (PFMs) of magnetic fusion devices are of great importance for the control of fuel particles and to ensure safety for maintenance work and waste processing of PFMs in fusion systems. The tritium imaging plate (IP) technique for detecting beta particles is useful to non-destructively determine the surface tritium distribution on PFMs [1–5]. By exposing the IP to the graphite tiles with a face-to-face contact, for some time, the image is easily obtained. An IP made of europium-doped BaFBr(I), a photostimulated luminescence (PSL) material, is a two-dimensional radiation sensor. This IP has many excellent properties making it suitable for this purpose, including high sensitivity, wide dynamic range over five orders of magnitude, a high degree of spatial resolution, and reusability by exposing the IP to visible light between uses [6].

Tritium emits beta particles with a maximum energy of 18.6 keV, with an average of 5.7 keV. These have a range of about several micrometers in graphite, and hence the IP technique is sensitive to tritium up to a depth of a few microns. In order to detect tritium in regions deeper than the escape depth of beta rays from tritium, we have been developing an approach to detect tritium using bremsstrahlung induced by beta rays with an IP [7,8]. The measurement principle in this approach to tritium detection is to observe the bremsstrahlung X-rays generated by the interaction between the beta particles from tritium and matter, on the basis that X-rays penetrate materials much more easily than the weak beta rays from tritium, which have a maximum energy of 18.6 keV.

The bremsstrahlung energy spectrum is a continuum with photon energies, varying based on the atomic number and thickness of the target (or absorbing) material. The PSL intensity of the IP is affected by the variation in energy spectrum [7]. In the IP technique utilizing bremsstrahlung X-rays, the tritium depth profile is required to quantify the amount of tritium in deeper regions. In this study, a new method to obtain the tritium depth profile using the combined technique of the IP and thin absorbers is presented.

2. Experimental

2.1. Imaging plate

A BAS-MS type-IP (Fujifilm Co., Ltd.) was used to detect bremsstrahlung X-rays from tritium. This IP consists of a 9-μm-thick polyethyleneterephthalate protective film and a 115-μm-thick photostimulable phosphor layer affixed to a 12-μm-thick plastic back layer and a 190-μm-thick polyethyleneterephthalate base layer [9]. It has a high sensitivity to photons. The BAS-MS

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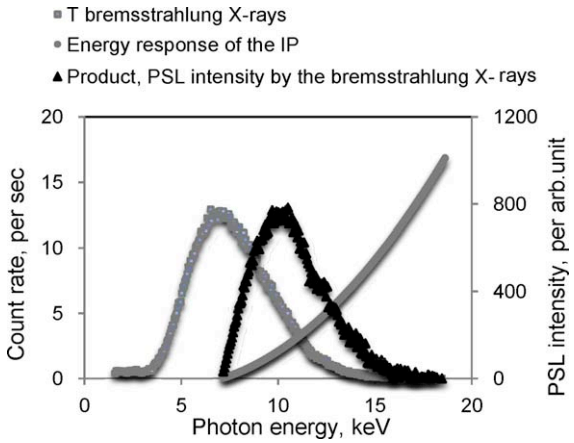

Fig. 1. Example of a bremsstrahlung energy spectrum and the energy response of BAS-MS type IP in gray with the product spectrum of these two values, PSL intensity by bremsstrahlung X-rays, in black.

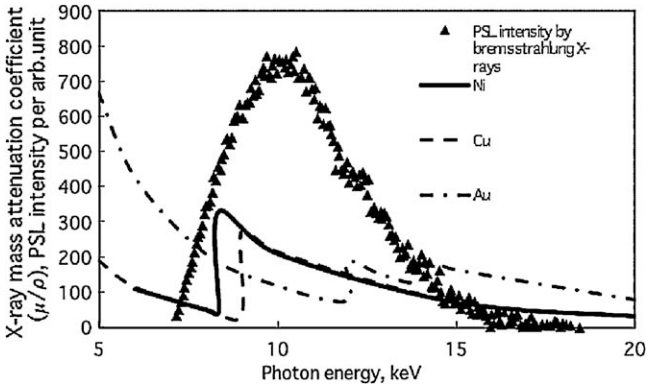

Fig. 2. X-ray mass attenuation coefficients of nickel, copper, and gold in an energy range of 5–20 keV. PSL intensity by bremsstrahlung X-rays is also exhibited.

type-IP can detect bremsstrahlung X-rays, but not the beta particles emitted from tritium because of its thick protective film.

In the sensitive phosphor layer of an IP, ionizing radiation creates a large amount of trapped centers, which record information about the deposited energy and its position. The IP is read out using a He–Ne laser (633 nm) within the image reader. The laser light induces PSL (390 nm) from the positions of the trapped centers, which is detected via a photomultiplier tube. In this study, a model FLA9000 IP reader (Fujifilm Co., Ltd.) was used with a spatial resolution of 100 mm and 8 bit of digital resolution dpi, followed by an image analysis with the Multi Gauge (ver.3.2).

2.2. Combined technique of the IP and absorbers

In the IP, when exposure time and the ambient temperature during the exposure is constant, the sum of PSL intensity is expressed as

$$I_{PSL} = A \int_{E_1}^{E_2} P(E) \cdot R(E)\, dE \quad (1)$$

where A is a constant, $P(E)$ is the number of photons, and $R(E)$ is the energy response of the IP, respectively. The sum of the intensity is the value obtained with the IP reader.

In Fig. 1, an example of a bremsstrahlung energy spectrum and the energy response of BAS-MS type IP are shown in gray, with the product spectrum of these two values exhibited in black. The bremsstrahlung energy spectrum was measured using tritium water in a polyethylene tip with a high purity Ge detector equipped with an ultra-thin beryllium window for efficient detection of low energy X-rays below 18.6 keV. It peaked at around 7.0 keV. The energy response of the IP was measured by using monoenergetic X-ray beam sources on a beam line at the Photon Factory (PF) of the High Energy Accelerator Research Organization (KEK), Tsukuba, Japan [7]. It shows that PSL intensity increases with energy deposition as the X-ray energy increases. PSL intensity is quite low at 8 keV, indicating that most X-rays below 8 keV are attenuated by the thick protective film of the IP. The product spectrum, meaning PSL intensity, by bremsstrahlung X-rays, has its peak at around 10.0 keV. It shifts to a higher energy compared to the original spectrum.

When a thin absorber is inserted between the IP and matter containing tritium during the exposure, and the thickness of the absorber increases, it changes the bremsstrahlung energy spectrum distribution consistently, depending on the physical characteristics of the absorber. A specific PSL decay curve for each absorber can also be obtained. When tritium migrates into matter, the bremsstrahlung energy spectrum distribution would change in the same manner, shifting its peak to higher energy because lower energy bremsstrahlung X-rays would be attenuated with matter. It makes the peak of the product spectrum shift to a higher energy as well, with reducing PSL intensity. It indicates that the depth at which tritium migrates would affect the PSL decay curve and there might be some relationship between the change in the PSL decay curve and depth. Hence, the change in the PSL decay curve is considered to be a useful indicator to obtain depth information. For this purpose, two metal absorbers of copper and gold foil (Nilaco Co.) were chosen, based on the tritium source migrating into nickel matter. In Fig. 2, X-ray mass attenuation coefficients of nickel, copper, and gold [10] are shown in the energy range 5–20 keV. The PSL intensity from bremsstrahlung X-rays is also exhibited in the figure. Copper foil can be used as a K-edge filter with X-ray absorption at 9.0 keV. Gold has L-edges X-ray absorption at around 13 keV. Increasing the copper absorber thickness rapidly reduces PSL derived from the lower energy range. On the other hand, the gold absorber is expected to work oppositely, rapidly reducing PSL derived from the higher energy range. Copper foil thickness varied in the range 0–32 μm in increments of 4 μm and gold foil in the range 0–35 μm in increments of 5 μm, respectively.

A 5-μm-thick nickel sheet was used to simulate tritium migration into nickel, varying its thickness in the range 0–35 μm in increments of 5 μm. The relationship between depth in matter (nickel thickness), and the decay pattern in PSL values was examined.

2.3. Irradiation

Five small borosilicate glass tubes, with a wall thickness of 0.088 mm, length of 6.36 mm, and diameter of 0.60 mm, filled with pure tritium gas of 50 MBq (manufactured by mb-microtec ag) were used as the tritium sources to generate bremsstrahlung X-rays. The IP was irradiated with bremsstrahlung X-rays by placing the tritium source directly on the IP or by inserting absorbers and/or nickel sheet for 1 h. The schematic diagram of the irradiation setup is shown in Fig. 3. Fig. 4 illustrates that bremsstrahlung X-rays from the tritium source penetrate into the nickel sheet completely (upper). Bremsstrahlung energy spectra vary depending on the thickness of the nickel sheets (lower), which are corresponding to the depths of tritium. During irradiation, the IP was kept inside an incubator with temperature controlled to 0 °C, in order to decrease the fading effect, although the BAS-MS-type IP shows good fading characteristics at room temperature [11]. The IP was kept for 20 min after irradiation and then read to avoid fading effects caused