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Uniform Irradiation using Rotational-linear Scanning Method for Narrow Synchrotron Radiation Beam

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At SPring-8, photon intensity monitors for synchrotron radiation have been developed. Using these monitors, the responses of radiation detectors and dosimeters to monoenergetic photons can be measured. In most cases, uniform irradiation to the sample is necessary. Here, two scanning methods are proposed. One is an XZ-linear scanning method, which moves the sample simultaneously in both the X and Z direction, that is, in zigzag fashion. The other is a rotational-linear scanning method, which rotates the sample moving in the X direction. To investigate the validity of the two methods, thermoluminescent dosimeters were irradiated with a broad synchrotron-radiation beam, and the readings from the two methods were compared with that of the dosimeters fixed in the beam. The results for both scanning methods virtually agreed with that of the fixed method. The advantages of the rotational-linear scanning method are that low- and medium-dose irradiation is possible, uniformity is excellent and the load to the scanning equipment is light: hence, this method is superior to the XZ-linear scanning method for most applications.

KEYWORDS: SPring-8, synchrotron radiation, ionization chamber, TLD, dose, uniform irradiation

I. Introduction

At the SPring-8 synchrotron radiation facility in Japan, a high-intensity monoenergetic photon beam up to one hundred keV is available. However, intensity monitors for the beam have not been fully developed because the energy region is so wide, ranging from ultraviolet to 100 keV, with photon intensity ranging from 10^8 to 10^{15} photons/s. Monitors for high-energy photons over 50 keV and high-intensity photons above 10^{13} photons/s from an insertion-device undulator would be especially useful: using the high-monoenergetic photons, characteristics of radiation detectors and dosimeters could be investigated. At undulator beamlines, the monitors would contribute to diagnosis of the beamlines and components in addition to detector research.

Synchrotron radiation has been already used extensively for response measurement of dosimeters such as thermoluminescent dosimeters, radiochromic films and MOSFET semiconductors[1-4]; these applications have taken particular advantage of its monoenergy characteristics. However, photon energies have been limited to the low energy range below 40 keV because of the low electron ring energy and lack of a reliable dose monitor.

Recently, we have developed a parallel-plate free-air ionization chamber[5] as a high-energy absolute photon intensity monitor. The plate separation is 8.5 cm and the chamber can be carried from beamline to beamline. Saturation was confirmed at 3 kV and the photon intensity measured using the chamber agreed within 3% with that measured using a Si-PIN photodiode for 50- to 150-keV monoenergetic photons. The disagreement corresponded to the electron loss calculated with an EGS4 Monte Carlo code [6]. At a bending-magnet beamline, an intensity of 10^8 to $2x10^9$ photons/s was measured.

When irradiation is made to sample as in this case, one problem that has to be solved is that the beam size is in general too small for most dosimeters; even for small dosimeters, dose estimation is not easy because precise measurement of a small beam area is difficult. Moreover, strength distribution inevitably exists in the beam. Accordingly, uniform irradiation using a two-dimensional scanning method is indispensable. Any method in which the sample is moved through an area homogeneously should be satisfactory. Of course, there exists the practical condition that scanning equipment be manipulated in a relatively trouble-free manner. To meet these conditions, two methods are proposed in the present work. One is an XZ-linear scanning method, which moves the X-axis and Z-axis stages simultaneously, in zigzag fashion; the other is a Zθ-scanning method, a rotational-linear scanning method, in which the sample is rotated as it moves in the X-direction. The movement is schematized in **Fig. 1**. The present purpose is to investigate the validity of the two methods using a broad-area beam of synchrotron radiation at SPring-8.

II. Materials and method

1. Estimation of dose to sample

(1) XZ-linear scanning method

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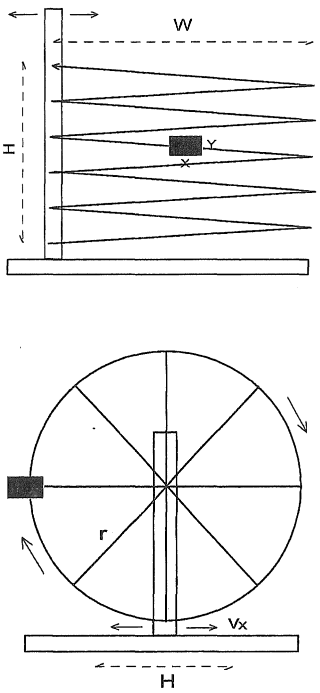

Fig. 1 XZ-linear (above) and rotational-linear (below) scanning methods. The filled area XY represents the photon beam.

In the XZ-linear scanning method, the dose to the sample is calculated from the observed value of the monitor using the beam area and the crossing time of the beam to the sample:

$$D=\frac{Fi}{XY}\frac{2X}{v_x}N=\frac{Fi}{XY}\frac{2X}{v_x}\frac{Y}{2v_z\frac{W}{v_x}}=\frac{Fi}{v_zW} \quad (1)$$

where F is the conversion function from current to dose, i is the average current of an ionization chamber monitor, X and Y the beam size, v_x and v_z the velocity in the X and Z directions, N the reciprocating number and W the scanning width in the X direction. Ultimately, the dose to the sample is estimated by dividing the average monitor dose rate by the Z-axis velocity and the scanning width; hence, the beam size is not relevant. To attain uniform irradiation, v_x should be large and v_z should be small. For fast v_x, however, the load to the scanning machine is heavy.

From another view point, it can be considered that the sample is set in an HW-size beam during total irradiation, in which H denotes the scanning length in the Z direction[7]:

$$D=\frac{Fi}{HW}\frac{H}{v_z}=\frac{Fi}{v_zW} \quad (2)$$

The same result as Eq. (1) was obtained; that is, the validity of the calculation method was confirmed. In Eq. (2), the value of FiH/v_z equals the total charge during the scanning and if the charge is used, the scanning lengths H and W have only to be known. This method is more convenient for actual measurement.

(2) Rotational-linear scanning method

Similarly, in the Zθ-scanning method, that is, the rotational-linear scanning method, the dose is obtained as follows:

$$D=\frac{Fi}{XY}\frac{X}{rv_\theta}N=\frac{Fi}{XY}\frac{X}{rv_\theta}\frac{Y}{v_x\frac{2\pi}{v_\theta}}=\frac{Fi}{v_x2\pi r}$$

(3)

where r denotes the radius at which the sample is set and v_θ the rotational velocity. For uniform irradiation, a large value of v_θ and small value of v_x is desirable. Correction for circular-arc-shape crossing is made using the factor

$$\eta=\frac{L}{2r\sin^{-1}\frac{L}{2r}} \quad (4)$$

in which L denotes the width of the sample. For most TLD chips, this factor was found to be negligible. From Eq. (3), it becomes clear that the dose depends only on v_x and r, and the beam size is irrelevant.

In the other solution using the total scanning area 2πrH, the dose is also expressed as

$$D=\frac{Fi}{H2\pi r}\frac{H}{v_x}=\frac{Fi}{v_x2\pi r} \quad (5)$$

The value of FiH/v_x equals the total charge, and only the scanning length H and radius r are used to calculate the dose from the charge. Constant rotational speed is required and a larger radius makes the error originating from the sample position smaller. In both methods, beam size is not an issue, an important point for the narrow synchrotron-radiation beam.

2. Experiment at SPring-8

The experiment was carried out at a bending-magnet beamline BL20B2. The beamline is unique, in that the experimental hutch is located 206 m from the source, making available a larger beam size than at other beamlines. The photon energy used was 30 keV and the collimated beam size was 8.0 mm by 8.5 mm, adjusted to the monitor chamber mouth. For the irradiation sample, thermoluminescent dosimeters (TLDs) of LiF:Mg,Cu,P, measuring 3 mm by 3 mm in area and 0.4 mm thick, were used. The linearity extends to 10 Gy at 30 keV[8]. For the TL reading, a Harshaw model 3500 was used.

The two irradiation methods used were the XZ-linear scanning and the Zθ-scanning methods. Some TLDs were fixed in the beam without movement and irradiated for comparison. The motorized stages used were Sigma Koki SGSP46-300 and 26-100, and the stepping motor drive was Mark-202. In the XZ-linear scanning method, the velocity was 0.2-0.25 cm/s on the X-axis and $4x10^{-4}$ to $5x10^{-3}$ cm/s on the Z-axis. In the rotational-linear scanning method, the radius at which the TLDs were set was 4.25 to 7 cm and the linear-scanning velocity was 0.1 to 0.4 cm/s.

For the photon intensity monitor, a parallel-plate free-air ionization chamber of 5-cm plate separation was used[8]. The applied voltage was 2900 V and saturation was confirmed at the beamline.

III. Result and discussion

1. Linearity

The relations of the TL signals with the estimated doses in the three methods were compared. **Figure 2** shows the result. All TL signal points in the fixed and rotational-linear scanning method landed on the same straight line as a function of the estimated dose. Values of the XZ-linear scanning method also landed on the same line, while some points were shifted from that at the fixed method, especially at 1 Gy. The reason is not clear.

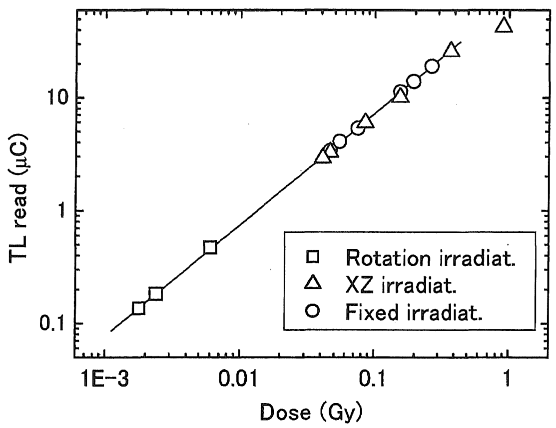

Fig. 2 Linearity of the three methods

In the scanning methods, the wait time of turning during linear scanning was one of the main origins of error. The time loss was estimated by dividing the total irradiation time by two times the reciprocating number and subtracting the span divided by the preset velocity from the result. The result showed only about 0.3 seconds at one turning in the present condition, which resulted in a 5% correction for the dose in the XZ-linear scanning method. In the rotational-linear scanning method, there was a 0.1% correction at 0.1-cm/s v_x and 4% at 0.4-cm/s v_x for 6-cm span H: to decrease the wait time, a small v_x and large H are suitable. These corrections are made to **Fig. 2**.

The other origin of errors was the accuracy of the sample position. As explained with regard to Eq. (5), the dose is in inverse proportion to the radius. In this context, a larger radius setting is preferable for position accuracy and improved dose estimation. While dose difference in the TLD owing to the different radius position also decreases with increasing radius, the values cancel out each other and the TL reading equals the value in the center.

2. Advantage and disadvantage of rotational-linear scanning method

A disadvantage of the XZ-axis linear scanning method is that the turning makes the high-speed scanning much more difficult and so the dose inevitably becomes very large as shown in **Fig. 2**. In the Zθ-scanning method, on the other hand, the rotational speed can be chosen to be 90 to 900 rpm, which is much faster than the linear scanning speed. That enables more uniform irradiation and low-dose irradiation. The load to the scanning equipment is also lighter.

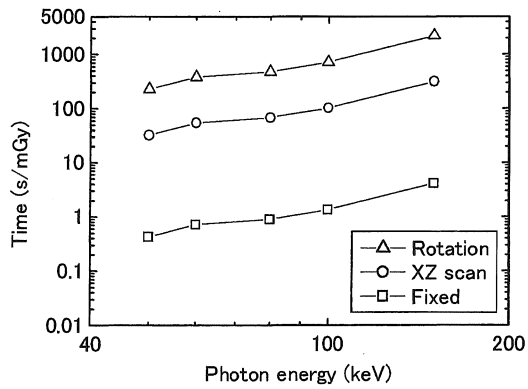

Fig. 3 Typical required time for 1-mGy irradiation at the fixed, XZ-linear and rotational-linear scanning methods at BL38B1 beamline

In the rotational-linear scanning method, the value of the span H cannot be shortened largely owing to the increase of the wait-time influence. The radius r also cannot be decreased much because of the larger sample position error that is induced. As a result, the value of v_x has to be adjusted to achieve the required dose. For large-dose irradiation, a small velocity v_x is suitable. In Eq. (5), however, the value of $2\pi r$ becomes larger than that of W in the XZ-scanning method in ordinary conditions; hence, the rotational-linear scanning method generally takes longer.

Figure 3 shows the calculated times necessary to obtain a 1-mGy dose in the fixed, XZ- and rotational-linear scanning methods, corresponding to the photon intensity at the bending-magnet beamline BL38B1. The H and W spans used were 3 and 1 cm, and the rotational radius was 7 cm. The required time increases with photon energy. The time for the rotational-linear scanning method is about seven times greater than that in the XZ-linear method. This ratio cannot easily be decreased, as explained above.

Consequently, the rotational-linear scanning method is useful for homogeneous irradiation with synchrotron radiation for both low- and medium-dose irradiation at the bending-magnet beamlines.

IV. Conclusion

For uniform irradiation using a narrow synchrotron radiation beam, the TL signal in the rotational-linear scanning method was measured and the validity was confirmed. At a bending-magnet beamline, the method can be used for low- and medium-dose irradiation; at undulator beamlines, high-dose irradiation becomes possible. For high dose irradiation at a bending-magnet beamline, the XZ-linear scanning method is also useful. Using these methods, dosimeter response between 50 and 150 keV can be measured.

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