Estimation of Synchrotron Radiation Dose Outside The Hutch of SPring-8 Beamline

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INTRODUCTION

Synchrotron radiation facilities are to get high brilliance and high power density of synchrotron radiation. Especially, the third generation synchrotron radiation facilities such as the European Synchrotron Radiation Facility (ESRF)(1), The Advanced Photon Source (APS)(2), and SPring-8(3) can get extremely high brilliance, high power density, and high energy photons. The shields of the beamlines must be designed for the radiation safety under the severe conditions.

The PHOTON II(4) code has actually been used to design the shields in synchrotron radiation beamlines. But the PHOTON II code underestimated doses outside the shield wall of the hutch (an enclosure of the beam, optical elements or experimental instruments) in some cases. The PHOTON II code has been validly created for calculations of the attenuation by filters, the isotropic scattering process by the optical elements without coherent scattering, and the shielding with the walls of the hutches ignoring the buildup effect of the synchrotron radiations emitted from a wiggler and bending magnet. The polarization effect is actually dominant in the synchrotron radiation and the code does not well simulate the scattering process. Furthermore, with the considerably high energy X-rays as generated in the third generation synchrotron radiation facilities, the dose outside the shield wall strongly depends on the scattering angle. A new shielding design code STAC8(5) was developed in order to fill up the deficiencies in the PHOTON II code and to be applicable to the calculations of the radiation emitted from the insertion devices including undulators, the effect of linear polarization of photons on the scattering process, and the angular dependence of both the coherent and incoherent scatterings. The buildup factors were also introduced in the shielding calculations.

Comparing with Monte Carlo simulations were performed the validity verifications of the STAC8 code. Verification of the validity of the code by using the actual synchrotron radiation sources is more important to rely on the shielding design of beamlines. However, the shield data of the practical beamline to perform the benchmark are quite insufficient.

The shielding designs of the SPring-8 beamlines were performed by STAC8 and the construction of the BL14B1 bending beamline(6) was completed. This beamline is very adequate for the benchmark experiments, because the high power of the radiation can be obtained without so called local shielding and the roof of the hutch were designed to shield in severe conditions in order to reduce the weight. Thus the leakage dose measurements outside the shield wall of the roof were planned to be carried out and compared with the calculations. The dose distribution around the scatterer (first mirror) was also measured to compare the calculations.

OUTLINE OF THE SPring-8 BL14B1 BEAMLINE

The BL14B1 beamline was designed to make experiments on various kinds of structural studies, particularly in the field of high-pressure, high-temperature science and surface-interface structural studies. This beamline can be operated in three modes with different experimental requirements. One is the white X-ray experiments in the white X-ray experimental hutch. One is the monochromatic X-ray experiments in the white X-ray experimental hutch, and the other is the monochromatic X-ray experiments in the monochromatic X-ray experimental hutch. On the beamline a set of two permanent filters (twin 0.25 mm of beryllium) was inserted. Figure 1 shows a layout of the beamline in the downstream experimental area in which an optics hutch and two experimental hutches are sited. The major optical elements are a slit, two view ports, two mirrors, a double crystal monochromator and two beam shutters. In addition, two photon stops and one beam stop were installed for radiation protection. The first mirror was installed to eliminate the higher harmonics of synchrotron radiation and to collimate the vertical component of synchrotron radiation. The second mirror is for focusing the vertical
Fig.1  Layout of the BL14B1 bending magnet beamline of SPring-8. The synchrotron radiation beam comes from the left side of the figure. The MBS is the main beam shutter. The white and monochromatic X-ray experiments can be performed in the upstream side of the experimental hutch. Experiments using only the monochromatic X-ray beam are permitted in the downstream experimental hutch.

component of synchrotron radiation. The double crystal monochromator was installed to monochromize the synchrotron radiation and to focus the horizontal component of synchrotron radiation. The main beam shutter (MBS) was installed inside the shielding wall of the storage ring to control the synchrotron radiation beam to be transmitted into the beamline and the beam shutter is control the white or monochromatic synchrotron radiation to be transmitted into the experimental hutch. The photon stop made of lead is to prevent gas bremsstrahlung (7) from expanding to the downstream position of the beamline, while the beam stop, usually installed at the most downstream of the beamline, is to prevent the monochromatic synchrotron radiation beam from leaking out of the experimental hutch wall. The optical elements, which installed in the downstream position in the optics hutch, can be moved up and down to adequate for the experimental purpose. Therefore the local shielding made of lead, which is normally installed to standard beamlines of SPring-8, cannot be employed. The walls of both the optics and experimental hutches are designed to shield against scattered synchrotron radiation. The thickness of the hutch wall was determined depending on the location of the hutch and the direction against the beam path.

EXPERIMENTAL CONDITIONS

The synchrotron radiation white beam injected into the first mirror and then the doses outside the first mirror case were measured by using TLD-100 thermo-luminescence dosimeter (Harshaw/Bicron USA). The dose distributions outside the shield wall of the roof were measured with AE133L ionization chamber made by Oyo Giken Co. Ltd. in Japan by using synchrotron radiation white beam. The first mirror and the location of the TLD dosimeters are illustrated in Fig.2, including the injected condition of the synchrotron radiation beam.

Fig.2  Illustration of the first mirror and the location of the four TLD dosimeters. The synchrotron radiation beam injected into the rhodium coated silicon body mirror. The soft X-ray component of synchrotron radiation is reflected and transmitted to the monochromator by the inclining mirror.
The dose measurements were made by the synchrotron radiation from the bending magnet and the key parameters are given in Table 1. During the measurements, the upstream optical aperture was fixed at the angular divergence of 1.0 mrad (vertical) x 1.55 mrad (horizontal) corresponding to the beam size of 35 mm (vertical) x 54 mm (horizontal) at the center of the first mirror. However, the vertical divergence of the synchrotron radiation from bending magnet is nearly 0.063 mrad so that the aperture size of vertical is extensive sufficiently and the true beam size is 4.4 mm in vertical at the center of the first mirror. The size of the first mirror made of rhodium coated silicon body is 50 mm in thickness, 90 mm in width, and 800 mm in length. As shown in Fig.2, the white beam of synchrotron radiation injects into the first mirror. The soft X-ray component is reflected and transmitted to the monochromator by the inclining mirror of 4 mrad, and the other component is scattered mainly by the mirror and the support made of stainless steel. The photon dose measured on the stainless steel box of the mirror was scattered from the mirror and the support. The roof wall of the optics hutch was designed and constructed with the lead plate of 8 mm thick, sandwiched by the iron plates of 5.6 mm.

Table 1 The key parameters of the BL14B1 beamline of SPring-8 and experimental conditions

<table>
<thead>
<tr>
<th>Light source</th>
<th>Storage ring energy</th>
<th>Peak strength of magnetic field</th>
<th>Bending radius</th>
<th>Critical energy</th>
<th>Opening angle (Vertical)</th>
<th>Critcal energy (Horizontal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending magnet</td>
<td>8 GeV</td>
<td>0.68 T</td>
<td>39.27 m</td>
<td>29.0 keV</td>
<td>1.0 mrad</td>
<td>1.55 mrad</td>
</tr>
<tr>
<td>Beam size</td>
<td>4.4 mm x 54 mm (V x H)</td>
<td>at the center of the first mirror</td>
<td></td>
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<tr>
<td>Permanent filters</td>
<td>Be</td>
<td>0.25 mm x 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Maximum inclined angle of first mirror</td>
<td>4 mrad</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum stored beam current</td>
<td>100 mA</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Cumulative stored current during the measurements</td>
<td>2.996 x 10⁶ mA·s</td>
<td></td>
<td></td>
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<tr>
<td>Polarization vector is on the horizontal plane</td>
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</table>

DOSE CALCULATIONS

The dose calculations were made at two important sampling points, one is the outside the roof of the optics hutch and the other is the outside the mirror box. See Fig.1 and 2. In this calculation, a silicon rod of 540 mm in length and 2.0 mm in radius was used as the first mirror, because a cylindrical scatterer is normally employed in shielding design calculations and can only be calculated in PHOTON II and STAC8 code. The average path length in the mirror for the spread photon of the divergence of 63 µradian is 540 mm, and 2.0 mm for the scattered photon of 90 degrees in the case of the inclining mirror of 4 mradian. The incident photons would be possible to hit the mirror support so that a scatterer made of steel was also considered in the same size of the silicon scatterer. The distances between the scatterer and the outside the roof and mirror box were 1900, 185 mm, respectively.

The roof wall spans parallel to the plane expanded with the beam path and the polarization vector. The slant length is considered to depend on both the azimuthal and the scattering angle to introduce the polarization effect in STAC8 calculation. On the other hand, in the calculations without the polarization effect, the slant length of the shield wall is considered not to depend on the azimuthal angle.

RESULTS and DISCUSSION

The spectra of radiation as emitted from the bending magnet and those attenuated by the beryllium filter of 0.5 mm in thickness are shown in Fig.3, including the reflected photon spectrum by the inclined rhodium coated silicon body mirror of 4 mradian. The part of the synchrotron radiation photon is reflected and moves into the monochromator, and the rest is scattered by the mirror. The reflected photon spectrum were calculated by using X-ray reflection theory(8) without considering the roughness of the rhodium surface.
Fig. 3  Photon spectra of the BL14B1 beamline. The solid line indicates the synchrotron radiation source emitted from the bending magnet. The open circle and dot line indicates the attenuated spectrum by beryllium filters. The open diamond and dot-dashed line indicates the reflected spectrum by inclining the rhodium coated silicon body mirror of 4 mradiaun.

Figure 4 shows the calculations of the dose due to a scattering of the photons outside the mirror box. The measurement data by using TLD dosimeters are also plotted. The vertical axis indicates the cumulative absorbed dose in air during the synchrotron radiation irradiation of 2.996 x 10⁶ mA·s, and the horizontal axis indicates the distance from the center of the top plate of the mirror box. The calculations by using PHOTON II are also plotted. In the calculation, two scatterer materials, silicon and steel, are considered. This figure indicates that the dose strongly depends on the sampling points of the mirror box, and the calculations by using STAC8 show good agreement with the measurements. On the other hand, the results of the PHOTON II calculations underestimated the measurements.

The calculations of the dose distribution outside the roof of the optics hutch are shown in Fig.5, including measurement results. This figure indicates that the dose strongly depends on the scattering angle and almost of the measurement results are between the calculations by using the silicon scatterer and the steel scatterer. Both the dose distributions, measurement results and calculations by using STAC8, are very similar and that the maximum position of the distribution is well coincident with those of the measurements. The doses calculated by the PHOTON II code are also plotted in Fig.5, indicating that the PHOTON II obviously underestimated the dose values. The reason of this underestimation is thought to be caused by the neglect of coherent scattering process and the buildup effect, however without considering the self-shielding of the scatterer in PHOTON II calculations. Besides, isotropic scattering is assumed with the ninety degrees scattered photon energy.

Figure 6 indicates the azimuthal angle dependence of the dose distributions obtained in consideration of the linear polarization effect and slant length outside the roof of the optics hutch. The azimuthal angle is defined
Fig. 4  Dose distributions of the scattered photons outside the mirror box. Horizontal axis indicates the distance from the center of the top plane of the mirror box and vertical axis indicates the absorbed dose in air. Black circles indicate the measurement data by using the TLD dosimeters. Open circle and solid line indicates the results of the STAC8 calculation by using the silicon scatterer. Open square and dot-dashed line indicates the STAC8 calculations by using the steel scatterer. Double circle and open diamond indicate the results of the PHOTON II calculation using the silicon scatterer and the steel scatterer, respectively.

Fig. 5  Dose distribution outside the roof of the optics hutch of the BL14B1 beamline. Black circles indicate the measurements results by using the ionization chamber. Open triangle and dot line, and inverse triangle and dot-dashed line indicate the STAC8 calculations without considering the polarization effect by using the silicon scatterer and the steel scatterer, respectively. Double circle and open diamond indicate the results of the PHOTON II calculations using the silicon and the steel scatterer, respectively.
to be 0 degree on the horizontal plane. These distributions were calculated at the scattering angles, 50 degrees, 55 degrees, and 60 degrees, corresponding to the maximum dose values and positions. The measurement data, which corresponds to dose at the positions of the scattering angle of 53.6 and 57.2 degrees, are also indicated.

As shown in Figs. 5 and 6, the dose distributions strongly depend on the scattering angle and azimuthal angle because of the anisotropic scattering process of photons and the angular dependence of slant length. The dose is especially high in the scattering angle range 55 to 65 degrees and azimuthal angle range to 80 to 100 degrees. The STAC calculations show the fairly good reproducibility to the measurements results.

CONCLUDING REMARKS

In order to verify the validity of the calculation with shield design code “STAC8” using the practical beamline of the bending magnet, the BL14B1 beamline of SPring-8, it was compared with the measurements by using the TLD dosimeters and the ionization chamber. The calculations and measurements had fairly good agreement and the dose distributions strongly depend on the scattering angle and azimuthal one. The maximum position of the calculated leakage dose distribution by using STAC8 is well coincident with those of the measurements. This concludes that STAC8 is very reliable for a shielding design calculation of the beamline hutch. On the other hand, with PHOTON II the dose of the scattered photons were underestimated.

REFERENCES