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Study on Spatial Distribution of Electromagnetic Shower Around a Lead Block Irradiated by 700-MeV Bremsstrahlung

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Abstract

We measured electromagnetic showers around a Pb block set on a photon beam line extended from a straight section of a storage ring by using thin NaI(Tl) scintillation counter. We also performed simulations of the experiment by using EGS4 Monte Carlo code and compared with the experimental results. We apply the calculation to evaluate the dose equivalent of electromagnetic shower and neutrons generated in a Pb shielding block irradiated by 1-GeV bremsstrahlung.

1 Introduction

Electron storage rings constructed for sources of synchrotron radiation usually have some straight sections in which insertion devices are installed to generate intense light. Gas bremsstrahlung, which is produced by interaction of circulating electrons with residual gas in the straight section passes through a beam line and then cause electromagnetic shower in a shielding block. There are many studies for shielding the bremsstrahlung by measuring the electromagnetic shower behind shielding blocks. In a facility of small storage ring, we usually work near the ring or beamlines in which the shielding blocks for the bremsstrahlung are constructed so that it is needed to investigate the distribution of radiations all around the shielding blocks.

The study of spatial distribution of the electromagnetic shower around the shielding block is necessary to estimate the radiation dose in order to make effective shields for radiations. We measured energy deposition of electromagnetic shower in a thin NaI(Tl) scintillation counter positioned around a small Pb block and compare the results with calculations performed by using EGS4 Monte Carlo code.

2 Experiment

The measurement was performed at Hiroshima Synchrotron Radiation Center (HiSOR), Hiroshima University. The storage ring is of a racetrack type and consists of two long straight sections of 8.24 m and two bending magnets of 2.7 tesla. The electron energy is 700 MeV and the stored current just after injection was about 100 mA.

Experimental set up is shown in Figure 1. Gas bremsstrahlung produced in a vacuum duct of the straight section passed through a sapphire exit window and injected into a 5 cm $\times$ 5 cm $\times$ 2 cm lead block which was set in the air. NaI(Tl) scintillation counter was used to detect the electromagnetic shower from the lead block. The diameter and the thickness of the NaI(Tl) was 2.45 cm and 1.8 mm, respectively. We calibrated the counter by using a ^{137}Cs standard radiation source. The detection

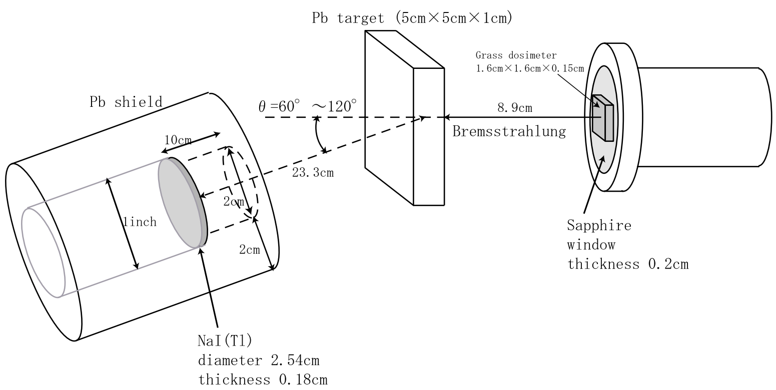

Figure 1: Experimental set up is schematically shown.

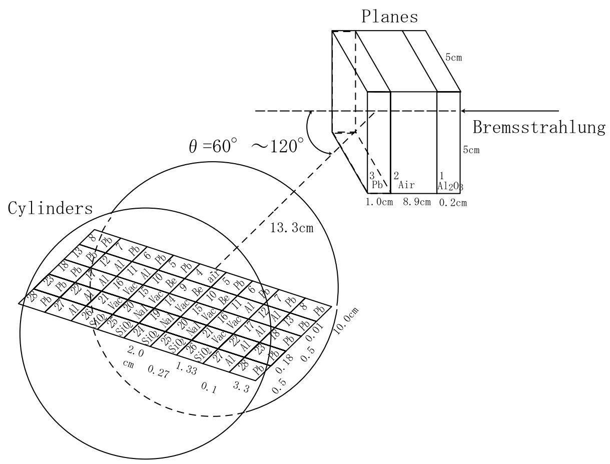

Figure 2: Geometry of the Pb block and NaI(Tl) counter used in EGS4 calculation.

angles were 60°, 75°, 90°, 105°, 120° and the distance from the lead block to the NaI(Tl) counter was 23 cm. A lead collimater of 2.0 cm diameter was set in front of the NaI(Tl) detector.

The intensity of the gas bremsstrahlung is normalized by the absorbed energy in the grass dosimeter, 1.6 cm × 1.6 cm × 0.15 cm, set behind the sapphire window in order to compare the data of the experiment and the simulation.

3 Simulation using EGS4

We performed simulation of our experiment by using EGS4 Monte Carlo code. Figure 2 shows the geometry used in our calculation.

We sampled photon energy uniformly between 0.1 MeV to 700 MeV. A weight for the calculation of electromagnetic cascade caused by a photon of each energy is decided by the following bremsstrahlung cross section of complete screening [1, 2].

$$\sigma_k dk = 4\alpha r_0 Z(Z+1)\frac{dk}{k}\left(\left(1+(\frac{E}{E_0})^2-\frac{2}{3}\frac{E}{E_0}\right)\ln{(183Z^{-\frac{1}{3}})}+\frac{1}{9}\frac{E}{E_0}\right), \tag{1}$$

where α is fine structure constant, r_0 is the classical electron radius, Z is effective atomic number of residual gas, k is photon energy and E_0 is the electron energy circulating in the storage ring. The radius of bremsstrahlung was assumed to be 1cm.

Figure 3(a)-(e) shows the measured and the calculated pulse hight distribution of energy deposition of electrons, positrons and photon in the NaI(Tl) counter at the detection angle of 60°, 75°, 90°, 105°, 120°, respectively. One incident photon of bremsstrahlung causes electromagnetic shower in the Pb target and a number of electrons, positrons and photons are generated. Some of these particles enter the NaI(Tl) counter and deposit their energy.

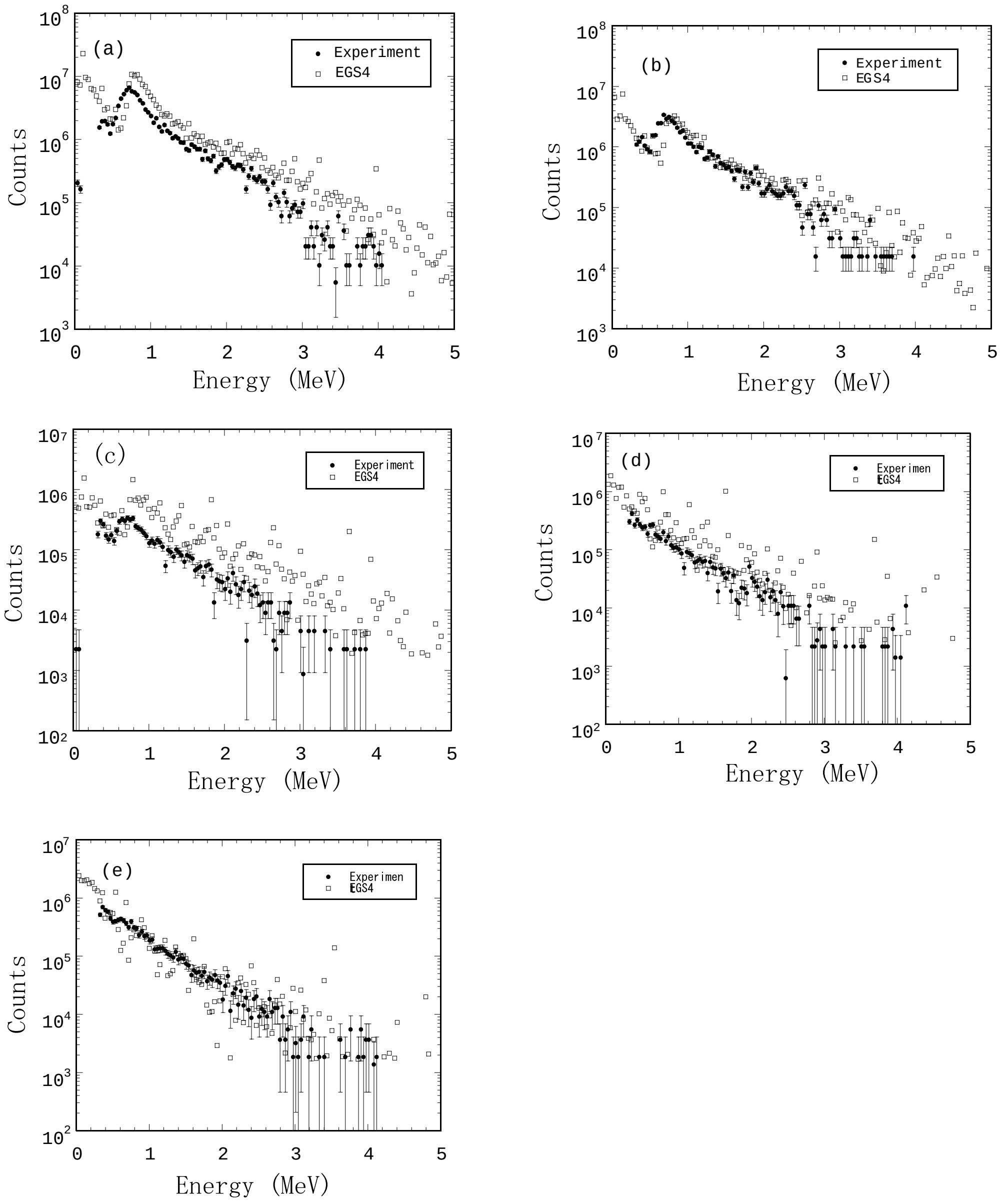

Figure 3: Energy deposition of electromagnetic shower in the NaI(Tl) counter. The detection angle are (a)60°, (b)75°, (c)90°, (d)105° and (e)120°. Closed circles and open squares show the experimental and calculated results, respectively.

The peaks near 0.8 keV in Figure 3(a),(b),(c) agree with the energy of the minimum ionization loss of electrons in NaI(Tl) of 1.8 mm thick. The data of calculations give good agreement with the experiment.

4 Radiation shielding for 1-GeV bremsstrahlung

There is a plan to construct a small synchrotron radiation facility in Nagoya University. The electron energy, current and circumference of the storage ring are 1 GeV, 300 mA and 36 m, respectively. The storage ring is planed to have 6.40 m straight sections.

We calculated energy deposition of electromagnetic shower in water placed around a Pb shielding block irradiated by 1-GeV bremsstrahlung generated in the straight section in order to evaluate the dose equivalent for various thicknesses of the Pb shielding block. In the calculation, we sampled the energy of bremsstrahlung between 100 MeV to 1 GeV. The atomic number of residual gas in the storage ring was assumed to be 10.

The dose equivalent H is expressed as

$$H = DQ. \tag{2}$$

D is the average energy deposition in water with unit mass. D was evaluated at the depth of 1 cm from the surface of the water. Q is quality factor and equal to 1 for photons, electrons and positrons[3].

Figure 4 shows the dose equivalent of electromagnetic shower in water which was placed at 1 m from the Pb block for one incident photon. The cross section of the Pb blocks was 10 cm $\times$ 10cm. The calculation was performed for three thicknesses of Pb blocks. Open diamonds, open squares and crosses are the results for the thickness of 5 cm, 10 cm and 15 cm, respectively.

Figure 5(a)-(c) show spatial distribution of the dose equivalent of electromagnetic shower for one week of running time. In this calculation, we assumed that the electron current was constant of 300 mA and the storage ring worked 40 hours in a week.

High energy photons generate neutrons in the shielding block by photo-nuclear reactions[3]. We calculated neutron yield caused by giant resonance in the Pb shielding block. The neutron yield Y is expressed by the following equation[4],

$$Y = N_0 \frac{\rho}{A} \int_{E_{th}}^{E_{max}} \frac{dl}{dk} \sigma(k) dk \tag{3}$$

$$\sigma(k) = \frac{\sigma_m}{1 + \frac{(k^2 - k_m^2)^2}{k^2 \Gamma^2}}, \tag{4}$$

where N_0 is Avogadro constant, ρ is the density of Pb block, A is the mass number of Pb, $E_{max} = 40$ MeV is maximum photon energy for giant resonance and $E_{th} = 6.7$ MeV is the threshold energy for giant resonance. $\frac{dl}{dk}$ is differential track length calculated by EGS4. $\sigma(k)$ is the cross section of one neutron production by giant resonance. σ_m, k_m and Γ are the maximum cross section of giant resonance (639 mb), the photon energy for σ_m (13.4 MeV) and half width of the cross section (4.07 MeV), respectively. The dose equivalent D is

$$D = \frac{YH}{4\pi r^2}, \tag{5}$$

where r is the distance from the Pb block.

Figure 6 shows the result of our calculation of the dose equivalent of neutrons caused by giant resonance at 1 m from the Pb block. Open squares and open diamonds show the results for 1 GeV- and 0.7-GeV bremsstrahlung, respectively. The dose equivalent increases with the thickness of the Pb block and saturate at 10 cm.

In this calculation, we do not consider the absorption of neutrons in the Pb block so that the dose equivalent is constant for the thicknesses over 10 cm.

5 Conclusion

We measured electromagnetic shower using NaI(Tl) scintillation counter placed around a Pb block irradiated by 700-MeV gas bremsstrahlung at HiSOR. We performed simulation of the experiment by using EGS4 Monte Carlo code. The simulation gave good agreement with the experiment.

We evaluated the dose equivalent of electromagnetic shower and neutrons caused by 1-GeV bremsstrahlung in order to estimate the thickness of a shielding Pb block. Pb block of 10 cm $\times$ 10 cm $\times$ 15 cm is needed to restrict dose equivalent under 1mSv/w. The dose equivalent of neutrons are the same order as that of electromagnetic shower for the 15 cm thick Pb block.

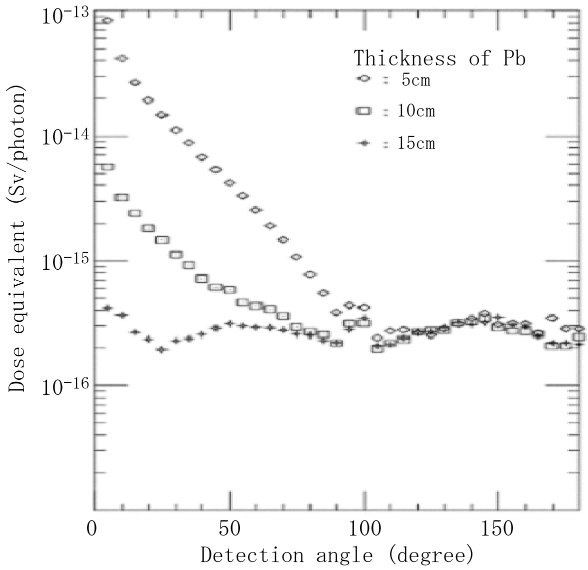

Figure 4: Calculated results of dose equivalent of electromagnetic shower at 1 m from Pb block irradiated by 1-GeV bremsstrahlung. The cross section of the blocks is 10 cm × 10 cm and the thickness is 5 cm (open diamonds), 10 cm (open squares) and 15 cm (crosses).

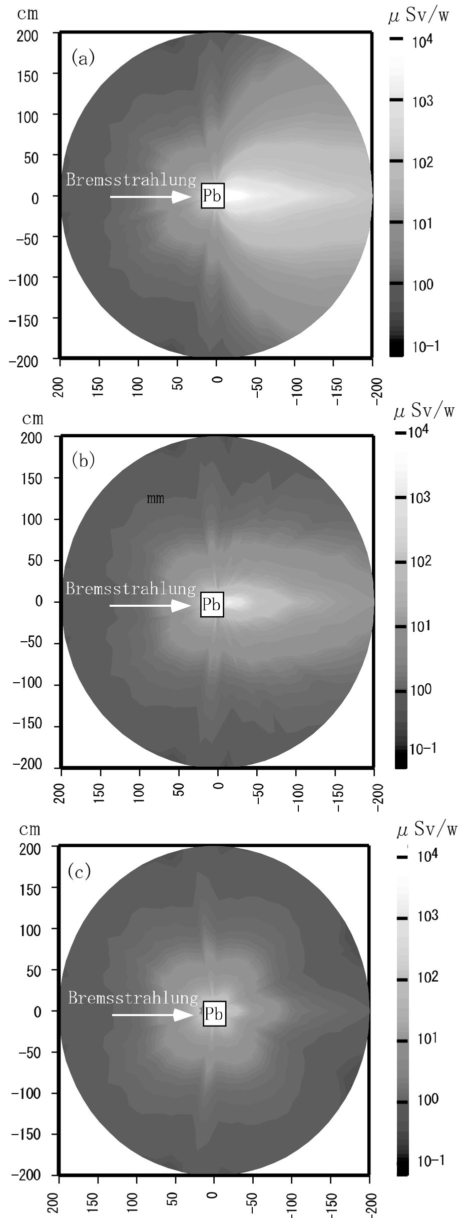

Figure 5: Spatial distribution in horizontal plane of dose equivalent of electromagnetic shower around a Pb block irradiated by 1-GeV bremsstrahlung calculated by using EGS4. The size of the Pb blocks are (a)10 cm × 10 cm × 5 cm, (b)10 cm × 10 cm × 10 cm and (c)10 cm × 10 cm × 15 cm.

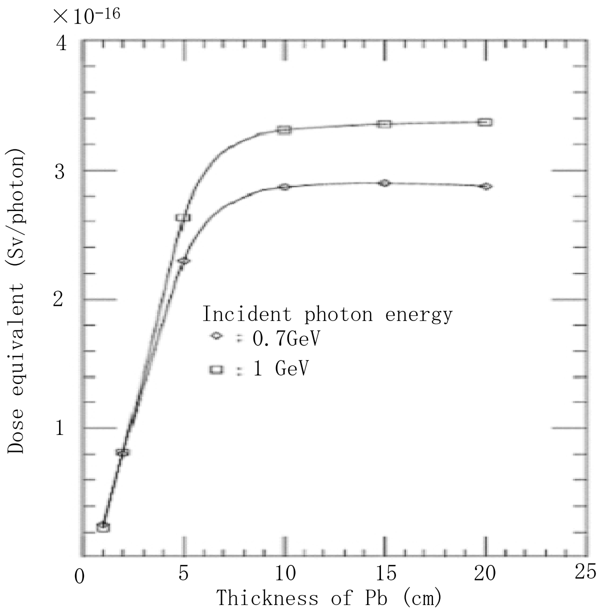

Figure 6: Calculated results of dose equivalent by neutrons generated in Pb block caused by giant resonance. The cross section of the Pb block is 10 cm × 10 cm. Open squares and open diamonds show the data for 1-GeV and 0.7-GeV bremsstrahlung.

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