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Shielding calculation for the thickness of the SR facility safety shutter

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Abstract The safety shutter of the SR (synchrotron radiation) facility located at the front end of the facility is an indispensable component for radiation protection. Its thickness is decided by the gas bremsstrahlung produced in the SR facility storage ring by the interaction of electrons with the residual gas molecules in the vacuum chamber of the storage ring. In the calculation, the 3.5 GeV, 300 mA electron beam and a 15 m long insertion-device straight section (0.133 μPa) were taken into account, and the safety shutter was assumed to be located 12 m away from the end of the straight section. The EGSnrc code based on the Monte-Carlo method and empirical formulas were used, respectively, to calculate the thickness to satisfy the shielding requirement of the safety shutter at the front end of the SR facility, and the results were compared and the availability of EGSnrc was proved.

Key words SR facility, Safety shutter, Monte-Carlo method, EGSnrc code

CLC numbers TL594, TL71

1 Introduction

The gas bremsstrahlung is produced in the storage ring of the SR facility by the interaction of electrons with the residual gas molecules in the vacuum chamber of the storage ring. At the front end of the insertion-device beam-lines, the straight section of the insertion-device is 15 m long, and the distance between the end of the straight section and the safety shutter's location is 12 m. The radiation emerges in a narrow cone tangential to the beam path with the characteristic emission angle mc^2/E, which is the ratio of the rest mass of the electron to its kinetic energy [1]. The high-energy radiation spectrum is simulated for the 15 m long section and a 1×10^4 Pa pressure by EGSnrc and then linearly scaled to 0.133 μPa, as shown in Fig.1.

From Fig.1, it is concluded that the maximum energy of this high-energy radiation can extend up to the electron energy (3.5 GeV), which can be a severe challenge in shielding because of its high energy.

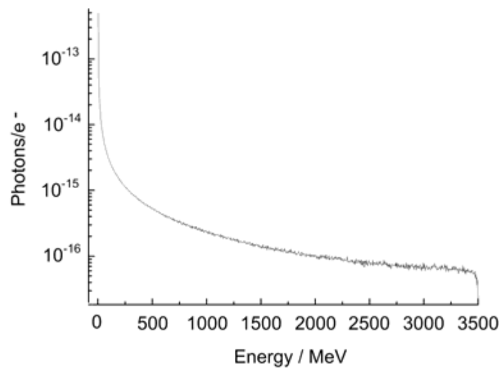

Fig.1 Gas bremsstrahlung spectrum for the 15 m long, 0.133 μPa straight section.

The gas bremsstrahlung, comprising of high-energy photons, produces an electromagnetic shower when it encounters the safety shutter. If the safety shutter is not thick enough to fully contain an electromagnetic shower, considerable scattering of the high-energy radiation may occur. On the other hand, the electromagnetic showers may also produce photoneutrons, especially in high-Z materials.

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A total dose rate of less than 2 μSv·h^{-1} is adopted as the shielding objective. This corresponds to an annual cumulative dose of 4 mSv[2] for 2000 hours of occupancy. However, in the case of the primary bremsstrahlung scattering, half of the dose allowance is reserved for the photoneutrons. Therefore, the design criterion adopted in such cases has a photon dose rate less than 1 μSv·h^{-1} [3].

2 Calculation method

2.1 Semi-empirical formula

Using the equation developed by Tromba and Rindip[1], the primary dose rate because of the gas bremsstrahlung is depicted as:

$$D.R._{(10\mathrm{m})} = 1.7\times10^{-10} E^{2.43} \frac{P}{P_{\mathrm{atm}}} IL \qquad (1)$$

where $D.R._{(10\mathrm{m})}$ provides the dose rate (μSv·h^{-1}) at 10 m from the end of the straight section, E is the electron energy (MeV), (P/P_{atm}) is the ratio of the gas pressure to the atmospheric pressure, I is the beam current (e$^-$/s), and L is the length of the straight section (m).

A more generalized equation provides the dose rate at any distance r(m) from the center of the straight section as depicted below:

$$D.R._{(r)} = D.R._{(10\mathrm{m})}\left(\frac{10+L/2}{r}\right)^2 \qquad (2)$$

Another analysis by Ferrari *et al.*[4] developed the following equation for the primary dose rate caused by the gas bremsstrahlung:

$$D.R. = 2.5\times10^{-21}\left(\frac{E}{mc^2}\right)^{2.67}\left(\frac{L}{D(L+D)}\right) I \left(\frac{P}{P_0}\right) \qquad (3)$$

where E is the electron energy(MeV), mc^2 = 0.511 MeV, (P/P_0) is the ratio of the vacuum pressure to 0.133 μPa, I is the beam current (e$^-$/s), L is the length of the straight section (m), and D is the distance between the end of the straight section and the location of the shutter (m).

2.2 Monte-Carlo calculation by EGSnrc

The interaction of bremsstrahlung with materials can be simulated by EGSnrc, which is a powerful Monte-Carlo computer code that simulates the coupled transport of photons and electrons with energies ranging from 1 keV to several TeV. It also contains a stand-alone preprocessing program PEGS4, which provides cross-sections to be used by EGSnrc, using cross-section tables for elements 1 through 100. The physical processes that are simulated in this program are: bremsstrahlung production, positron annihilation at rest and in flight, Moliere multiple scattering, Moller and Bhabha scattering, Compton scattering, coherent scattering, pair production, photoelectric effect, the continuous energy loss and the relaxation of excited atoms. The geometry input and output are to be specified by the user-written subroutines [5]. EGSnrc calculates the gas bremsstrahlung dose at a given location in a configuration from the energy deposited in the standard ICRU (International Commission on Radiation Units and Measurements) tissue placed at that location. As the EGSnrc result is expressed as the dose per photon, the dose rate from the bremsstrahlung is obtained by multiplying the dose per photon with the total number of photons produced per unit time in the insertion-device vacuum chamber.

3 Results and discussion

3.1 Calculation results using semi-empirical formulas

According to Eq.(1), the dose rate at 10 m from the end of the straight section is 2575 mSv·h^{-1}. Based on this result and Eq.(2), the dose rate at the location of the safety shutter is 2074 mSv·h^{-1}. The thickness of the safety shutter can be calculated using the following equation:

$$t = -\frac{1}{\lambda}\ln\left(\frac{D_r}{D_0}\right) \qquad (4)$$

where t is the total thickness of the safety shutter (cm), D_{r} is the dose limitation of the SR facility, D_0 is the dose rate without shielding, and λ is the minimum linear attenuation coefficient (cm^{-1}) denoted as $\lambda = \mu\rho$[6], where μ is the minimum mass attenuation coefficient (cm^2·g^{-1}) and ρ is the material density (g·cm^{-3}).

Thus, the thickness of the safety shutter is determined by the mass attenuation coefficient of the material. In general, the materials having large mass attenuation coefficients are always chosen for the safety shutter shielding. It is most likely that either tungsten or lead is the material to be used. Figs.2 and 3 show the photon attenuation as a function of energy, in Pb and W, respectively [7].

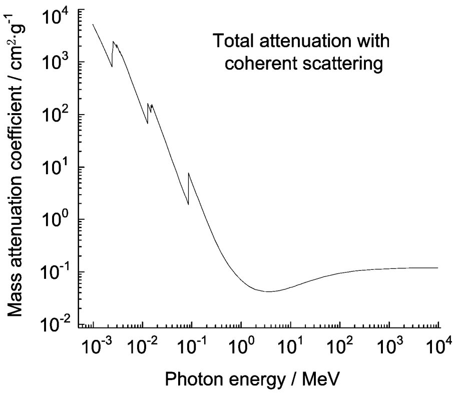

Fig.2 The mass attenuation coefficient for Pb.

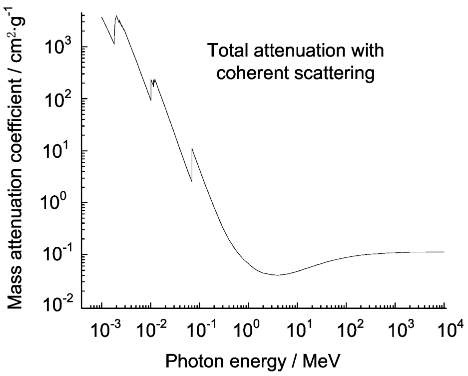

Fig.3 The mass attenuation coefficient for W.

As shown in Fig.2, the minimum mass attenuation coefficient of Pb (ρ = 11.35 g·cm^{-3}) is 0.042 cm^2·g^{-1}. The minimum linear attenuation coefficient λ is 0.4767 cm^{-1}. In view of conservative estimate, the minimum linear attenuation coefficient is used for calculating the thickness of the safety shutter. On the other hand, by using tungsten (ρ = 19.3 g·cm^{-3}) as the shielding material, as shown in Fig.3, a conservative estimate of μ = 0.0404 cm^2·g^{-1} and λ = 0.7792 cm^{-1} is obtained.

It is easy to calculate the thickness of the safety shutter, and the mass attenuation coefficient of W or Pb using Eq.(4). The 29.1 cm thick lead or 17.8 cm thick tungsten is sufficient to satisfy the dose-rate criteria. Also, in this study, the thickness of the safety shutter is calculated using Eqs.(3) and (4). A 30.3 cm thick Pb or 18.5 cm thick W can satisfy the shielding requirements of the SR facility.

3.2 Calculation results by EGSnrc

In the EGSnrc code system, the gas bremsstrahlung is simulated by the 3.5 GeV electron beam, which interacts with normal pressure air [8] of 1 m length. The radiation of the gas bremsstrahlung directly hits the safety shutter. At the rear of the safety shutter, several 1 cm^3 small tissue cubes that are in contact with the safety shutter are used as dose absorbers. A total of 10 million events are simulated. The simulation scheme is shown in Fig.4.

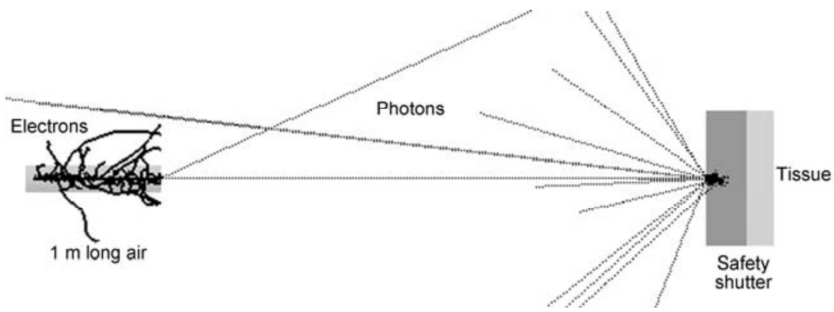

Fig.4 Simulation scheme (not scaled).

Before calculating the thickness of the shielding material, the depth–energy curve should be drawn first to adjust the interaction of the gas bremsstrahlung with the shielding material.

It is clear from Fig. 5 that the deposit energy in the safety shutter decreases as the depth increases according to the exponential decay law at a depth of about 5 cm. Based on this result and the deposit energy in the 1 cm^3 tissue cubes, several thicknesses (> 5 cm) of the two common shielding materials (Pb, W) are simulated by EGSnrc, and the maximum dose rate of each thickness is then calculated at 0.133 μPa and 15 m long straight section for a 3.5 GeV, 300 mA electron beam using the linear scale.

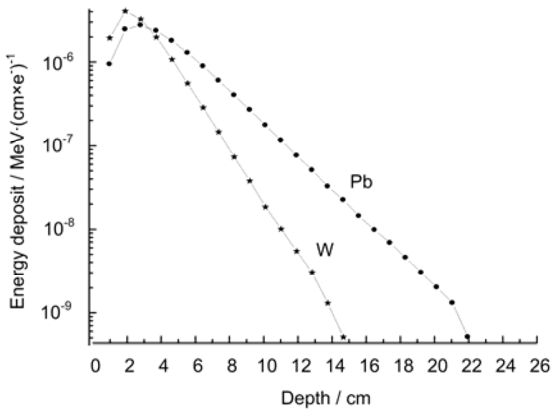

Fig.5 Energy deposit in Pb or W.

The fit equation is then formed according to the exponential decay law:

$$D = e^{a} \times e^{(-bx)} \quad (5)$$

where $a = 16.28 \pm 0.25$ and $b = 0.59 \pm 0.02$ for Pb, and $a = 16.52 \pm 0.12$ and $b = 0.97 \pm 0.01$ for W.

Considering personal safety, the conservative fit line is made to calculate the thickness of Pb or W. Fig. 6 shows the dose rate with different thickness of Pb or W shielding under the condition of the most serious error. According to the shielding objectives, it is clear from Fig.6 that the 29 cm thick Pb or the 17.5 cm thick W is sufficient to meet the shielding requirements.

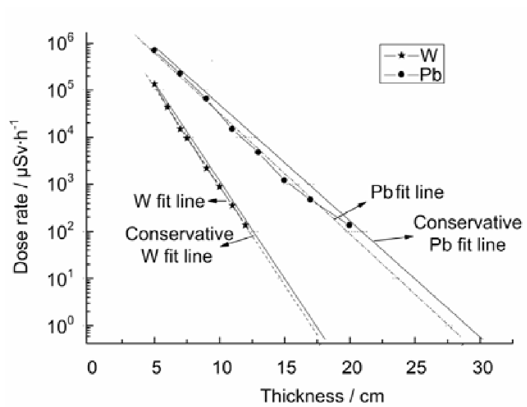

Fig.6 The Pb or W thickness vs. the dose rate.

4 Conclusions

The following conclusions are drawn based on the calculation for the safety shutter located at the front end of the SR facility using the semiempirical equation and EGSnrc:

(a) A thickness of more than 29 cm for lead or 17.5 cm for tungsten is sufficient to satisfy the dose objectives.

(b) When the storage ring parameters are changed, the thickness of the safety shutter needs to be recalculated using the same methods.

(c) The calculation results of EGSnrc and the semiempirical calculation are almost the same. Therefore, EGSnrc can be used for the shielding calculation.

(d) The empirical equation was developed using the EGS old version EGS4. As EGS4 simulates only the high-energy electron and the gamma shower, and at the high-energy section, the attenuation coefficient tends to be steady and close to the minimum attenuation coefficient, it is reasonable to use the minimum attenuation coefficient as the exponential decay coefficient. Considering the low-energy transport model in EGSnrc, the exponential decay coefficient simulated by EGSnrc is larger than the minimum attenuation coefficient obtained from the result.

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