Estimate of the Shielding Parameters for the Heavy Ion Accelerator Facility by Using a Monte Carlo Simulation

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For a conceptual shielding design of the Korea Rare Isotope Accelerator (KoRIA) project, the shielding parameters for the source terms and the attenuation lengths for a simple exponential formula were determined based on simulations using the PHITS Monte Carlo code. Simulations were performed for angular and energy spectra of secondary neutrons from an iron target of full stopping thickness or a thin graphite target bombarded by heavy ions of $^{238}$U, $^{86}$Kr, $^{48}$Ca (200 ~ 270 MeV/u) and protons (600 MeV). Using the thus obtained neutron energy spectra for various angles, we also simulated attenuations of high-energy neutrons through 8-m-thick shields of concrete or iron. By fitting the exponential formula to the attenuation profiles, we obtained shielding parameters for various combinations of projectile, target, angle and shielding material. The parameters were summarized for a point beam loss and for a uniform beam loss along the accelerator beam line. Appropriate shielding thicknesses of concrete and iron could be estimated comparatively easily for various conditions in the heavy ion accelerator facility.

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I. INTRODUCTION

For the Korea Rare Isotope Accelerator (KoRIA) project, a few hundred kW power of the heavy ion beam is planned to produce RI beams effectively. For such a high-power accelerator facility, a massive shielding wall, several meters in thickness, is necessary between the beam line and the personnel working area to suppress the prompt radiation. Since neutrons have high penetrability, the prompt radiation is mainly composed of neutrons originally generated by beam losses at a beam dump, a target or beam-line components.

Recently, Monte Carlo codes have been widely used to simulate beam interactions with materials and the radiation environment at the accelerator facility. However, simulation of particle transmission with deep penetration through a massive shield generally needs sophisticated techniques and a large computing time. To avoid such a complexity in the early stage of conceptual design of a facility, empirical equations with an exponential form, such as the Moyer Model [1], are often used to evaluate the external dose rate due to the prompt radiation behind a massive shield. However, the parameters for the model have been well studied mostly for proton accelerators in an energy range above several GeV [2,3]. In this work, the shielding parameters for source terms and the attenuation lengths for a simple exponential formula were investigated for heavy ions in an energy range around several hundred MeV based on simulations using the PHITS Monte Carlo code [4].

II. MONTE CARLO SIMULATIONS

1. Secondary Neutrons from Target or Beam-line Components due to Beam Interactions

The characteristic of the targets used for the simulations are given in Table 1. A thin graphite target of 0.9 g/cm² in thickness was employed as an in-flight target for the RI beam production. The target size used in the simulation was a 25-mm radius and a 4-mm thickness with a density of 2.25 g/cm³. This target thickness is equivalent to 5 mm with a density of 1.8 g/cm³. On the other hand, thick iron targets were chosen to estimate the source term at beam-line components caused...
Table 1. Characteristics of targets used in the simulations.

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Carbon (2.25 g/cm$^3$)</th>
<th>Iron (7.8 g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 MeV/u U-238</td>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>240 MeV/u Kr-86</td>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>270 MeV/u Ca-48</td>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>600 MeV proton</td>
<td>25</td>
<td>4</td>
</tr>
</tbody>
</table>

by beam loss due to a beam halo or an operation failure. The iron target thickness was determined to be around 1.1 $\sim$ 1.2 times thicker than the stopping range of projectiles because the maximum fluxes of high-energy neutrons with energies above 20 MeV, except in the 600-MeV proton case, are available in the forward direction when the thickness is the projectile range. The self-shielding effect of high energy neutrons in the forward direction is not negligible for 600-MeV protons in the 30-cm-thick iron target. However, reducing radius suppresses the self-shielding effect not only for the side and the backward directions but also for the forward direction. The radius of the iron target for all projectiles was determined to be 5 mm, which is short enough to neglect the neutron self-shielding effect; escape of the primary beam from side of the target is also negligible.

The angular and the energy spectra of secondary neutrons from these targets bombarded by heavy ions or protons were simulated in the energy range above 1 MeV. The spectra of neutrons of 9 angles for various projectile injections are shown in Figs. 1 and 2 for iron and carbon targets, respectively.

Figures 3(a) and (b) shows the angular flux of high-energy neutrons integrated over energies above 20 MeV, which are normalized to a 1-kW beam injection, in the iron and carbon targets, respectively. From these figures, secondary neutrons due to heavy-ion bombardments have strong forwardness compared to those due to proton bombardment. At the same beam power, higher fluxes in the side and the backward directions were obtained on both targets for 600-MeV protons compared with heavy ions.

2. Dose Attenuation through a Massive Shield

Using the thus obtained neutron energy spectra from the target by projectile injections, we performed transmission simulations of high-energy neutron above 20 MeV through massive shielding of concrete or iron up to 8 m in thickness by using the PHITS code. An importance method was used as a variance reduction technique in the Monte Carlo simulation to get good statistics for neutrons in deep shielding regions. Figure 4 shows attenuation profiles of the prompt dose rate of high-energy neutrons through 8-m-thick shields of concrete and iron simulated using the source neutron spectra at various angles. Only for 150 $\sim$ 180 degrees, the attenuation profiles strongly depend on the poor statistics of high energy part of the spectrum of the source term because of the strong forwardness of secondary neutrons due to heavy ion injection. In order to avoid the risk of underestimating the dose rates, therefore, we will use shielding parameters for 110 $\sim$ 150 degree for all projectile-target combinations in directions above 150 degree.

A transmission simulation through an 8-m concrete shield with neutrons in the energy range down to thermal energy (0.025 eV) was also performed only for one case using the neutron source from a graphite target at 0 degrees for a 200 MeV/u$^{238}$U beam. The neutron energy spectra down to thermal neutron energy at various depths in the concrete shield are shown in Fig. 5. From this figure, neutron energy spectra down to thermal energy are in an equilibrium state, keeping their spectral shapes, in a concrete shield after a massive shield. The total prompt dose rates, including photons and neutrons, in the whole energy range were found to be 1.6 $\sim$ 1.9 times that of the high-energy neutrons for all angles [5]. Therefore, using a correction factor of 2.0 on the safe side, we can predict the total prompt dose rate behind the last concrete shield from the results of the transmission simulations with high-energy neutrons above 20 MeV.

III. FORMULA AND PARAMETERS

1. Formula for the Shield Thickness Determination

Generally, prompt dose rates behind a massive shielding can be approximately expressed using a simple exponential formula. For point beam loss, the prompt dose rate $H$ [$\mu$Sv/h] at an estimation point is expressed as

$$H = JH_0 \frac{1}{\sqrt{2\pi}} \exp \left( -\frac{d\rho}{\lambda} \right),$$  

where

$J$: beam injection at a source point [W],

$H_0$: prompt dose rate at a shielded point [$\mu$Sv/h],

$d\rho$: penetration depth of the primary beam [$cm$],

$\lambda$: mean free path of the primary beam [$cm$].

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$\lambda$: mean free path of the primary beam [$cm$].
Fig. 1. (Color online) Simulated angular and energy spectra of secondary neutrons from an iron target.

Fig. 2. (Color online) Simulated angular and energy spectra of secondary neutrons from a graphite target.
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Fig. 3. (Color online) Angular flux of high-energy neutrons above 20 MeV for various projectile-target combinations normalized to a 1-kW beam injection.

Fig. 4. (Color online) Attenuation profiles of the high-energy neutron dose through an 8-m thick concrete shield.

Fig. 5. (Color online) Neutron energy spectra down to thermal energy inside the concrete shield.

\[ H = J H_0 \frac{1}{r} \exp \left( -\frac{d_1 \rho_1}{\lambda_1} \right) \exp \left( -\frac{d_2 \rho_2}{\lambda_2} \right) \cdots \] (2)

On the other hand, in case of beam loss uniformly along the beam line, the dose rate behind massive shield is expressed as

\[ H = \frac{dJ}{dL} H_0 \frac{1}{r} \exp \left( -\frac{d\rho}{\lambda} \right), \] (3)

where

\( (dJ/dL) \): amount of uniform beam hit per unit length [W/m].

\( H_0 \): source term [\((\mu Sv/h) \text{ cm}^2 / \text{W}\)].

The other parameter in Eq. (3) are the same as those in Eq. (1).
Table 2. Shielding parameters of $H_0$ for point loss and uniform loss.

<table>
<thead>
<tr>
<th>Target</th>
<th>Beam</th>
<th>$H_0$ [($\mu$Sv/h) cm$^2$/W] for point loss</th>
<th>$H_0$ for uniform loss [($\mu$Sv/h) cm/(W/m)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$0^\circ$ – $5^\circ$</td>
<td>$10^\circ$</td>
</tr>
<tr>
<td>Carbon (0.9 g/cm$^2$ thick)</td>
<td>200 MeV/u U-238</td>
<td>8.3E+10</td>
<td>3.7E+10</td>
</tr>
<tr>
<td></td>
<td>240 MeV/u Kr-86</td>
<td>1.1E+11</td>
<td>4.2E+10</td>
</tr>
<tr>
<td></td>
<td>270 MeV/u Ca-48</td>
<td>1.1E+11</td>
<td>4.0E+10</td>
</tr>
<tr>
<td></td>
<td>600 MeV proton</td>
<td>1.0E+10</td>
<td>1.8E+09</td>
</tr>
<tr>
<td>Fe (full stop)</td>
<td>200 MeV/u U-238</td>
<td>3.5E+10</td>
<td>1.8E+10</td>
</tr>
<tr>
<td></td>
<td>240 MeV/u Kr-86</td>
<td>8.1E+10</td>
<td>3.5E+10</td>
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<tr>
<td></td>
<td>270 MeV/u Ca-48</td>
<td>1.5E+11</td>
<td>6.5E+10</td>
</tr>
<tr>
<td></td>
<td>600 MeV proton</td>
<td>9.7E+10</td>
<td>8.5E+10</td>
</tr>
</tbody>
</table>

* Interpolation is recommended for angles where parameters are not given.

Table 3. Shielding parameters of $\lambda$ for point loss and uniform loss.

<table>
<thead>
<tr>
<th>Shield</th>
<th>Beam</th>
<th>$\lambda$ [g/cm$^2$] for point loss</th>
<th>$\lambda$ [g/cm$^2$] for uniform loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$0^\circ$ – $5^\circ$</td>
<td>$10^\circ$</td>
</tr>
<tr>
<td>Concrete</td>
<td>200 MeV/u U-238</td>
<td>117</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td>240 MeV/u Kr-86</td>
<td>124</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>270 MeV/u Ca-48</td>
<td>126</td>
<td>126</td>
</tr>
<tr>
<td></td>
<td>600 MeV proton</td>
<td>128</td>
<td>129</td>
</tr>
<tr>
<td>Iron</td>
<td>200 MeV/u U-238</td>
<td>143</td>
<td>143</td>
</tr>
<tr>
<td></td>
<td>240 MeV/u Kr-86</td>
<td>147</td>
<td>147</td>
</tr>
<tr>
<td></td>
<td>270 MeV/u Ca-48</td>
<td>149</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>600 MeV proton</td>
<td>150</td>
<td>150</td>
</tr>
</tbody>
</table>

* Interpolation is recommended for angles where parameters are not given.

2. Parameter Estimate

All obtained attenuation profiles for the prompt dose rates were fitted with Eq. (1), and shielding parameters of $H_0$ and $\lambda$ for high-energy neutrons were obtained for various projectile-target combinations for various angles from the beam direction. The fitting images are exemplified in Fig. 6. The values of $H_0$ were obtained as the values at 0-cm-thickness shielding on the extrapolated fitting lines and were generally higher in forward angle and lower in backward angle than the original data at 0 cm because of the spectral build up shown in Fig. 6. Finally, the values of $H_0$ for the high-energy dose were converted to those for the total dose with the correction factor 2.0, which is mentioned in the previous section. Two $H_0$ values, are for a concrete shield and the other for an iron shield, were obtained for one combination of target-projectile, and generally the values for the iron shield are a little higher than those for the concrete shield because of steeper slope of fitting curve for the iron case. Therefore, the $H_0$ value for iron was employed for each source term. The maximum difference is less than a factor of 2 in this work. The obtained shielding parameters for the total prompt dose rate are given in Tables 2 and 3 for $H_0$ and $\lambda$, respectively.

The shielding parameters for uniform loss were also estimated by using Eq. (1) and its parameters to integrate the dose rates due to multiple point losses. The uniform...
beam hit of 1 W/m for iron targets of full stopping thickness was modeled by locating 0.5-watt point losses every 0.5 m along the beam line from -30 m downstream to 10 m upstream. Dose contributions from all the beam loss points to the estimation point at 0-m location were integrated, and dose rates for uniform loss were obtained at various depths up to a 10-m thickness of a concrete or an iron shield. After the thus obtained attenuation profiles for all projectiles had been fitted to Eq. (3), shielding parameters of \( H_0 \) and \( \lambda \) were obtained as given in Tables 2 and 3.

3. Conditions and Limitations for Practical Applications

The parameters obtained in this study are applicable in the following conditions and limitations.

(i) Total thickness of concrete and 2.5 times of the iron thickness should be at least 2.5 m. The fitting regions of the attenuation profiles are between 250 cm and 700 cm for a concrete shield and between 100 cm and 600 cm for an iron shield; therefore, these parameters should be used for dose estimation points in shielding regions thicker than 250 cm for concrete and 100 cm for iron. Since the shielding ability of iron is about 2.5 times higher than that of concrete, summation of the concrete thickness and 2.5 times the iron thickness should be above 250 cm for the multilayer shielding case.

(ii) Concrete should be placed for the last shield. The shielding parameters were estimated with an assumption that the neutron energy spectrum is in the equilibrium state behind a concrete shield. An energy spectrum behind an iron shield generally has a broad peak around a few hundred keV due to inelastic scattering of neutrons, and photons usually accompany inelastic reactions. These neutrons and photons dominate the prompt dose rate in the iron shielding region. However, placing a concrete shield behind the iron shield reduces these neutrons and photons, and the energy spectrum settles into the equilibrium state in the last layer of the concrete shield. The required thicknesses of the last concrete are evaluated to be 0.4 m, 0.6 m, 0.8 m, 1.2 m, and 1.6 m for iron shield thicknesses of 1 m, 2 m, 4 m, 6 m, and 8 m, respectively [5].

(iii) For the point loss case, the angle from a line perpendicular to the shield is recommended to be below about 30 degrees as shown in Fig. 7. For larger angles from the perpendicular line, the shield part of the direct line becomes much longer as shown in Fig. 7(d), and neutrons through another thinner path sometimes contribute considerably under actual conditions. Since the estimated parameters were obtained by using neutron shielding simulations with a perpendicular injection, small angles from the perpendicular line are recommended for using the equation and the parameters to avoid underestimates. In the case when the beam is parallel to the shield, like Fig. 7(a), an estimation directions of 60 – 120 degree from the beam direction (± 30 degree from the perpendicular line) is recommended; however, results obtained by using the formula sometimes provide underestimates in thick regions for forward angles below 80 degrees [5].

(iv) For the uniform line loss case, Eq. (3) can be used only for a beam line parallel to the shielding wall, and the parameters \( r, d, \) and \( a \) are the distances in a direction perpendicular to the shield.
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REFERENCES