Shielding parameter evaluation
for KoRIA heavy ion accelerator facility

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Pohang Accelerator Laboratory
POSTECH
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Pohang Accelerator Laboratory (PAL), Pohang, 790-784 Korea

For a conceptual shielding design of the Korea Rare Isotope Accelerator (KoRIA) project, shielding parameters of source terms and attenuation lengths for a simple exponential formula were determined based on Monte Carlo simulations using the PHITS 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, attenuations of high energy neutrons through 8-m thick shields of concrete or iron were also simulated. By fitting the exponential formula to the attenuation profiles, shielding parameters were obtained 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 thickness of concrete and iron can be estimated comparatively easily for various conditions in the heavy ion accelerator facility.

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 such as a several meter thickness is necessary between a beam line and a personnel working area to suppress the prompt radiation. Since neutrons have high penetrability, the prompt radiation is mainly composed of neutrons which are originally generated by beam losses at a beam dump, a target or beam line components.

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

II. MONTE CARLO SIMULATIONS

1. Code validation

For a conceptual shielding design of the KoRIA facility, the PHITS code was used to estimate a source term due to the beam interaction to target materials. First of all, neutron production simulations for existing data of the heavy ion experiments were performed to validate the PHITS simulation code. Fig. 1 shows angular and energy spectra of neutrons produced from targets bombarded by heavy ions.
compared between the HIMAC experiments [5] and PHITS code simulations. From the figures, PHITS code generally provides good agreements with the experimental data within a factor of 2 in most of the energy range.

2. Secondary neutrons from target or beam line components by beam interaction

Characteristic of targets used for the simulations are given in Table 1. A thin graphite target of 0.9 g/cm² thickness was employed as an in-flight target for the RI beam production. The target size used in the simulation was 25-mm radius by 4-mm thickness with density of 2.25 g/cm³. This target thickness is equivalent to 5-mm with density of 1.8 g/cm³. On the other hand, thick iron targets were chosen for estimation of source term at beam line components by beam loss due to a beam halo or an operation failure. Iron target thickness was determined to be around 1.1~1.2 times thicker than the stopping range of projectiles since the maximum flux of high-energy neutrons above 20 MeV are available in the forward direction when the thickness is the projectile range except in the 600-MeV proton case. Self-shielding effect of high energy neutrons in forward direction is not negligible for 600-MeV proton in the 30-cm thick iron target. However, reducing radius suppresses the self-shielding effect not only for side and backward direction but also for a forward direction. The radius of iron target for all projectiles are determined to 5-mm which is short enough to neglect neutron self-shielding effect yet escaping primary beam from side of the target is also negligible. An ISOL target is also used for the RI beam production only using 70 MeV protons.

Angular and energy spectra of secondary neutrons from these targets bombarded by heavy ions or protons were simulated in the energy range above 1 MeV. A part of simulation geometry is shown in Fig.2. The spectra of neutrons in 9 angles by various projectile injections are shown in Figs.3, 4 and 5 for iron, carbon and ISOL target respectively.

Figs. 6(a) and (b) shows angular flux of high energy neutrons integrated above 20 MeV which are normalized by 1-kW beam injection into the iron and carbon targets, respectively. From these figures, secondary neutrons by heavy-ion bombardments have strong forwardness compared with the proton bombardment. In the same beam power, higher fluxes in side and backward direction were obtained by 600-MeV protons on both targets compared with those by heavy ions.

3. Dose attenuation through massive shield

Using the thus obtained neutron energy spectra from the target by projectile injections, transmission simulations of high-energy neutron above 20 MeV through massive shielding of concrete or iron up to 8-m were performed also using the PHITS code. Pencil beam of neutron source is injected into the center of the shield slab, and an importance method was used as a variance reduction technique in the Monte Carlo simulation to get good statistics of neutrons in deep shielding regions. Fig. 7 shows Two-dimensional neutron track plots on the shielding transmission simulations with 8-m thick concrete or iron shield using the neutron source from the graphite target at 0 degree by 200 MeV/u²³⁸U beam as an example. Energy spectra of neutron integrated over the planes in the same depth were scored with surface crossing estimator. Dose rates of high energy neutrons were estimated with the spectra and flux to dose conversion factor [6].

Figs. 8-11 show attenuation profiles of the prompt dose rate of the high-energy neutrons through 8-m thick shield of concrete and iron simulated using the source neutrons spectra of various angles. Only for 150-180 degree, attenuation profiles strongly depend on the poor statistics of high energy part of spectra of source term because of strong forwardness of secondary neutrons due to heavy ion injection. In order to avoid the risk of underestimation of dose rates, therefore, shielding parameters for 110-150 degree will be used for all projectile-target combinations in the direction above 150 degree.
A transmission simulation though 8-m concrete shield with neutrons in the energy range down to thermal energy (0.025eV) was also performed only for one case using the neutron source from the graphite target at 0 degree by 200 MeV/u $^{238}\text{U}$ beam. The neutron energy spectra down to thermal neutron energy at various depths in the concrete shield were shown in Fig. 12. From this figure, neutron energy spectrum down to thermal energy is in equilibrium state, which is keeping its spectrum shape, in a concrete shield after a massive shield. Fig.13 shows a comparison of dose-rate attenuation profiles of total neutrons, high-energy neutrons above 20MeV and photons for 200 MeV/u $^{238}\text{U}$ on Fe target (0 degree) case. Fig.14 shows the ratios of total dose to high-energy neutron dose through concrete shield compared among various angles. From the figure, it was found that total prompt dose rates including photons and neutrons in the whole energy range are 1.6~1.9 times of that of the high-energy neutrons for all angles. Therefore, with using the correction factor of 2.0 as a safer side, total prompt dose rate behind the last concrete shield can be predicted from the results of the transmission simulations with high-energy neutrons above 20 MeV.

III. FORMULA AND PARAMETERS

1. Formula for shield thickness determination

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

$$H = JH_0 \frac{1}{r^2} \exp \left( -\frac{d\rho}{\lambda} \right)$$

where

- $J$ : beam injection at a source point [W]
- $H_0$ : source term [($\mu$Sv/h) cm$^2$/W]
- $r$ : distance between a beam hit and an estimation points ($r=a+d$) [cm]
- $a$ : space part of distance $r$ [cm]
- $d$ : shield part of distance $r$ [cm]
- $\rho$ : density of shielding material [g/cm$^3$]
- $\lambda$ : attenuation length [g/cm$^2$]

In case of multi-layer shielding structure, the formula can be expressed with that multiplied by an additional exponential part for another material like

$$H = JH_0 \frac{1}{r^2} \exp \left( -\frac{d_1\rho_1}{\lambda_1} \right) \exp \left( -\frac{d_2\rho_2}{\lambda_2} \right) \cdots$$

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

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

where

- $\frac{dJ}{dL}$ : amount of uniform beam hit in unit length [W/m]
- $H_0$ : source term [($\mu$Sv/h) cm / (W/m)]

The other parameter in Eq.(3) are the same as those in Eq.(1).
2. Parameter estimations

The obtained all attenuation profiles of 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 depending on 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 generally higher in forward angle and lower in backward angle than the original data at 0 cm because of spectrum build up as shown in Fig.15. 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 for concrete and iron shield were obtained for one combination of target-projectile, and generally the values for iron shield is a little higher than those for concrete shield because of steeper slope of fitting curve for iron case. Therefore, $H_0$ 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 the uniform loss were also estimated by integrating the dose rates due to multiple point losses using Eq. (1) and its parameters. Uniform beam hit of 1 W/m to iron targets of full stopping thickness was modeled by locating 0.5-Watt point losses at 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 10-m thickness of concrete or iron shield. After the thus obtained attenuation profiles for all projectiles were 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 application

These parameters are applicable in the following conditions and limitations.

(i) Total thickness of concrete and 2.5 times of iron thickness should be at least 2.5m

The fitting regions of attenuation profiles are between 250-cm and 700-cm thick for concrete and between 100-cm and 600-cm thick region for iron shield, therefore, these parameters should be used for dose estimation points in the shielding region thicker than 250-cm concrete or 100-cm iron. Since shielding ability of iron is about 2.5 times higher than that of concrete, summation of a concrete thickness and a 2.5 times of iron thickness should be above 250 cm for multi-layer 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 equilibrium state behind a concrete shield. As shown in Fig.16, an energy spectrum behind an iron shield generally has a broad peak around a few hundred keV due to inelastic scattering neutrons, and photons are accompanied by the inelastic reactions. These neutrons and photons dominates prompt dose rate in the iron shielding region. However, placing concrete shield behind the iron shield reduces these neutrons and photons, and the energy spectrum settles in the equilibrium state in the last layer of the concrete shield. Figs.17-21 shows dose rate attenuation of total neutrons, high-energy neutrons and photons inside the various thickness of iron shield followed by concrete shield. From the results, required thicknesses of the last concrete are roughly evaluated as follow.

<table>
<thead>
<tr>
<th>Iron thickness</th>
<th>1m</th>
<th>2m</th>
<th>4m</th>
<th>6m</th>
<th>8m</th>
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<tr>
<td>Required last concrete thickness</td>
<td>0.4m</td>
<td>0.6m</td>
<td>0.8m</td>
<td>1.2m</td>
<td>1.6m</td>
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</table>
(iii) For the point loss case, angle from the line perpendicular to the shield is recommended to be below about 30 degree as shown in Fig.22.

In the larger angle from the perpendicular line, shield part of the direct line becomes much longer as shown in Fig.22(d), and neutrons through the other thinner path sometimes contribute considerably in actual condition. Since the estimated parameters were obtained by the neutron shielding simulations with a perpendicular injection, small angles from perpendicular line is recommended for using the equation and parameters to avoid underestimation.

Using simple shielding structure, dose rate results by the formula were compared with the results by the PHITS code using 1-m and 3-m distances between target and shield. Comparisons were performed along the location and angle in the same shield depth for the parallel beam and perpendicular beam to the shield as shown in Figs.23-28 and Figs.29-34, respectively. Proton beam case, results by formula give a good agreement with those by PHITS. However, because of strong forwardness of neutrons by the heavy ion injection, results by the formula sometimes underestimate in thick regions, as shown in Fig.25 as an example, for forward angle in the range below 80 degree even within 30 degree from perpendicular direction of 90 degree.

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

Fig.34 shows a practical application result for a multi-layer shielding case using Eq.(2) with the parameters obtained in this work.

ACKNOWLEDGEMENT

Authors appreciate Dr. Hiroshi Iwase (KEK) and Dr. Koji Niita (RIST) for their useful advices for the PHITS Monte Carlo code.

REFERENCES

Table 1: Characteristics of targets used in the simulations.

<table>
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<td>200 MeV/u U-238</td>
<td>5</td>
<td>2.0</td>
<td>1.7</td>
<td>25</td>
<td>4</td>
<td>167.6</td>
<td>32.4</td>
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<tr>
<td>240 MeV/u Kr-86</td>
<td>5</td>
<td>5.0</td>
<td>4.5</td>
<td>25</td>
<td>4</td>
<td>52.0</td>
<td>188.0</td>
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<tr>
<td>270 MeV/u Ca-48</td>
<td>5</td>
<td>10.0</td>
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<td>25</td>
<td>4</td>
<td>25.9</td>
<td>244.1</td>
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<tr>
<td>600 MeV proton</td>
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<td>300.0</td>
<td>270</td>
<td>25</td>
<td>4</td>
<td>2.1</td>
<td>597.9</td>
</tr>
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</table>

ISOL target (Graphite 1.8 g/cm², UC₂ : 2.5 g/cm²)

| 70 MeV proton | R=35mm graphite window (4mm) + UC₂(30mm) + graphite dump(5.4mm) | Full stopping |

Table 2: Shielding parameters of H₀ for the point loss and the uniform loss.

<table>
<thead>
<tr>
<th>target</th>
<th>Beam</th>
<th>0°-5°</th>
<th>10°</th>
<th>20°</th>
<th>35°</th>
<th>50°</th>
<th>70°</th>
<th>110°</th>
<th>150-180°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>200MeV/u U-238</td>
<td>8.3E+10</td>
<td>3.7E+10</td>
<td>6.9E+09</td>
<td>7.8E+08</td>
<td>1.1E+08</td>
<td>1.5E+07</td>
<td>7.3E+05</td>
<td>2.4E+04</td>
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<tr>
<td>(0, 9g/cm²)</td>
<td>240MeV/u Kr-86</td>
<td>1.1E+11</td>
<td>4.2E+10</td>
<td>7.7E+09</td>
<td>1.1E+09</td>
<td>2.3E+08</td>
<td>3.6E+07</td>
<td>2.2E+06</td>
<td>5.4E+04</td>
</tr>
<tr>
<td>(thick)</td>
<td>270MeV/u Ca-48</td>
<td>1.1E+11</td>
<td>4.0E+10</td>
<td>7.0E+09</td>
<td>1.2E+09</td>
<td>3.0E+08</td>
<td>5.4E+07</td>
<td>3.8E+06</td>
<td>1.3E+05</td>
</tr>
<tr>
<td>600MeV proton</td>
<td>1.0E+10</td>
<td>1.8E+09</td>
<td>1.6E+09</td>
<td>6.7E+08</td>
<td>2.7E+08</td>
<td>9.0E+07</td>
<td>1.5E+07</td>
<td>3.8E+06</td>
<td>-</td>
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<tr>
<td>Fe</td>
<td>200MeV/u U-238</td>
<td>3.5E+10</td>
<td>1.8E+10</td>
<td>3.5E+09</td>
<td>4.7E+08</td>
<td>8.7E+07</td>
<td>1.6E+07</td>
<td>1.0E+06</td>
<td>6.9E+04</td>
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<tr>
<td>(full stop)</td>
<td>240MeV/u Kr-86</td>
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<td>3.5E+10</td>
<td>6.9E+09</td>
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<tr>
<td>(stop)</td>
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<td>1.5E+11</td>
<td>6.5E+10</td>
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<tr>
<td>600MeV proton</td>
<td>9.7E+10</td>
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<td>3.8E+10</td>
<td>1.9E+10</td>
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<td>4.0E+07</td>
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<tr>
<td>70MeV proton</td>
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<td>2.6E+09</td>
<td>2.6E+09</td>
<td>1.4E+09</td>
<td>5.4E+08</td>
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<td>ISOL UC₂</td>
<td>70MeV proton</td>
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<td>3.3E+08</td>
<td>1.5E+08</td>
<td>6.3E+07</td>
<td>1.2E+07</td>
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* Interpolation is recommended for angles where parameters are not given.

Table 3: Shielding parameters of λ for the point loss and the uniform loss.

<table>
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<th>Shield</th>
<th>Beam</th>
<th>0°-5°</th>
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<th>70°</th>
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<th>150-180°</th>
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<td>117</td>
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<td>111</td>
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* Interpolation is recommended for angles where parameters are not given.
Fig. 1: Benchmark simulations of PHITS code compared with HIMAC experimental data for angular and energy spectra of neutrons produced from targets.

Fig. 2: Part of simulation geometry for angular and energy spectra of secondary neutrons from targets.
Fig. 3: Simulated angular and energy spectra of secondary neutrons from the iron target
Fig. 4: Simulated angular and energy spectra of secondary neutrons from the graphite target
Fig. 5: Angular and energy spectra of secondary neutrons from the ISOL target

Fig. 6: Angular flux of high energy neutrons above 20 MeV for various projectile-target combinations normalized by 1-kW beam injection.
Fig. 7: Two-dimensional neutron track plots on the shielding transmission simulations using the neutron source from the graphite target at 0 degree by 200 MeV/u $^{238}$U beam.
Fig. 8: Attenuation profiles of the high-energy neutron dose through shield for 200MeV/u $^{238}$U beam.
Fig. 9: Attenuation profiles of the high-energy neutron dose through shield for 240MeV/u $^{86}$Kr beam.
Fig. 10: Attenuation profiles of the high-energy neutron dose through shield for 270MeV/u $^{48}$Ca beam.
Fig. 11: Attenuation profiles of the high-energy neutron dose through shield for 600 MeV proton beam.
Fig. 11: Attenuation profiles of the high-energy neutron dose through shield for 70MeV proton beam.
Fig. 12: Neutron energy spectra down to thermal energy inside the concrete shield for 200 MeV/u $^{238}$U on Fe target (0 degree).
Fig. 13: Comparison of attenuation profile of dose rate of total neutrons, high-energy neutrons above 20MeV and photons for 200 MeV/u $^{238}$U on Fe target (0 degree).

Fig. 14: Ratios of total dose to high-energy neutrons through concrete shield compared among various angles for 200 MeV/u $^{238}$U on Fe target.
Fig. 15: Image of fitting for the attenuation profile of high-energy prompt dose rate in the iron shield.
Fig. 16: Neutron energy spectra down to thermal energy inside the 6m-iron followed by 2m-concrete shield for 200 MeV/u $^{238}$U on Fe target (0 degree).
Fig. 17: Dose rate attenuation profiles of total neutrons, high-energy neutrons and photons inside the 1m-iron followed by concrete shield.

Fig. 18: Dose rate attenuation profiles of total neutrons, high-energy neutrons and photons inside the 2m-iron followed by concrete shield.
Fig. 19: Dose rate attenuation profiles of total neutrons, high-energy neutrons and photons inside the 4m-iron followed by concrete shield.

Fig. 20: Dose rate attenuation profiles of total neutrons, high-energy neutrons and photons inside the 6m-iron followed by concrete shield.
Fig. 21: Dose rate attenuation profiles of total neutrons, high-energy neutrons and photons inside the 8m-iron followed by concrete shield.

Fig. 22: Images of applicable angle range (a)(b)(c). Angle up to 30 degree from the perpendicular line (dotted line) is applicable to the formulae. $\theta$ is the angle from the beam direction. Example beyond the applicable range (d) is also shown.
Fig. 23: Two dimensional track plots of neutrons with 8m concrete shield for 2-mm-thick Fe target injected by 200 MeV/u $^{238}$U beam in parallel direction to shield surface. (a) 1-m distance and (b) 3-m distance between shield surface and beam injecting point.
Fig. 24: Comparisons of dose rate distributions obtained by PHITS and the formula, along the location in the same shield depth inside 8m concrete shield for 2-mm-thick Fe target injected by 200 MeV/u $^{238}$U beam in parallel direction to shield surface. (a) 1-m distance and (b) 3-m distance between shield surface and beam injecting point.
Fig. 25: Comparisons of dose rate distributions obtained by PHITS and the formula, along the angles from the beam direction in the same shield depth inside 8m concrete shield for 2-mm-thick Fe target injected by 200 MeV/u $^{238}$U beam in parallel direction to shield surface. (a) 1-m distance and (b) 3-m distance between shield surface and beam injecting point.
Fig. 26: Two dimensional track plots of neutrons with 8m concrete shield for 30-mm-thick Fe target injected by 600 MeV proton beam in parallel direction to shield surface. (a) 1-m distance and (b) 3-m distance between shield surface and beam injecting point.
Fig. 27: Comparisons of dose rate distributions obtained by PHITS and the formula, along the location in the same shield depth inside 8m concrete shield for 30-mm-thick Fe target injected by 600 MeV proton beam in parallel direction to shield surface. (a) 1-m distance and (b) 3-m distance between shield surface and beam injecting point.
Fig. 28: Comparisons of dose rate distributions obtained by PHITS and the formula, along the angles from the beam direction in the same shield depth inside 8m concrete shield for 30-mm-thick Fe target injected by 600 MeV proton beam in parallel direction to shield surface. (a) 1-m distance and (b) 3-m distance between shield surface and beam injecting point.
Fig 29. Two dimensional track plots of neutrons with 8m concrete shield for 2-mm-thick Fe target injected by 200 MeV/u $^{238}\text{U}$ beam in perpendicular direction to shield surface. (a) 1-m distance and (b) 3-m distance between shield surface and beam injecting point.
Fig. 30: Comparisons of dose rate distributions obtained by PHITS and the formula, along the location in the same shield depth inside 8m concrete shield for 2-mm-thick Fe target injected by 200 MeV/u $^{238}$U beam in perpendicular direction to shield surface. (a) 1-m distance and (b) 3-m distance.

Fig. 31: Comparisons of dose rate distributions obtained by PHITS and the formula, along the angles from the beam direction in the same shield depth inside 8m concrete shield for 2-mm-thick Fe target injected by 200 MeV/u $^{238}$U beam in perpendicular direction to shield surface. (a) 1-m distance and (b) 3-m distance.
Fig. 32: Two dimensional track plots of neutrons with 8m concrete shield for 30-mm-thick Fe target injected by 600 MeV proton beam in perpendicular direction to shield surface. (a) 1-m distance and (b) 3-m distance between shield surface and beam injecting point.
Fig. 33: Comparisons of dose rate distributions by PHITS and the formula, along the location in the same shield depth inside 8m concrete shield for 30-mm-thick Fe target injected by 600 MeV proton beam in perpendicular direction to shield surface. (a) 1-m distance and (b) 3-m distance.

Fig. 34: Comparisons of dose rate distributions by PHITS and the formula, along the angles from the beam direction in the same shield depth inside 8m concrete shield for 30-mm-thick Fe target injected by 600 MeV proton in perpendicular direction to shield surface. (a) 1-m distance & (b) 3-m distance.
Fig. 35: Example using the formula and parameters for 200 MeV/u $^{238}$U beam in the iron target.