MARS14 MONTE CARLO SIMULATION FOR THE SHIELDING STUDIES OF THE J-PARC 3 GeV RING

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MARS14 Monte Carlo simulations were performed for collimation and shielding studies of the J-PARC 3 GeV synchrotron ring. The beam line module locations in the 348.3 m ring and the curved tunnel sections were described by the ‘MAD-MARS beam line builder’ tool. A 400 MeV proton beam loss distribution, calculated with the STRUCT code, was used as a 4 kW source term in the collimator region, with 1 kW source terms in the injection and extraction regions at 400 MeV and 3 GeV, respectively. Deep penetration calculations were carried out with good statistics using a newly developed three-dimensional multi-layer technique. Prompt dose-rate distributions were calculated inside and outside the concrete and soil shield up to the ground level. Using the calculation results obtained thus, an effective shielding design was made.

INTRODUCTION

A high-energy, intense proton accelerator facility (J-PARC, Japan Proton Accelerator Research Complex) projected by KEK and JAERI is now under construction in the JAERI site. In the facility with a MW beam power machine, neutron penetration through the shield, activation of materials near beam line due to secondary particles produced by a beam loss are serious problems. In this work, simulations by the MARS14 Monte Carlo code1-3 for collimation and shielding studies of the J-PARC 3-GeV synchrotron ring were performed, and effective designs of the tunnel and local shields were determined. In addition, residual dose rates and absorbed dose rates in beam line materials were calculated. This paper describes the prompt dose calculation in the region from injection through collimator, and a detailed description including numerical data are reported in KEK Report 2004-14.

The J-PARC project consists of a 400 MeV linac, a 3 GeV RCS (rapid cycling synchrotron), a 50 GeV synchrotron ring and some experimental halls. Figure 1 shows a horizontal cross section of the MARS14 calculation geometry for the whole beam line tunnel of the 3 GeV RCS. The circumference of the ring is 348.333 m and the position of the charge-exchange foil is set to be at 0.0 m, as shown in Figure 1. 400 MeV protons from the linac are injected through the septum magnet to the foil, followed by the collimator region in the first straight section. Kickers and four extraction septa are located in the second straight section and 3 GeV protons are transported to a 50 GeV ring or to the spallation neutron target. The maximum beam current is scheduled to be 0.333 mA, which is 133 kW at 400 MeV and 1 MW at 3 GeV.

BEAM LOSS DISTRIBUTION

The 400 MeV protons of the beam halo, which are scraped initially at the collimator target, were traced along the whole ring using a multi-turn tracking Monte Carlo code, STRUCT5 for the estimation of the beam-loss distribution6. The beam pipe and the collimator aperture and the magnet fields were taken into account and 50,000 particles were traced...
in the calculation. If the particles go outside the beam pipe boundaries, or lose >30% of the primary kinetic energy, the traces are terminated and particle information is stored for the MARS14 calculation.

The loss in the collimator region from 10 to 60 m was normalised to 4 kW, which is 3% of the total injected beam power predicted based on the space-charge calculation using the Simpson code. From the view point of shielding design of the synchrotron vault, the loss at the septum magnet was assumed to be 1 kW, which is <1% of the total injected beam power. Beam losses at the collimator during injection and extraction that are assumed in this work are given in Table 1.

**MARS MODELLING**

Figure 2a and b show cross sections of the calculation geometries of the beam line tunnel along the beam axis in the region from the injection through the collimator. The beam line is 11.8 m below the ground level and 1.2 m above the floor of the main tunnel. Flux detector regions for the simulation, which are described as rectangular cells, were defined at various positions of the concrete wall and soil region, as shown in the figures, to estimate prompt doses for the study of shield thickness in four directions (up, down, inward and outward) with respect to the beam line. Figure 3 shows a vertical cross section of the tunnel at the collimator, which indicates the names of the flux detector cells.

In the high-beam-loss areas, such as the injection and extraction septa and collimators, prompt dose rates at the soil boundary and ground level become locally much higher than those in the other areas. To avoid the increase of the tunnel wall thickness and minimise the overall amount of the shielding concrete, additional local shields were proposed around the septa and collimators in the shielding design. Detailed geometry, materials and magnetic field distributions for the beam line modules, such as the magnet, collimator, target, septum, bump, kicker and beam pipe, were taken into account. Figure 4a shows the vertical cross section of the bending dipole magnet as an example. A beam pipe of elliptic shape is made of 0.5-cm-thick ceramic. Several detector cells were defined in the yoke region to estimate the dose rates at the inner and outer surfaces. The locations of the beam line modules and the curved tunnel structures in Figure 1 were described by the help of the ‘MAD–MARS beam line builder’ (MMBLB) prepared in the MARS code. MARS build-in materials were used for all materials for shielding and beam line modules. Densities for the shielding materials of concrete, iron and soil were changed as 2.2, 7.7 and 1.5 g cm$^{-3}$, respectively.

<table>
<thead>
<tr>
<th>Region</th>
<th>$E_p$ (GeV)</th>
<th>Power (kW)</th>
<th>Current (µA)</th>
<th>Particle (proton s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection</td>
<td>0.4</td>
<td>1.0</td>
<td>2.5</td>
<td>$1.56 \times 10^{13}$</td>
</tr>
<tr>
<td>Collimator</td>
<td>0.4</td>
<td>4.0</td>
<td>10.0</td>
<td>$6.20 \times 10^{13}$</td>
</tr>
<tr>
<td>Extraction</td>
<td>3.0</td>
<td>1.0</td>
<td>0.333</td>
<td>$2.08 \times 10^{13}$</td>
</tr>
</tbody>
</table>

Table 1. Beam losses at collimator, injection and extraction

Figure 2. Vertical and horizontal cross sections of the beam line tunnel with flux detector cells from the injection through collimators.

Figure 3. Flux detectors and their names used in the calculation in the vertical cross sections of the beam line tunnel perpendicular to the beam axis.
Figure 4. Vertical cross sections of (a) the bending dipole magnet and (b) the injection septum perpendicular to the beam axis.

Figure 5. Calculated prompt dose rate distributions inside the shield of the ceiling wall through the ground level in the region from the injection through the collimator. Vertical shield structure and beam loss distribution are also shown in the same region. Positions and sizes of the flux detectors (UC1~US4) are shown in Figure 3.
The beam loss at the injection was uniformly distributed at the inner coil surface of the septum, as indicated in Figure 4b. The beam loss at the collimator region was given at the corresponding coordinate in the beam line with kinetic energy and vector which were defined by the STRUCT calculation results.

In order to obtain good statistics of particle fluxes and doses up to the ground level through thick concrete and soil shields with a reasonable computing time in the Monte Carlo simulation, a three-dimensional multilayer technique (10,11) was used in the MARS14 calculation. It is reported that the calculation results reproduced the measurement of 4m shield penetration within 60% for high energy neutron flux using this method (10,11). The three-dimensional geometry was divided into several layers of 2–3 m thickness, and a step-by-step calculation was carried out to multiply the number of particles leaked from the previous layer like a splitting method.

RESULTS AND DISCUSSIONS

The calculated prompt dose rate distributions inside the concrete and soil shield in the upward direction is shown in Figure 5 together with the beam loss distribution, the vertical tunnel structure. Although the beam losses of the septum, target and five collimators are dominant, the local shields at these areas attenuated prompt dose rates. The prompt dose rate at the inner surface of the beam line tunnel (UC1) has a peak after the first collimator (COL1) because of the forward scattering at the target and COL1. The soil region, US1, is at the soil–concrete boundary just above the thick concrete shield at the ceiling. As seen in Figure 5, the prompt dose rate distribution of US1 is much lower than 5 mSv h⁻¹ in the collimator region and 11 mSv h⁻¹ in the injection region which are the regulatory limits at the soil–concrete boundary for distributed (line) beam loss and for localised (point) beam loss, respectively. However, these thick concrete shields are inevitable for the distribution of US4 to satisfy the regulatory limit of 0.25 mSv h⁻¹ at the ground level. The same estimation and adjustment were performed also for the extraction region, and shield thickness of the tunnel wall and local shields in the region of the injection, collimator and extraction were finally determined based on these calculation results.

SUMMARY

MARS14 Monte Carlo simulations were performed for shielding studies of the J-PARC 3 GeV RCS. The beam loss distribution calculated by the STRUCT code was used for the collimator region, and local losses of 1 kW were assumed at the injection. A three-dimensional multilayer technique was developed for a deep penetration calculation, and radiation transport through a very thick shield was carried out with good statistics using MARS14 code. An effective shielding design was made using the calculated prompt dose rate distributions inside and outside the shield.

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REFERENCES