Deep Penetration Monte Carlo Calculations for the European Spallation Source ESS

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Abstract. The design of high intensity spallation sources, like the European Spallation Source (ESS) [1] with a proton beam energy of 1334 MeV and a beam power of 5 MW, requires best possible estimates for the biological shield. The use of Monte Carlo simulation techniques in the shielding design calculations represents an increasingly important alternative to the traditional semi-empirical calculations and multidimensional discrete ordinates calculations. In this paper, a Monte Carlo shielding design calculational strategy which utilizes a large body of variance reduction techniques is described. This strategy was implemented to perform a rough evaluation of the proposed conceptual design of the ESS target station shield.

1 Introduction

Shielding design is important for the construction of high-energy accelerator and spallation source facilities, since the cost for the radiation shielding contributes a considerable part of the total cost. Moreover, a shield that is too thick reduces the particle fluxes needed by increasing the distance to the detector. On the contrary, the shield that is too thin results in an unwanted additional radiation exposure to personnel.

Intrinsic to shielding calculations are problems with accuracy as large flux attenuations of several orders of magnitude are to be traced through thick shields. Spallation sources produce neutrons covering about 14 decades in energy. The presence of high-energy deeply penetrating neutrons as a result of nucleon-nucleon spallation reactions complicates the design of the biological shield. The high-energy neutrons have a strong angular dependence and they can, particularly in the extreme forward direction of the proton beam, reach energies up to the energy of the incident protons. Neutrons are attenuated by elastic and inelastic scattering, and especially, below the lowest energy threshold for inelastic scattering (the pion production threshold is about 290 MeV) they can build up and penetrate the shield in large numbers since elastic scattering is not an effective means of absorbing high-energy neutrons. Thus, forward-going neutrons constitute the most significant shielding problem. Moreover, the attenuation of the high-energy neutrons generates (i) secondary evaporation neutrons, which are emitted isotropically and have energies down to the thermal region, and (ii) additional secondary gamma rays. Thus, deeply penetrating neutrons together with their progeny determine the local dose rate inside the shield and on the outer shield's surface.

The biological shield of a neutron spallation source can be designed by employing different computational approaches like the classical methods, as for instance discrete ordinate methods or semi-empirical calculations based on the Moyer model, and, nowadays, Monte Carlo (MC) based methods. The increasing speed and memory capacity of modern computers together with the implementation of variance reduction techniques turned the application of MC codes in the design of biological shields into an alternative of growing importance. Advantages of the MC shielding simulation are: (i) the particle distributions in the complicated geometry around the target assembly can be precisely evaluated, (ii) charged particles and photons can be treated, (iii) the shield with its beam ducts and holes, where the narrow gaps provide paths for radiation streaming, can be modeled by a detailed description, and (iv) no high energy material-dependent cross-section library is required.

By applying different variance reduction techniques in the MC simulations, a proper convergence of the tally scores within reasonable computing time (most importantly, for the tallies near and at the outer boundaries of the shield) can be achieved. Therefore, the chosen random walk sampling amounts to preferentially sampling “important” particles at expense of “unimportant” particles. However, by use of proper variance reduction techniques the efficiency of MC calculations can be increased dramatically.

We present in this paper some deep penetration MC calculations in an attempt to verify the preliminary conceptional design of the target station shield of the ESS made by Forschungszentrum Jülich.

2 Calculational Strategy and Geometry Models

The new LAHET [2] /MCNP [3] code merger MCNPX [4] was the main calculational tool used in our deep penetration study. The simulations were performed in a two-step process.

2.1 MC Calculations of the Particle Flux Spectra from the Target Vicinity

In a first step MCNPX was employed to obtain the high energy, angular dependent neutron and proton leakage from the target-moderator-reflector(TMR) system. This required the development of an exact geometrical TMR model which is based on the one used for the simulation of the JESSICA experiment [5]. JESSICA [6] is a 1:1 sized ESS TMR mock-up and test facility for advanced cold moderators for high-power spallation neutron sources. A cutaway view of the TMR geometry model used is shown in Fig. 1.

In all these calculations the pre-equilibrium model which describes the situation after the intranuclear cascade was active. This step is an analog simulation of the multiple particle transport, where a detailed description of the nucleon-meson cascade is obtained. Because primary low-energy neutrons in the lead-reflected-target vicinity contribute negligibly to the dose at the target station shield surface, it was able to set the neutron low energy cutoff to 10 MeV for all the calculations in the first step. The transport parameters of all neutrons and protons leaving the cylindrical reflector of the TMR region were saved on file to obtain the proper source for the deep penetration transport in the next stage of the calculations.

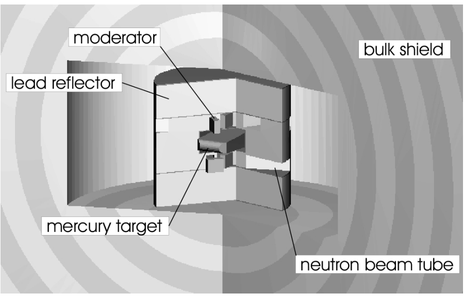

Fig. 1. Cutaway view of the MC geometry used to obtain the proper source for the bulk shielding calculations

2.2 Bulk Shielding Calculations

In the second stage the particle penetration through the target station shield is simulated. The new expanded MCNPX nuclear data tables (proton and neutron libraries to 150 MeV) were used in our simulations. These enable a detailed description of the nuclear structure effects up to an energy of 150 MeV, where the simpler INC physics can model reaction probabilities adequately. Thus, also secondary neutrons from high energy protons are included in the problem. A simplified cylindrical model of the target station shield was constructed to determine the radiation flux spectra and the bulk shielding requirements. The starting-point for the construction were the preliminary geometric parameters of the ESS ([7],Section 4.6.5). An effective modeling within the MCNPX framework required a subdivision of the iron-concrete shield into concentric spherical shells. An incremental radius of 25 cm proved to be most successful. A model of the ESS target shield divided into concentric spheres is presented in Fig. 2.

We analyzed the influence of different biasing techniques and their combinations on the efficiency of calculations. A combination of two techniques proved to be most efficient, namely, energy dependent weight windows and an exponential transform technique. The weight window is a space-energy-dependent splitting and Russian roulette technique, and the exponential transform technique stretches distances between collisions in a defined direction. The spatial weight windows (only one energy range) are obtained from previously optimized cell importances from the geometry-splitting technique. On the basis of these, the parameters for the energy dependent weight windows were obtained empirically

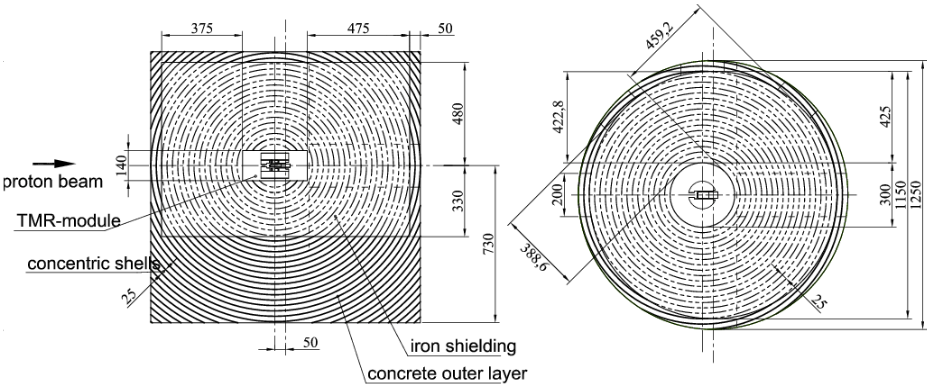

Fig. 2. Schematic view of the ESS target station shield. All dimensions in cm

by making a careful statistical analysis of history distributions. As an example, Fig. 3 demonstrates neutron weight windows used for the computation of the radiation flux spectra in the proton beam direction. In all calculations, special care was taken to match the space-energy weight windows at the boundaries at which the equilibrium neutron spectrum is disturbed by a change in the shielding material. To additionally increase the calculational efficiency, space-dependent

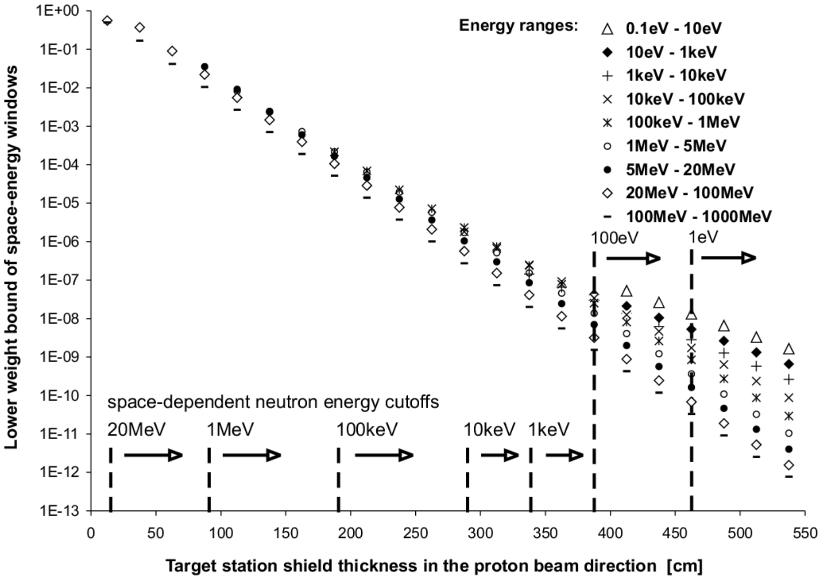

Fig. 3. Weight windows assigned to the spherical shells on the thicker shield side in the proton beam direction

neutron energy cutoffs were employed to terminate particle tracks of negligible importance for the dose rate on outside shield surfaces (see Fig. 3).

3 Shielding Analysis

The described calculational strategy allows to determine the neutron fluence spectra at different locations within the shield and makes it possible to calculate the neutron ambient dose equivalent rates on the outer surface of the biological shield. These rates were found by folding the corresponding fluence to dose conversion factors with the local neutron fluences. For this reason, the ambient dose conversion coefficients included in MCNPX, which are based on the ICRP74 Recommendations [8], were extended to the high energy region [9]. In Tab. 1 the neutron dose values at the outer perimeter of the shield are compared to those of the preliminary study of the target station shielding for different angles relative to the incident proton beam direction. The preliminary shielding design was scaled by FZ-Jülich using a semiempirical code CASL [10] as well as a method of coupling HETC with ANISN [11]. The results obtained using MCNPX indicate lower dose values than the results of the preliminary study calculated with the HETC-ANISN method. The comparison indicates also, particularly in the backward direction of the proton beam, that the CASL dose rates have been overestimated.

Table 1. Comparison of neutron dose rates outside the bulk shield calculated with MCNPX and values of the preliminary study performed by FZ-Jülich.

MCNPX deep penetration calculations				**ESS shield design calculations made by FZ-Jülich**				
Angle to the beam (degree)	Shield thickness (cm)		Neutron dose rate (µSv/h)	Angle to the beam (degree)	Shield thickness (cm)		CASL (µSv/h)	HETC-ANISN (µSv/h)
	iron	concrete			iron	concrete		LESS THAN
0	475	50	0.7 (9%)	0 - 20	520	40	1 - 10	7.5
45	460	50	0.6 (11%)	20 - 40	470	40		7.5
90	423	50	0.3 (13%)	80 - 100	460	30	1 – 10	7.5
135	389	50	0.5 (18%)	100 - 150	420	30		7.5
180	375	50	0.8 (20%)	150 - 180	390	30	10 - 100	7.5

Furthermore, shielding design calculations have been performed in order to get a neutron dose rate less than 1 μSv/h at the shield surface. These results indicate that an iron shield of 475 cm thickness and an outer concrete layer of 50 cm thickness in the proton beam direction seem to be reasonable. Namely, during normal operation the shielding should be designed in such a way that dose rate on accessible surfaces of the shield is less than 5 μSv/h.

Moreover, the photon dose equivalent rates as a result of the prompt decay can also be determined within and outside of the shield. Our preliminary results prove that in the case of an iron-concrete shield prompt photons are an important component of the total dose rate.

4 Conclusions

A calculation strategy utilizing the MCNPX code, suitable for performing shielding design analyses, is described. It was used in an attempt to verify the preliminary conceptional design of the target station shield of the ESS. The results obtained using this strategy show partly lower values than those from the preliminary study calculated with the HETC-ANISN method. In a future analysis, the shielding models need to be refined to account for beam ducts and holes in the target station shield.

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