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NUMERICAL ESTIMATION OF THE EQUIVALENT DOSE RATE AFTER THE IRRADIATION OF A TUNGSTEN COLLIMATOR BY A LOW ENERGY PROTON BEAM

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Abstract

The issue of activation of a Tungsten collimator by protons is considered for the incident energy of 12.2 MeV. Two different simulation approaches using the Monte Carlo programs MCNPX and FLUKA are applied to estimate the equivalent remanent dose rate after the irradiation of the collimator. The results of the numerical simulation are then compared to the measured dose levels of the collimator of the COMET cyclotron at Paul Scherrer Institut (PSI).

INTRODUCTION

The department of Large Research Facilities (GFA) of PSI operates several particle accelerators. Among them are the high intensity proton accelerator complex that delivers a 590 MeV proton beam with a maximum current of 2.4 mA and the 250 MeV proton cyclotron COMET used for proton radiation therapy [1]. The layout of the proton accelerator complex is illustrated by Fig. 1. Running these proton accelerator facilities with high intensity beams involves the handling of highly activated components directly hit by the proton beam or its halo. Knowledge about the nuclide inventories for these activated components is a requirement for their disposal. Monte Carlo particle transport codes are employed to solve this task. The results of the numerical calculations have to be normalized to the absolute value of the lost proton current. Although the proton current delivered by the accelerators is well known, uncontrolled losses are generally not. To overcome this difficulty dose rate mappings of the activated component are performed after irradiation prior to their disposal; the nuclide inventory obtained by Monte Carlo simulation is then re-scaled to reproduce the measured dose rate values. This in addition allows to deduce the amount of the lost beam current. In this paper we present a specific case for which both the exact irradiation history and the dose rates at several cooling times are known; results obtained by the re-scaling method are discussed and the conditions of its applicability are examined.

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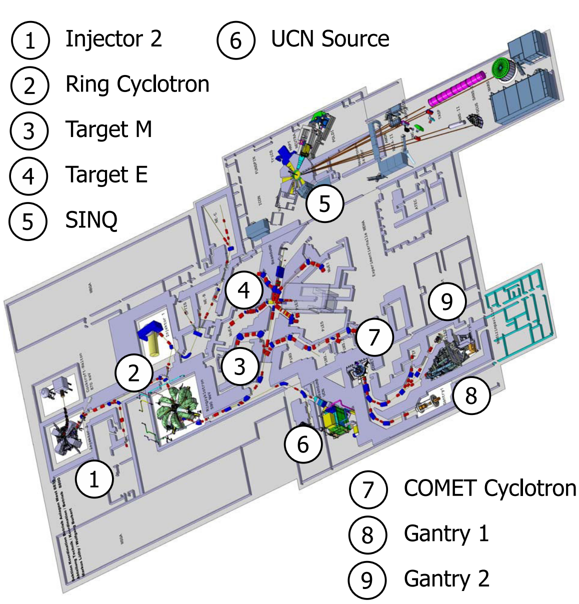

Figure 1: General layout of the high intensity proton accelerator at the PSI experimental hall.

IRRADIATION HISTORY

The superconducting cyclotron COMET provides beam for the proton radiation therapy facility at PSI; its extraction efficiency is larger than 80 % [2]. The remaining 20 % of the beam are lost and absorbed inside the cyclotron and activate the machine components. Existing measurements of the equivalent dose rates performed during the maintenance of the cyclotron showed that already for losses of the moderate integral charge of 800 μAh non-negligible dose rates of $\sim$ 3–6 mSv/h are observed at different locations in the cyclotron; those values were compared to Monte Carlo calculations, see [3].

One machine component that became activated during the cyclotron operation is the Tungsten collimator, intercepting the 12.2 MeV beam halo protons, located at a radius of 20 cm from the cyclotron center. The range of protons in Tungsten at this energy is about 0.24 mm and the nonelastic nuclear interaction probability is 0.03 % [4]. During operation from 2006 – 2010 the current of the lost proton beam intercepted by the Tungsten collimator was continuously monitored and varied between 35 to 823 nA. In 2010 the Tungsten collimator was removed from the cyclotron and its equivalent dose rate was measured with a gamma detector at the distance of 10 cm during a cooling period of 48 hours.

MONTE CARLO PARTICLE TRANSPORT SIMULATION

The collimator from the COMET cyclotron is depicted in Fig. 2. The parts of the collimator directly hit by the proton beam are two cylindrical Tungsten rods each 2 mm in diameter. In the simulations the proton beam was directed perpendicular to the plane connecting the central axis of the rods. The 12.2 MeV beam was simulated to be uniformly distributed over a spot of 3 mm diameter; no divergence was assumed and a proton transport threshold of 1 keV was used.

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The simulation results were normalized to the lost proton currents measured during operation of the collimator.

Figure 2: The FLUKA simulation model of the Tungsten collimator from the COMET cyclotron.

Two different general purpose Monte Carlo transport programs were used to simulate the particle transport and interactions leading to the activation. The first simulation was done with the MCNPX version 2.7.0 [5] and the second code used was FLUKA version 2011.2b [6]. Simulations were performed with identical 3D geometry models and pure Tungsten as the rods material. The geometry model used for the FLUKA simulation is shown on the right-hand side of Fig. 2 together with a picture of the collimator from the COMET cyclotron (left-hand side of Fig. 2).

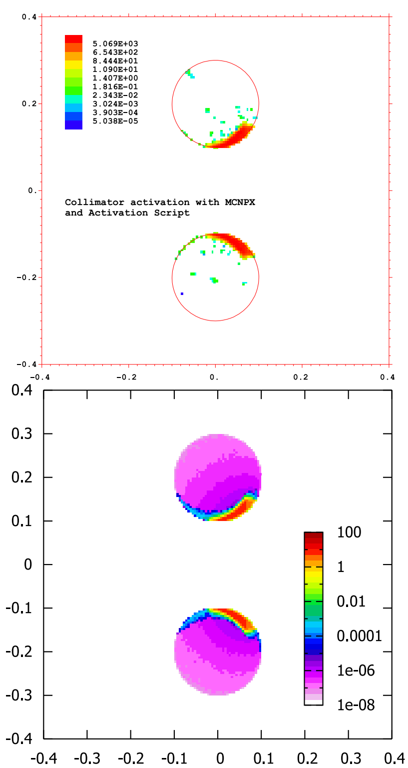

Figure 3: The xy distribution, averaged over the length of the collimator rod, of the energy deposition (MeV/cm^3) simulated with MCNPX (upper figure) and FLUKA (lower figure).

The distribution of the deposited energy in the Tungsten rods in the beam plane simulated with MCNPX and FLUKA is given in Fig. 3. As can be seen from Fig. 3 the dose rates will strongly depend on the azimuthal angle of the detector position due to self-shielding effects. To properly account for this effect, the FLUKA simulation results of the dose rate were scored with an azimuthal binning at a radius of r = 10.0–10.1 cm from the vertical z axis of the collimator. Moreover, the results were integrated over $z = \pm\ 1.5$ mm.

For activation and dose rate calculations with the MCNPX program a special set of tools exists to automatize the activity calculation; the tool is called Activation Script [7]. These tools use the simulated spectra of particle flux densities to calculate nuclide inventories and derived quantities. The MCNPX proton spectrum used in the present calculation is shown in Fig. 4. The spectrum was passed from MCNPX to the nuclear inventory code FISPACT version 2007 [8] to calculate isotope activities and estimate the dose rate. FISPACT was setup to estimate the dose rate of a point-like source at a distance of 1 m; subsequently results were rescaled by the $1/r^2$ law to 10 cm distance to allow a direct comparison with the measured dose rates. The results of the coupled MCNPX and FISPACT calculation are denoted as MCNPX in the following.

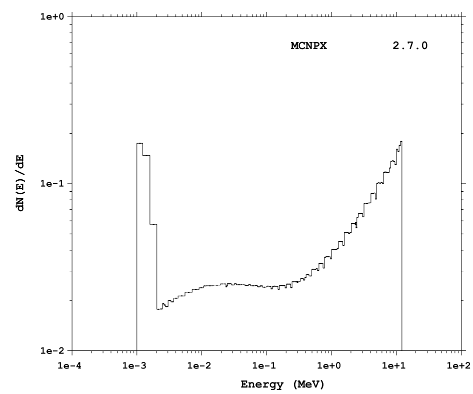

Figure 4: Proton spectrum simulated with MCNPX.

COMPARISON BETWEEN SIMULATIONS AND MEASUREMENTS

The dose rate values from MCNPX calculation are shown in Fig. 5 and are given in Table 1. The position $\phi = 0°$ in Fig. 5 corresponds to the direction of the incident proton beam. Because a point-like source is assumed for the dose rate calculation there is no angular dependence of the MCNPX results (dashed lines in Fig. 5). For a cooling time of 0 hours the maximum dose rate estimates of MCNPX and FLUKA are in good agreement, see Table 1. With increasing cooling time the difference between FLUKA and MCNPX becomes larger, but even in the worst case the maximal dose rate from MCNPX does not differ by more than 15 % from the FLUKA one. Solid lines in Fig. 5 denote the measured dose rates, also given in Table 1; the angular variation of the dose rate was not measured so that the solid lines in Fig. 5 serve just for presentation reasons. The points where the measured dose rate and the FLUKA angular dose rate distributions are equal are marked with the enlarged symbols. Good agreement between the FLUKA results and the measured dose rates are found for an angular range of ± (75°, 85°).

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Table 1: Minimal, maximal and average dose rate as calculated by FLUKA and the dose rate estimated with MCNPX, the difference Δ between maximal and minimal FLUKA values, the difference between the maximal value simulated with FLUKA and the MCNPX results, the measured value of the dose rate and its difference from the MCNPX results.

Dose rate (mSv/h)	**Cooling time 0 h**	**24 h**	**48 h**
FLUKA min	3.92	2.09	1.36
FLUKA max	6.71	3.87	2.70
FLUKA average	5.29	2.95	2.00
±Δ (%)	26	30	33
MCNPX	6.57	4.18	3.18
Δ(Max−MCNPX) (%)	2	7	15
Measured value, $\dot{D}_E$	5.42	2.59	1.58
Δ($\dot{D}_E$−MCNPX) (%)	21	61	101

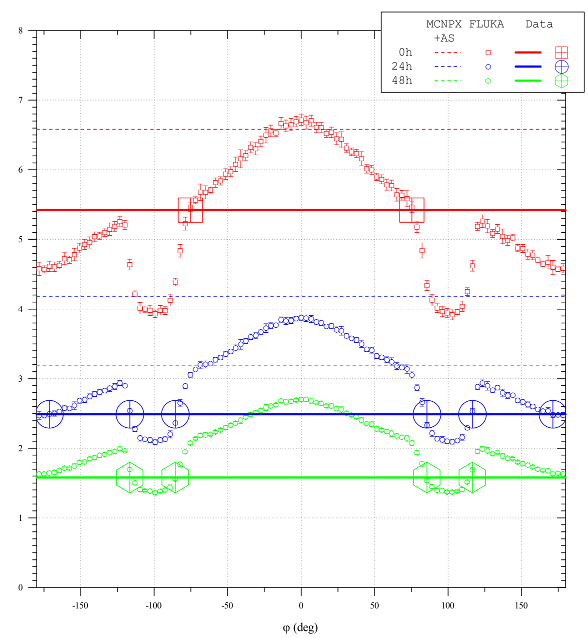

Figure 5: Dose rate as a function of the azimuthal angle around the phase slit, as calculated by FLUKA (small symbols), compared to the results of the MCNPX simulation (dashed lines) and the measured data (solid lines and large symbols with the cross).

CONCLUSION

The combination of the MCNPX particle transport simulation with the FISPACT inventory calculation automated by the Activation Script allows for a fast estimate of the maximal dose rate. The simulation results obtained with MCNPX are consistent with the maximal dose rate estimates of the detailed, more realistic FLUKA simulation. As the dose rate estimate of the MCNPX–FISPACT calculation is based on a point-like source and therefore is not accounting for the self-shielding effects, this evaluation can lead to significantly larger dose rates (up to factor of 2 as Table 1 shows) than the realistic estimate by FLUKA. The comparison of the experimental results and the simulations with FLUKA and MCNPX shows that without a detailed geometry description of the irradiated object, the detailed irradiation/cooling history and the exact knowledge of the experimental conditions an accurate reproduction of the nuclide inventory and derived quantities with the Monte Carlo simulations is questionable. Variations of about ± 30 % around the average simulated dose rate values are found for the detailed problem description with FLUKA. The fast esimate using MCNPX coupled with FISPACT, assuming a point-like gamma source, clearly overestimates the dose rates.

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