VI. RADIATION ECOLOGY

RADIATION SHIELDING AND DOSE ASSESSMENT OF THE CYCLOTRON FACILITY AT INRNE-BAS

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Abstract. The Institute for Nuclear Research and Nuclear Energy at the Bulgarian Academy of Sciences is working on the construction of a cyclotron centre. The facility is on a design level. At this stage of the project, an important task is the radiation shielding assessment of the facility. Nowadays, the Monte Carlo transport codes have become the tool of choice for solving this type of problem. In the current paper, the transport code FLUKA is used for the calculations. It is widely applied for shielding design and analysis of accelerators and their components. The distributions of the radiation fields inside and outside the cyclotron bunker are presented in this paper. Both different irradiation scenarios and bunker configurations are considered in the conducted Monte Carlo simulations. These results will be used as a guidance in site planning.

Key words: TR-24 cyclotron, Radiation protection, Monte Carlo simulations, FLUKA

INTRODUCTION

The project for a new cyclotron facility at the Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences (INRNE-BAS) is at a design level. At this stage, the cyclotron radiation shielding should be evaluated. For this purpose, a common practice is to perform Monte Carlo (MC) simulations [1-8]. In its essence, the Monte Carlo technique is a methodology for the evaluation of the expected value of a population by the estimation of the expected value of a sample from it. Pseudo-random number generators are used for the sampling process. The MC technique is highly applicable in simulations of stochastic processes such as the transport of particles and their interaction with matter, which is the case in our study. All the necessary tools for MC simulation are implemented in transport codes such as FLUKA [9, 10]. That is the MC transport code chosen to perform the simulations.

The number of imaging procedures in Bulgaria using fluorodeoxyglucose (^{18}F -FDG) has increased in the last decade and, thus, the focus of the current study is on the production of the ^{18}F . It is a product of a (p, n) reaction on an ^{18}O enriched water target. As a result, high radiation fields are generated. In the current study results for their distribution are presented. Respectively, for two irradiation scenarios: during a session for production of ^{18}F and after the end of bombardment (EOB). The distribution of the radiation fields at three cooling times is studied in the second scenario.

DESCRIPTION OF THE MODEL

The implementation of the bunker model is presented in Fig. 1. Its dimensions are: 17 m (length), 9 m (width), 3.25 m (height). The thickness of the outside wall (walls, ceiling, floor) is

2.5 m. The internal walls are 60 cm thick. The four internal doors of borated polyethylene (BP) are marked with blue rectangles, which separates the four irradiation areas of the bunker. The BP doors are 2.2 m high, 1.2 m wide and 30 cm thick. The chemical compositions of the concrete with Portland cement (CPC) and of the BP are standard. The mass fraction of the different elements is taken from the literature [11]. For the CPC they are the following: 1% H, 0.1% C, 52.9% O, 1.6% Na, 0.2% Mg, 3.4% Al, 33.7% Si, 1.3% K, 4.4% Ca, 1.4% Fe [11]. For BP: 12.5% H, 10% B, 77.5% C. Their densities are $\rho = 2.3 \text{ g/cm}^3$ (CPC) and $\rho = 1 \text{ g/cm}^3$ (BP) [11]. In Fig. 1, the direction of the proton beam and the position of the target are pointed with a black arrow. A simplified target for production of ^{18}F is considered in the current simulations. It is implemented as a 2.5 ml cube of water enriched with ^{18}O . Two bunker configurations are considered: configuration 1 – without Door 1; configuration 2 – Door 1 present (Fig. 1). The distribution of the radiation fields for two irradiation scenarios is obtained: during target irradiation; 2 sessions for production of ^{18}F . The profiles of the ambient equivalent dose rates along the Line (Fig. 1) are extracted from the second scenario to evaluate the efficiency of Door 1.

The USRBIN score type is used to calculate neutron and gamma-ray fluences. Coupled with an AUXSCORE card it scores the respective ambient dose equivalent rates ($H^*(10)$). For this conversion, fluence-to-dose coefficients, provided by the ICRP 74 [12], are selected. Additionally, the DCYSCORE card is coupled to the USRBIN to score the dose rates at the chosen cooling times after EOB. To achieve high statistics 10^9 primary particles are simulated for every considered configuration and irradiation scenario.

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Fig. 1. FLUKA MC model of the bunker (look from above).

The set of predefined transport settings chosen for the simulations in the current work is NEW-DEFA. In it are enabled the necessary physical mechanisms. These include the transport of photons, electrons and positrons; low energy neutron transport; delta ray production; heavy particle bremsstrahlung.

RESULTS AND DISCUSSION

Ambient dose equivalent rates during target irradiation

The distributions of the gamma and the neutron dose rates (Fig. 2) are obtained for the worst-case scenario – simplified target for production of ^{18}F irradiated with a 24 MeV proton beam at a maximum current of 100 μA . In Fig. 2 (a, b), the distributions of the gamma and neutron dose rates are presented for configuration 1, respectively, in Fig. 2 (c, d) for configuration 2. For the two configurations, the gamma radiation dose rate (Fig. 2(a, c)) varies inside the irradiation area (along the black line) in the range 3.6×10^5 – 5.6×10^5 $\mu\text{Sv/h}$, respectively, the neutron dose rates (Fig. 2 (b, d)) are in the range 2×10^7 –

3×10^7 $\mu\text{Sv/h}$. The gamma dose rate maximum value in the central area of the bunker for configuration 1 is 2.9×10^5 $\mu\text{Sv/h}$ (along the black line, near the BP door) and for configuration 2 is 9.5×10^4 $\mu\text{Sv/h}$. It is about 3 times lower in the central area of the bunker, along the black line. The BP is a good neutron moderator. For configuration 1 the neutron dose rate in the central area of the bunker is about 11×10^6 $\mu\text{Sv/h}$ (along the black line, near the BP door) whereas for the second one it is 9.3×10^4 $\mu\text{Sv/h}$. The high dose rates are expected inside the bunker. It should be noted that the bunker is an exclusion zone for the personnel during the cyclotron operation. In this case, the attenuation of the radiation fields in the outer walls is relevant. Our results show that for the two configurations, the dose rates outside the bunker are about an order of magnitude lower than the background radiation 0.14-0.2 $\mu\text{Sv/h}$ (for Sofia).

We can conclude that walls with a thickness of 250 cm provide the necessary protection for the personnel during the cyclotron operation.

Fig. 2. Distribution of the gamma (a, c) and neutron (b, d) ambient dose equivalent rates, for the two configurations, expected at beam current of 100 μA .

Ambient dose equivalent rates after two irradiation sessions

The purpose of the following simulations is to map the radiation fields inside the bunker after two irradiation sessions, each lasting two hours, for production of ^{18}F . Again, the worst-case scenario is considered – irradiation with a 24 MeV proton beam at a maximum current of 100 μA . Radiation fields are generated by the induced radioisotopes in the bunker walls. They contribute to the dose rates presented in Figures 3, 4. In Fig. 3 the distribution of the dose rates is shown for the two configurations (left column – configuration 1, right column – configuration 2), for two cooling times (one day – Fig 3 (a, b); three days Fig. 3 (c, d)). Usually the activities in the irradiation area are planned for a day after the last target bombardment. The results in Fig. 3 show that highest dose rates in the central area of the bunker are in front of the BP door. For configuration 1 the dose rate after 1 day of cooling is

190 $\mu\text{Sv/h}$ (Fig 3 (a)), after three days – 20 $\mu\text{Sv/h}$ (Fig 3 (c)), respectively, for configuration 2 the dose rates are 38 $\mu\text{Sv/h}$ (one day of cooling, (Fig 3 (b)) and 4 $\mu\text{Sv/h}$ (three days cooling, (Fig 3 (d)). The dose rates in the irradiation area reach up to 1000 $\mu\text{Sv/h}$, after a day of cooling (Fig 3 (a, b)). It should be noted that in Bulgaria the legal annual dose limit for personnel is 20 mSv. This means that the occupancy of the area will be limited to 20 working hours per year. Our previous research shows that the dose rates are decreased substantially if low activation concrete is set as bunker walls material and local target shielding of standard materials is applied [8]. After three days the dose rate is 60 $\mu\text{Sv/h}$. In Fig. 4 are presented the attenuation profiles of the gamma ambient dose equivalent along the Line (Fig. 1) at the two cooling times. These profiles show that the BP door (Door 1) decreases the dose rate about four times in the central area of the bunker.

Fig 3. Distribution of the gamma ambient dose equivalent rates $H(*10)$, for the two configurations, respectively, configuration 1 (a, c,) and configuration 2 (b, d,) at two cooling times (1 day (a, b) and 3 days (c, d)).

Fig. 4. Attenuation profiles along the black lines (Fig. 3) of the gamma ambient dose equivalent rates $H(*10)$ for the two configurations at two cooling times: (a) 1 day; (b) 3 days.

If further measures are taken the safety of the personnel will be improved. Some ideas are: walls made of low activation concrete, additional shielding on the walls encompassing the irradiation area, local target shielding.

CONCLUSION

MC simulations for two bunker configurations and irradiation scenarios are performed. The radiation dose rates during the target irradiation are high, but the outer walls of the bunker provide the

necessary protection for the personnel operating the facility. The distribution of the radiation fields inside the bunker for two cooling times (one day and three days) after two sessions for production of ^{18}F is studied. The outcome is that after a day of cooling the occupancy of the irradiation area is limited to 20 working hours per year. Thus, additional features of the radiation shielding, which will lower the radiation fields, are listed.

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