FLUKA SIMULATIONS ON THE THICK TARGET YIELD OF 18F PRODUCTION BY PROTON-INDUCED REACTION

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Abstract

Nowadays radioisotope labeled molecules are widely used in medical imaging that provides insights into various mechanisms of human physiology. ^{18}F is one of the most often used PET radioisotopes and single doses of it can be produced even on small hospital cyclotrons. Since 2015 Institute for Nuclear Research and Nuclear Energy has a cyclotron capable to deliver proton beams with parameters exceeding the ones needed for ^{18}F solely.

Utilizing Monte-Carlo simulations, a well known approach towards the optimization of the production yield of the radioisotopes and the shielding performance of the cyclotron vault in the facility a model of a commercially available target was simulated using the FLUKA package.

This contribution shows the thick target yield using the reaction $^{18}O(p,n)^{18}F$ on $[^{18}O]H_2O$ for different irradiation conditions in terms of beam energy and current. The results agree well with published experimental data. Neutron and gamma source terms to be used for assessment of the shielding are also obtained.

Key words: *cyclotron, 18F, radiopharmaceutical, thick target yield, Monte-Carlo simulations*

Introduction

The Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, is working on a cyclotron facility that will be used for production of established radiopharmaceuticals and emerging ones for R&D. The cyclotron is an ASCI-developed TR-24 [1] with a possibility for dual target irradiation, maximal proton beam energy of 24 MeV and current of 400 μA. Such a cyclotron can also be used for the production of a variety of PET and SPECT radioisotopes.

Before advancing towards building the facility housing the cyclotron vault and its adjoining laboratories, the INRNE needs to evaluate the design of the shielding of the vault itself with respect to neutrons and gamma rays, generated during the target irradiation. For that purpose an approach based on Monte-Carlo numerical simulations was undertaken.

Monte-Carlo Methodology

The simulations are done using FLUKA [2, 3] which is a well-established tool for target and shielding design and activation analysis.

The production yield of ^{18}F from a thick target is determined at predefined beam current and energies for the reaction ^{18}O (p, n) ^{18}F on a [^{18}O]H_2O liquid. Then the spectra of the generated neutrons and gamma-rays, that are needed for further simulations of the shielding properties of the vault and estimation of the products of activation in the equipment used and the vault itself, are obtained:

18F production yield

Two sets of simulations were done to evaluate the yield of ^{18}F. In the first case only an ^{18}O-enriched water filled cylindrical volume is irradiated with proton beams of different energies. The results at the end of the bombardment (EOB) are compared to experimental data given in [4]. The beam used is a monoenergetic pencil-like one. A relatively good agreement can be seen in **Figure** where the simulated yield (red diamonds) is superimposed on data from [4] shown with a solid blue line. FLUKA slightly underestimates the production yield up to about 9 MeV energy of the proton beam and after that the trend inverts. The discrepancy between the results increases with the beam energy.

In the second set of simulations a detailed ASCI high-current target with volume of 3.8 mL was modeled. As the target vessel by design is not symmetric, the beam hits a covering Havar foil off center. The irradiation time is six hours. The yield was evaluated for 18 and 24 MeV beam energies and the results obtained are 1593 ± 1.6 GBq/C and 1793 ± 1.8 GBq/C. The 18 MeV result corresponds well to the results for the simple cylindrical target. The IAEA data do not include results with 24 MeV.

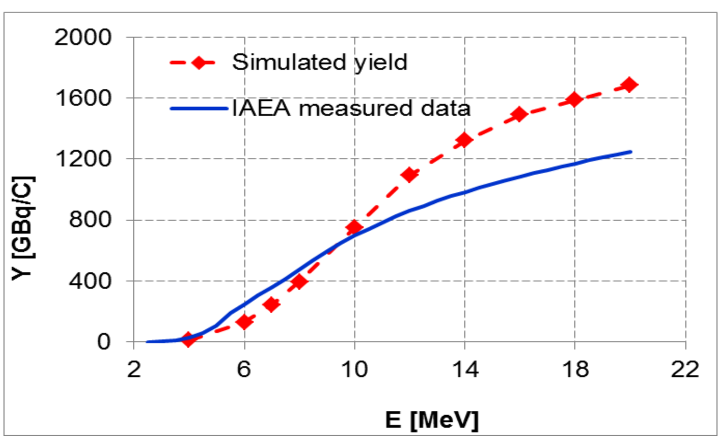

Figure 1. Simulated yield of ^{18}F at EOB, red diamonds, vs IAEA data shown in solid blue.

Figures 2a and 2b show the ^{18}F activities in the target for the full period of irradiation and decay for two beam energies and two currents - 100 μA and 400 μA. The six-hours thick-target EOB total yields are 1593 GBq/C and 1793 GBq/C taking into account the decay of ^{18}F during the irradiation.

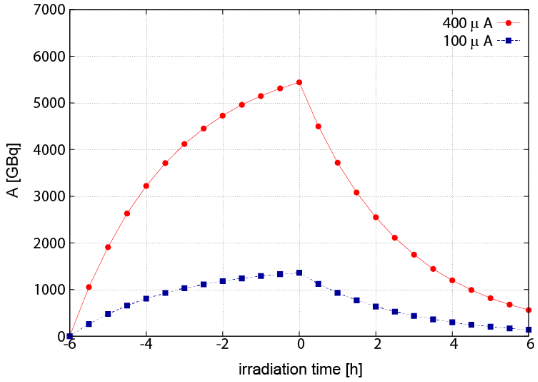

Figure 2a. Activity for beam energy of 18 MeV, the corresponding value at EOB is 1593 ± 1.6 GBq/C.

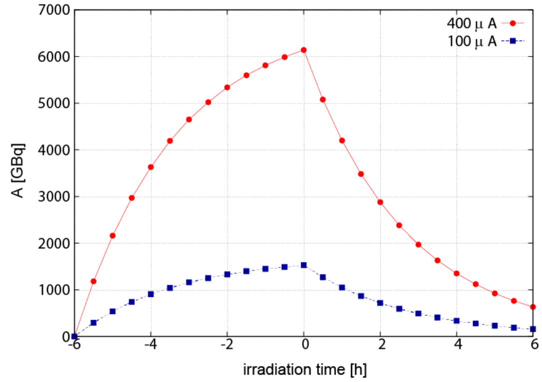

Figure 2b. Activity for beam energy of 24 MeV, the corresponding value at EOB is 1793 ± 1.8 GBq/C.

Emission of secondary particles

The design of the vault should be validated with respect to the flux of secondary particles emitted and the possibilities to activate components of the target, the cyclotron and the vault. For that purpose the fluence of neutrons and gammas emitted in a spherical volume surrounding the target, without cutoff on their energies, are scored in FLUKA. 90-degree angle of incidence of the proton beam with respect to the target has been chosen as it has been shown to result in the highest flux of neutrons [5]. Three different beam energies are considered – 12, 18 and 24 MeV. For each energy $3x10^9$ primaries were simulated. The resulting neutron and gamma spectra are shown in Fig. 3.

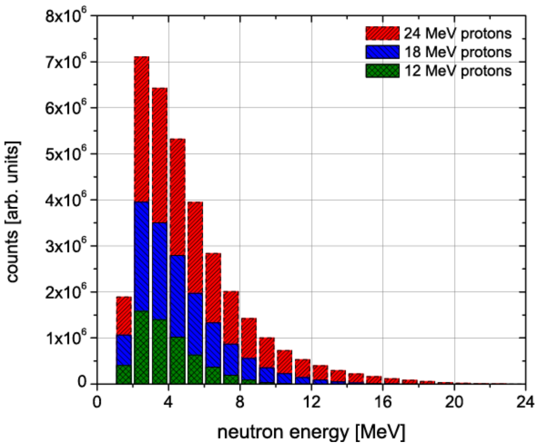

Figure 3a. Neutron spectra.

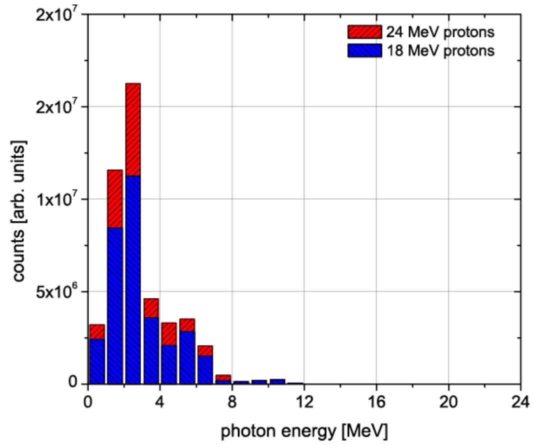

Figure 3b. Gamma spectra.

Figure 3. Neutron and gamma spectra for three different proton beam energies. The secondary particle count is scored in a 4π-volume surrounding the target.

The neutron spectrum for beam energy of 12 MeV agrees well with experimental data for 10.5 [5] and 11 [6] MeV protons – the shape of the curve, the location of the peak and the extent of the energy range.

Assuming beam intensity of 2.5×10^{15} protons/s and beam energy of 24 MeV, the resulting neutron rate is 2.9×10^{13} neutrons/s. The spatial distribution of neutrons and gammas in the (x, y)-plane for 24 MeV beam is shown in Fig. 4. The colour scheme shows the density of the generated secondary particles per primary one. The number of generated gammas per primary is an order of magnitude more than that of the emitted neutrons.

The data on the properties of the secondary particles generated in the target are essential to simulating the radiation field inside the vault, the activation of the whole installation, and the radiation field outside the bunker for the purpose of radiation safety and decommissioning planning.

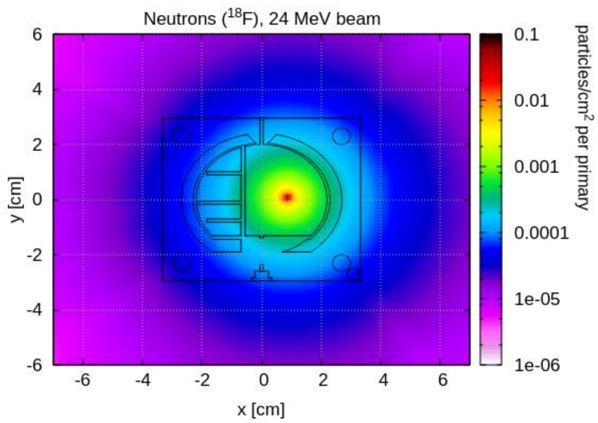

Figure 4a. Neutron distribution.

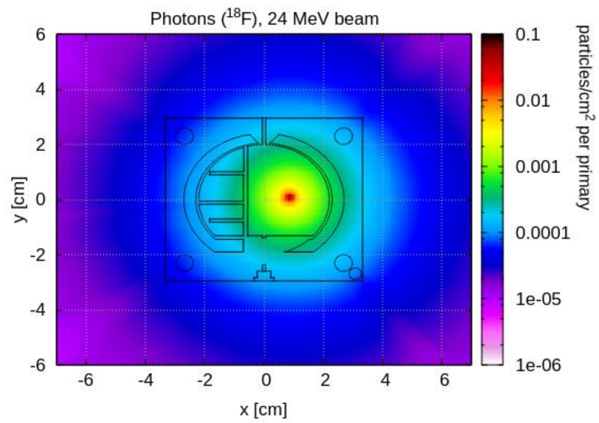

Figure 4b. Gamma distribution.

Figure 4. Spatial neutron and gamma distribution in the (x, y)-plane for 24 MeV proton beam. The protons are hitting the target upwards from the plane of the paper.

Conclusions

This work is the first step to assess the radiation shielding properties of the cyclotron vault in the future INRNE facility. Further simulations are needed to evaluate the activation of components – the target, the cyclotron, the air within the vault, the concrete walls, etc. An important assessment to be done is also the effective dose for the personnel maintaining the cyclotron.

The simulations on radioisotope production yield shown here agree with published experimental data. The obtained neutron and gamma sources are both smooth and isotropic. This, together with the correspondence between measurements done in similar facilities and the Monte-Carlo results justifies the approach chosen here.

Acknowledgements

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