Monte Carlo Simulations for Optimization of the Radiation Shielding of TR-24 Cyclotron

A. Demerdjiev, N. Goutev, G. Asova, K. Shegunov and D. Tonev

Institute for Nuclear Research and Nuclear Energy (INRNE) - Bulgarian Academy of Sciences (BAS), 72 Tsarigradsko chaussee blvd., Sofia 1784, Bulgaria

Abstract. The results presented in the current paper are part of the studies which we are conducting in regards with the radiological characterization of the cyclotron facility that is currently being built by the Institute for Nuclear Research and Nuclear Energy at the Bulgarian Academy of Sciences. The facility is going to be dedicated to research and development of radiopharmaceuticals, and ^{18}F is of primary interest.

Adding a local shielding around the target will be useful in limiting the spatial distribution of the emitted secondary neutrons (during the target irradiation) and the activation of the bunker walls. The effect of adding a layer of borated polyethylene is studied. We are considering a simplified spherical geometry, divided into spherical shells, of the bunker walls. By employing the FLUKA Monte-Carlo transport code we obtained results for the distribution of the fluence of the secondary neutrons in the spherical shells.

Keywords: FLUKA simulations, ^{18}O target, borated polyethylene

1. INTRODUCTION

The Institute for Nuclear Research and Nuclear Energy at the Bulgarian Academy of Sciences (INRNE-BAS) has undertaken the task to build a cyclotron center. The facility is going to be dedicated to applied and fundamental research with radiotracers in areas related to life sciences and industry and to production of well-established radioisotopes for the nuclear medicine (Tonev et al, 2016; Tonev et al., 2018). The delivered in 2016 TR24 cyclotron, produced by the Advanced Cyclotron Systems, Inc., has variable energy of the proton beam from 15 to 24 MeV and current up to 400 μA (upgradable to 1 mA). Cyclotron with such parameters is suitable for production of large variety of PET and SPECT radioisotopes. Presently, the main part of the conducted research activities at the cyclotron laboratory are dedicated to numerical studies on the radiological characterization of the setup and capabilities to produce various medical isotopes.

Currently our effort is directed to the production of ^{18}F, since in Bulgaria, the number of nuclear imaging procedures in oncology which are using fludeoxyglucose (^{18}F-FDG) keeps increasing over the last 10 years (BULGARIAN MINISTRY OF HEALTH 2019). The ^{18}F is the product of (p, n) reaction on ^{18}O (enriched H_2O liquid target). The irradiation of the target also produces secondary particles (neutrons and gamma rays). It causes activation of long-lived radioactive nuclei in the bunker walls, which leads to a building up of radioactive waste. As suggested and implemented in the practice (Paans et al, 2003; Feng et al, 2013) in our previous studies (Yavahchova et al, 2016; Asova et al, 2018) we tested the idea of local shielding around the liquid target. It has been proven to be useful in limiting the spatial distribution of the secondary particles and thus lower activation of the facility components, longer lifetime of the facility and safer working environment for the personnel has been achieved.

In this work we tested the effect of adding borated polyethylene layer as a local shielding material. We employed a two-step approach for the study. In our previous study we simulated the irradiation of ^{18}O target and obtained collision tape files with secondary neutrons (Yavahchova et al, 2016). Here we developed a model with simplified spherical geometry. The source of secondary neutrons (our previously obtained collision files with neutrons) is positioned in the center of the modelling domain. The approach we are employing here is based on Monte-Carlo simulations using computer code FLUKA (Böhlen et al, 2014; Ferrari et al, 2005), since it is a well-established tool for target and shielding design, and activation analysis.

2. DESCRIPTION OF THE MODEL

The modelling domain for our simulations is shown in Fig. 1. In order to make the further descriptions clearer, the simulated geometry is presented, as a three-dimensional "melon slice" through the geometrical center.

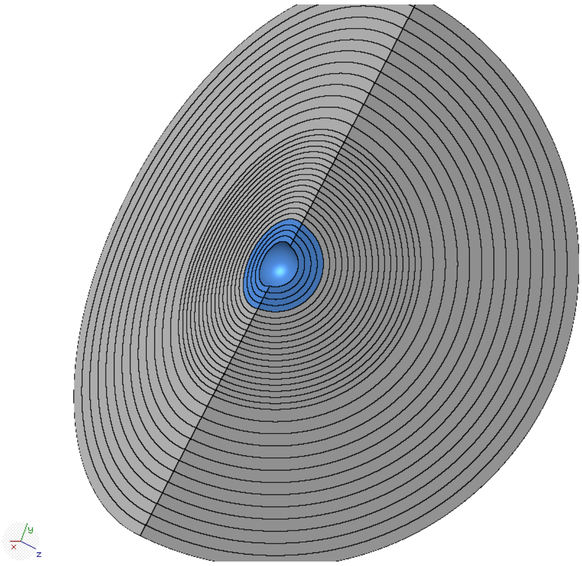

Fig. 1 Modelling domain – schematic presentation of the spherical shell and its division into layers (230 cm thick and it is divided into layers – the first 120 cm in layers of 5 cm and the rest into layers of 10 cm). The neutron source is positioned in the geometrical center.

The previously obtained neutron source (Yavahchova et al, 2016) is positioned in the center of the geometry. The source of secondary neutrons is obtained through simulation of ^{18}O target irradiation. In the simulation, the emitted neutrons are scored and written in files which are used in this work as a neutron source irradiating the vault. The particles are read one by one from the files and moved to a position defined for simplicity as the center of the spherical geometry. The FLUKA code is transporting the particles, and is doing numerical estimations. In this work we considered a simple scenario – target and respectively local shielding close to the vault walls. In the center of the geometry we have an air-filled sphere with radius of 20 cm containing the neutron source. The air-filled volume is surrounded by a spherical shell. It is 230 cm thick and it is divided into layers – the first 120 cm in layers of 5 cm and the rest into layers of 10 cm. The main material used to fill the spherical shell is standard concrete with Portland cement (CPC). Its material composition is as follows: 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, and its density is ρ = 2.3 g/cm^3 (McConn et al, 2011). The local shielding material that we considered in this study is borated polyethylene (BP) - 12.5 % H, 10 % B, 77.5 % C, with density of 1.0 g/cm^3 (McConn et al, 2011). It is well known and widely used material for neutron shielding since boron has good attenuating and absorbing properties for neutron radiation. In our paper are considered three cases: the whole spherecal shell is filled with CPC (no local shielding); first 10 cm of the innermost part of the spherical shell filled with BP, the rest is filled with CPC; and the third case – local BP shielding is 20 cm thick.

3. RESULTS AND DISCUSSION

The results for the distribution in depth of the generated radionuclides are confirmed by the distribution of the neutron fluence shown on Fig. 2. As it is expected local shielding of 20 cm BP (Fig. 2(b)) limits the penetration of neutrons in the CPC better than that of 10 cm.

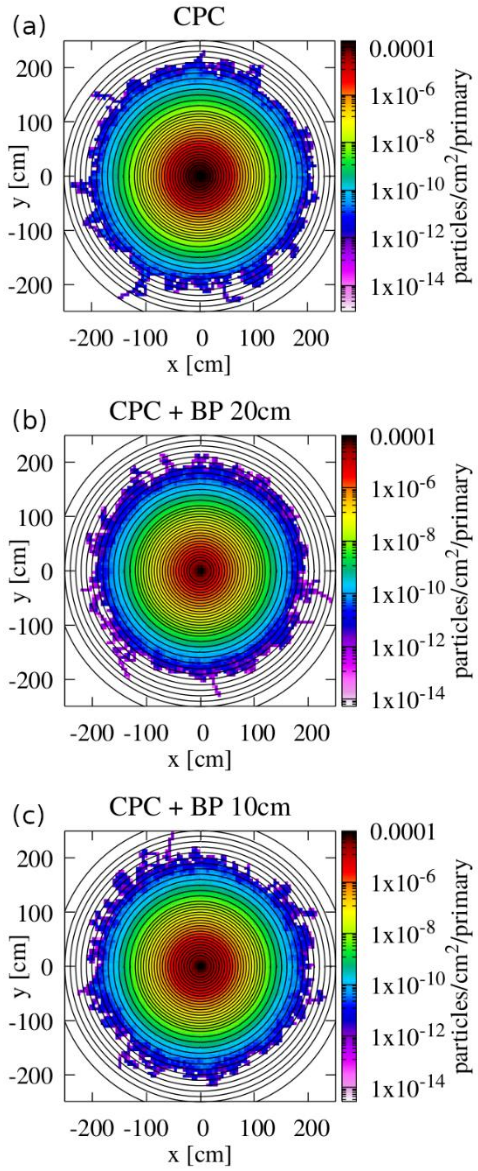

Fig. 2 Neutron superimposed on the geometry for the three cases without (a); with local target fluence shielding of borated polyethylene – 20 cm (b) and 10 cm (c).

of BP (Fig. 2c). There is a noticeable difference between the case where we have 20 cm layer of BP (Fig. 2b) and the one without local shielding (Fig. 2a).

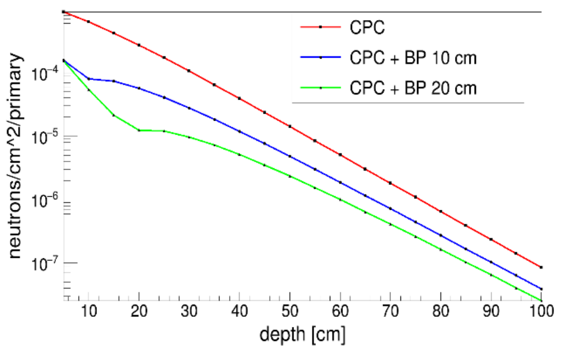

Fig. 3 Energy-integrated neutron fluence in relation to the wall depth for the three cases.

On Fig. 3 are presented the results for the atenuation of the neutron fluence (energy-integrated fluence) with respect to the depth for the three cases. It shows that adding a 20 cm layer of BP reduces on average 4 times the neutron fluence.

4. CONCLUSION

Evaluation of the distribution of the generated radionuclides and the neutron fluence, for the case of production of ^{18}F is calculated for three cases, using Monte-Carlo simulations. Our results show that adding a layer of 20 cm borated polyethylene around the target reduces considerably the penetration of the secondary neutrons.

ACKNOWLEDGEMENTS

This research has been funded by the Bulgarian Science Fund under contract DM 18/2 12.12.2017 and by the National programme “Post-doctoral students and young scientists”, funded by the Bulgarian Ministry of Education and Science.

REFERENCES

Tonev D., Goutev N. and Georgiev L. S. 2016. *Cyclotron laboratory of the Institute for Nuclear Research and Nuclear Energy*, J. Phys.: Conf. Series, 724, 012049.

Tonev D., Goutev N., Asova G., Artinyan A., Demerdjiev A., Georgiev L. S., Yavahchova M., Bashev V., Genchev S. G., Geleva E., Mincheva M., Nikolov A. and Dimitrov D. T. 2018. *National cyclotron centre at the Institute for Nuclear Research and Nuclear Energy, Nuclear Energy*, J. Phys.: Conf. Series, 1023, 012035.

Bulgarian Ministry of Health, National Center of Radiobiology and Radiation Protection 2019. *Report of the Activity of the National Center of Radiobiology and Radiation Protection for 2018* (in Bulgarian).

Paans A. M. J. 2003. *Compact cyclotrons for the production of tracers and radiopharmaceuticals*, NUKLEONIKA 48, Supplement 2: S169 –S172.

Feng W., Tao C., Tianjue Z., Xianlu J., Xingzhi Zh. and Zhen Guo L. 2013. *Radiation shielding design for medical cyclotron*, Proceedings of IPAC2013, 3339-3341.

Yavahchova M., Asova G., Goutev N. and Tonev D. 2016. *FLUKA Simulations on the Thick Target Yield of 18F Production by Proton-Induced Reaction*, Science & Technologies VI, 3.

Asova G., Goutev N., Tonev D. and Artinyan A. 2018. *Status of Simulations for the Cyclotron Laboratory at the Institute for Nuclear Research and Nuclear Energy*, J. Phys.: Conf. Series, 1023, 012008.

Böhlen T. T., Cerutti F., Chin M. P. W., Fassò A., Ferrari A., Ortega P. G., Mairani A., Sala P. R., Smirnov G. and Vlachoudis A. 2014. *The FLUKA Code: Developments and Challenges for High Energy and Medical Applications*, Nuclear Data Sheets 120, 211–214.

Ferrari A., Sala P. R., Fassò A. and Ranft J. 2005. *FLUKA: A multi-particle transport code (program version 2005)*, CERN-2005-010, INFN-TC-05-11, SLAC-R-773.

McConn Jr R. J., Gesh C. J., Pagh R. T., Rucker R. A. and Williams III R. G. 2011. *Compendium of Material Composition Data for Radiation Transport Modeling*, Pacific Northwest National Laboratory, Richland, Washington.

Regulation on Radiation Protection, State Gazette, 2018. Issue 16 of 20 February (in Bulgarian).