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SIMULATIONS OF THE ACTIVATION OF A PROTON THERAPY FACILITY USING A COMPLETE BEAMLINE MODEL WITH BDSIM

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Abstract

A detailed model of the IBA Proteus®One compact gantry system has been created with BDSIM (Beam Delivery Simulation) that has been validated against experimental data. Results regarding activation studies have been obtained for the first time using seamless simulations of the transport of protons in the beamline and their interactions with the environment. The activation of the concrete shielding of the system is estimated after a period of 20 years of operation. These main results are presented and discussed in detail.

INTRODUCTION

Beam transport simulations for proton transport systems are typically performed using a suite of simulation tools of increasing complexity. The leading order optical properties of the beamline are designed with an optics code (*e.g.* Transport [1], MAD-X [2]), finer details of the beam properties along the beamline and at isocenter, as well as the overall beamline transmission are computed with multi-particle tracking codes such as Zgoubi [3] or MAD-X/PTC [4]. However, the specifics of proton therapy beamline require that computations on models with a higher level of details include not only a higher order integration in magnetic fields but also include details of particle-matter interactions. Indeed, cyclotron-based proton therapy installations (such as the IBA Proteus®One compact system) use a fixed-energy accelerator with the energy modulation performed using an energy degrader. This energy degradation will be the main cause of emission of secondary particles; especially neutrons. They will interact with the concrete shielding and generate an activation of the concrete by capture or spallation reactions.

This activation is an issue from the point of view of waste management. The International Atomic Energy Agency (IAEA) has defined threshold values for acceptable activity concentration, called clearance levels [5]. If the activity concentration (A) of the isotope is above the clearance level, the material shall be considered a nuclear waste and must be treated adequately. A is given by the following relation:

$$A = \lambda N \times \int \phi(E)\sigma(E)dE\,, \tag{1}$$

where λ is the decay constant, N is the atomic density in g^{-1}, ϕ is the neutron flux in $MeV^{-1}\,cm^{-2}$ and σ is the cross section of the considered reaction (capture or spallation) in cm^2.

BDSIM has been recently developed to provide a unique tool to describe the tracking of particles inside the machine and to simulate particle matter interactions based on Geant4 [6], including for medical applications [7, 8].

The structure of this work is as follow. First, the properties of the beam at the exit of the accelerator and the BDSIM model of the Proteus®One are presented. Then, the model is validated against experimental data and an estimation of the quantity of radioactive concrete is computed after 20 years of system use, without dead-time.

BEAM PROPERTIES AT THE EXIT OF THE ACCELERATOR

The particle accelerator of a Proteus®One system consists of a superconducting synchrocyclotron (S2C2). The extraction of the beam is a complex process and has to be modelled. W. Kleeven et al. [9] have made an entire OPERA3D model of the S2C2 and have simulated with Advanced Orbits Code (AOC) the particle distribution at the exit of the accelerator. The phase space of the S2C2 beam obtained in that way is shown for both planes in Fig. 1 and is used as an input of our simulations.

BDSIM MODEL OF THE PROTEUS®ONE SYSTEM

Beam Delivery Simulation (BDSIM) is a C++ program which uses a suite of standard physics codes: GEANT4, ROOT and CLHEP. This software models the propagation of the beam along a beamline and simulates the interactions between the beam and the different components of the beamline [6]. A 3D model of the beamline is generated using optical descriptions of magnetic components and uses a thick lens first order matrices for tracking in vacuum. Moreover, realistic geometries from CAD software can be imported easily using the GDML format built from an external library (*pyg4ometry* [10]).

The BDSIM model of the ProteusOne beamline is shown in Fig.2. The proton beam (in blue) first interacts with a realistic model of the degrader (see CAD model in [11]) and then is transported up to the isocenter with quadrupoles (in red) and dipoles (in blue).

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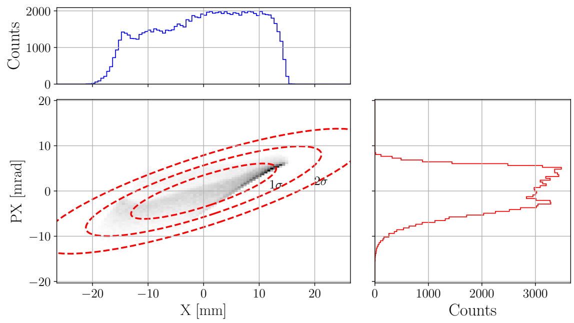
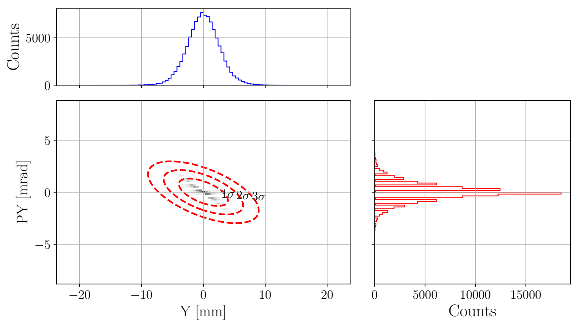


(a) Horizontal plane



(b) Vertical plane

Figure 1: Phase space of the beam in both planes. The projection over each axis is also shown.

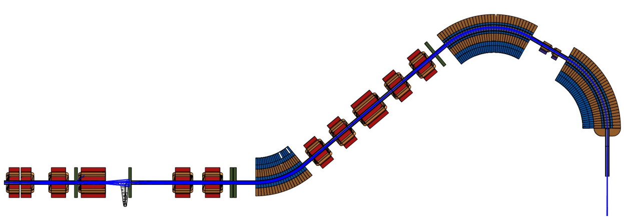


Figure 2: Complete model of the Proteus®One beam transport line made with BDSIM. The propagation of the proton beam is shown in blue. The secondary particles are not shown.

The beam losses along the beamline are evaluated for the reference optical solution. We observe in Fig. 3 that losses occur mainly around the degrader system but also in different places in the beamline following a complex pattern [12].

These interactions induce secondary particles and therefore an appropriate concrete shielding is used to limit exposition to these radiations [13]. These secondary particles are shown for example in yellow (photons) and in green (neutrons) in Fig. 4. The presence of the S2C2 is considered but the losses it generates are not taken into account in this study.

SIMULATION RESULTS

BDISM simulations are performed using 20 million primary particles sampled in the beam emittance distribution (see Fig. 1). The recommended QGSP_BIC_HP_EMZ physic list in used [14]. It contains the high precision model

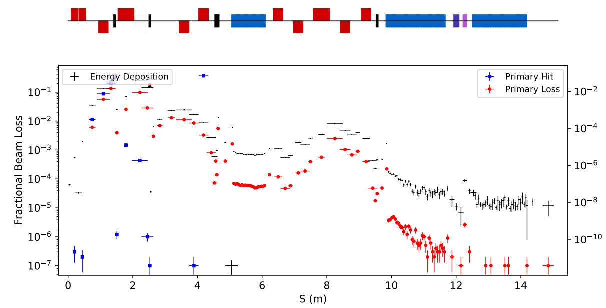


Figure 3: Locations of beam losses along the beamline. They are mainly located at the beginning and near the energy degradation system for an energy at isocenter of 70 MeV.

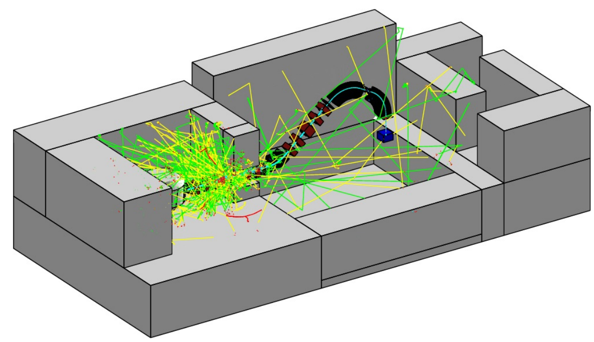


Figure 4: Realistic model of the Proteus®One system for BDSIM simulations combining the shielding and the beamline. The proton beam (cyan) is transported up to the isocenter but produces neutrons and gammas (green and yellow) when interacting mainly with the energy degrader.

for low energy neutrons and the most precise electromagnetic physics. An experimental validation has been performed using different Beam Profile Monitors (BPM) inside the beamline. The results are shown in Fig. 5. The good agreement shows that the model is suitable to determine the properties of the beam at any location in the beamline. It is then possible to characterize the types of secondary particles generated during interactions between protons and components of the beamline, especially the degrader, the collimators, the quadrupoles and the dipoles. Therefore, it is possible to conduct a complete radiation protection studies, and to calculate the activation of concrete shielding. Each wall of the concrete shielding is divided in cells and in each one, the activation concentration (number of created isotopes per unit of mass) is computed following Eq. (1). We compute the activation of the concrete shielding due to neutronic capture, which produce Eu152, and spallation reactions which generate Na22. Other isotopes are also produced but these are the most important [15]. For the neutronic capture, we use the cross-section as tabulated in the ENDF database and the data in [16] for the spallation reaction: a cube of water, located at the isocenter, is irradiated with a 160 MeV proton beam and, in each cell, the relation (1) is then computed taking into account the radioactive decay of the radionuclide. The results are presented in Fig. 6. It shows a top view of the

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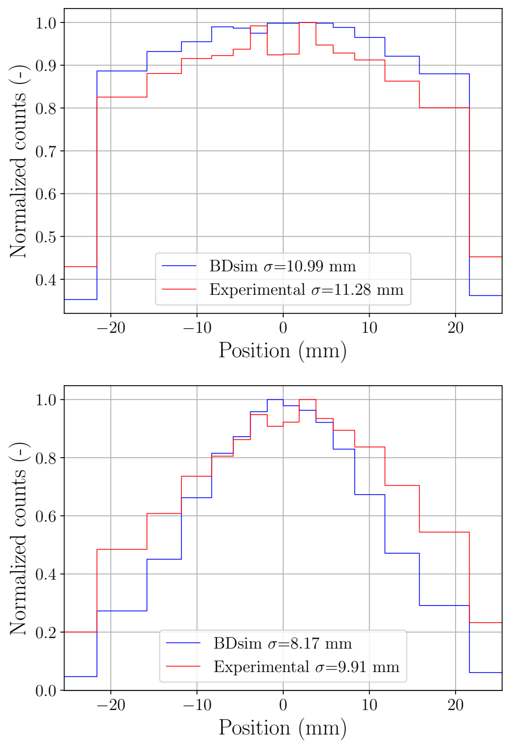


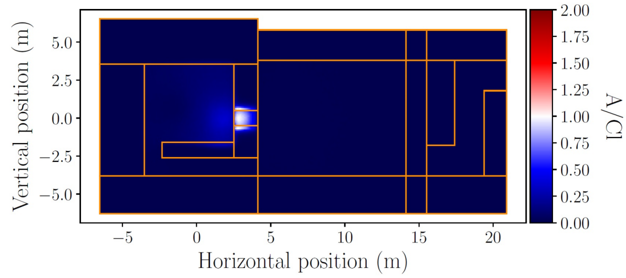
Figure 5: Comparison with experimental results at two positions in the beamline. The red line correspond to the experimental data and the blue line to the results obtained with our model.

center and the areas where the concrete has to be considered as a nuclear waste after 20 years of operation.

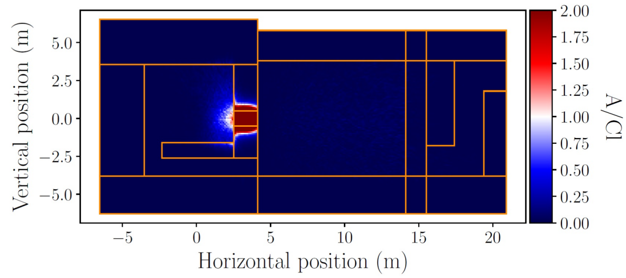
We observe that the major part of the activated concrete is located around the energy degradation system (degrader and collimator) for both isotopes. Moreover, due to low energy neutrons, the walls behind the beamline are also impacted and will be activated due to neutron capture.

CONCLUSION AND OUTLOOK

A 3D model of a Proteus®One system has been developed using BDSIM. This model is built using realistic geometries and takes into account the properties of the beam at the exit of the accelerator. This model has been validated against experimental data and permits for the first time a study of the activation using seamless simulations, i.e the tracking of primary beam and the generation of secondary particles simultaneously. Results show that an important quantity of concrete has to be treated as nuclear waste after 20 years of operation. Further developments include a study of the beam losses during the acceleration phase inside the accelerator and the development of a dynamic model that take into account the realistic beam workload for the treatment of patients.



(a) Neutronic capture



(b) Spallation reaction

Figure 6: Representation (top view) of the quantity of activated concrete due to neutronic captures in (a) and spallation reactions in (b). The walls are represented by the orange lines.

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