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STUDY OF A PROTON THERAPY BEAMLINE FOR EYE TREATMENT WITH BEAM DELIVERY SIMULATION (BDSIM) AND AN IN-HOUSE TRACKING CODE

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Abstract

The complete modelling of passive scattering proton therapy systems is challenging and requires simulation tools that have capabilities in both beam transport and in the detailed description of particle-matter interactions. Beam Delivery Simulation (BDSIM) allows the seamless simulation of the transport of particles in a defined beamline and its surrounding environment. A complete 3D model can be built from Geant4, CLHEP and ROOT to provide a complete analysis of the primary beam tracking. This capability is applied to the eye treatment proton therapy machine part of the IBA Proteus®Plus product line. Those simulations are compared with a fast in-house particle tracking code with a semi-analytical model of Multiple Coulomb Scattering. The preliminary results leading to the detailed knowledge of the beamline performance are discussed in detail.

INTRODUCTION

Ocular tumors treatment options include surgery (either local resection or enucleation), chemotherapy, thermotherapy and radiation therapy [1]. Proton therapy offers advantages to treat ocular melanomas given its ability to spare healthy ocular and cranial tissues. In such complex and heterogeneous organs, proton beams can offer better dose conformation compared to photons, thanks to the *Bragg Peak* property of charged particles.

The IBA Proteus®Plus system is a cyclotron-based multi-room proton therapy center. It can include multiple types of treatment rooms, including gantry and fixed-beam rooms. In this work we study the single scattering nozzle which can be featured in the so-called Fixed Small Treatment Room dedicated to eye treatment.

A schematic representation of the main components of this nozzle is shown in Fig. 1. From left to right, we can observe the first ionization chamber (IC1) which serves as a beam profile monitor at the nozzle entrance, the Lollipop Box (LB) which contains both the scattering (high Z and high density material) and the range shifting (low Z material) foils, the Neutron Shield (NS), a hollow polycarbonate cube, used to stop neutrons produced in the nozzle (mainly by the range shifting and scattering processes) and the Snout (SN), coupled with a 3 cm inner diameter aperture. The 3 cm aperture simulated in this work represents the maximum field size to be delivered. Actual patient-specific apertures are typically of smaller radii. A cubic Water Phantom (WP), placed 7 cm downstream of the aperture exit, is also shown.

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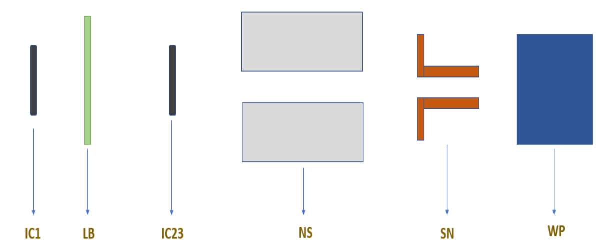

Figure 1: Schematic representation of the IBA single scattering eye treatment nozzle.

The transverse and depth dose profiles of the beam obtained at isocenter (7 cm downstream of the aperture exit) must meet tight clinical requirements: lateral uniformity, Spread-Out Bragg Peak (SOBP) flatness, optimal dose rate and lateral penumbra. The lateral penumbra is the distance between the 80% and 20% dose points and defines the sharpness of the field fall-off. It must typically be below 1.5 mm. The maximum field size (defined as the distance between the 50% dose points for a circular field at isocenter) and the penumbra define the so-called *Uniform Region*: the field size with a distance of twice the penumbra subtracted on each side. The dose profile of the uniform region must remain between 98% and 102% of the on-axis dose value.

All those properties are determined by the optical properties of the beam at the nozzle entrance, by the nozzle geometry and by the beam-matter interactions occurring in the beam modifying elements that are inserted in the nozzle (range shifters and scatterers). This work presents preliminary results obtained for the evaluation of these properties for a single-scattering nozzle design. Different models to compute the beam-matter interactions are developed for progressively more realistic geometries and compared. The Fermi-Eyges (FE) transport formalism [2] is used to perform a semi-analytical computation of the minimal Tantalum scatterer thickness, needed to achieve a 98% beam uniformity at isocenter, for a 3 cm field size. Then, the in-house code "MANZONI" is used to track the beam through the nozzle. It allows the tracking of a large number of particles through a beamline and implements various beamline and beam shap-

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ing elements [3]. This tracking permits the validation of the FE formalism for our geometry. It also allows to determine the effects of the aperture on the beam transverse penumbra. Finally, a 3D model of the nozzle is implemented with Beam Delivery Simulation (BDSIM), a Geant4 based beam tracking and beam-matter interactions code [4]. This 3D model allows to evaluate both the transverse and the in-depth dose deposition when the beam interacts in the water phantom.

MODELLING OF THE NOZZLE WITH MANZONI AND BDSIM

MANZONI implements a matrix formalism to propagate a given beam through a predefined beamline. For the beam-matter interactions, the Fermi-Eyges (FE) formalism is used to obtain the beam properties after a certain thickness of matter. The FE formalism is based on the Multiple Coulomb Scattering (MCS) theory and describes how a Gaussian beam propagates through a stack of homogeneous slabs. For a fixed geometry, let z be the beam propagation direction and x, y the transverse ones (y is up and x,y,z form a right handed frame). If a single proton enters the slab at $z = 0$, the probability to find it at some $z > 0$ with x in dx and θ (the transverse angle related to x) in $d\theta$ is :

$$P(x,\theta)dxd\theta = \frac{1}{2\pi\sqrt{A_0A_2 - A_1^2}} e^{-\frac{A_0x^2-2A_1x\theta+A_2\theta^2}{2(A_0A_2-A_1^2)}} \quad (1)$$

where the quantities A_i are the i^{th} order moments of the considered material scattering power $T(z)$ [5]. Their expressions are:

$$A_i(z) = \int_0^z (z-u)^i T(u)du \quad (2)$$

The θ (resp. (x)) marginal distribution can be obtained by integrating Eq. 1 over (x) (resp. θ).

MANZONI calculates these A_i step by step from the entrance to the exit of a given beamline. This allows to reconstruct the size of the beam at each element position during the propagation. Figure 2 shows the evolution of the beam enveloppe in the horizontal (X) plane when propagating through the nozzle.

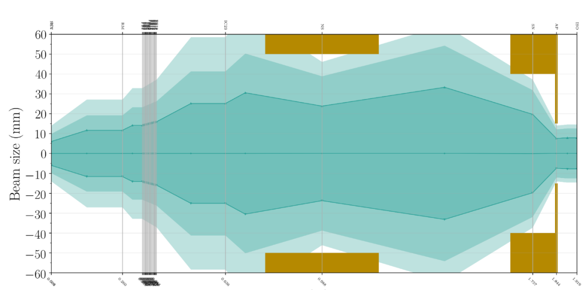

Figure 2: Evolution of the beam enveloppe through the nozzle in the horizontal (X) plane. Dark green is 1σ, intermediate green is 2σ and light green is 3σ.

The FE formalism only describes the electromagnetic beam-matter interactions. For a more precise evaluation of the beam properties in the water phantom, a detailed 3D Monte Carlo model has to be built. This can be achieved with BDSIM, a C++ toolkit which models the propagation of the beam inside a beamline and simulates the beam interactions with all the modelled line components [4]. The model built for the IBA single scattering eye treatment nozzle is shown in Fig. 3.

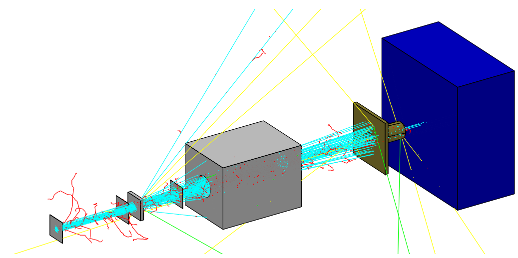

Figure 3: BDSIM model of the IBA eye treatment nozzle. The primary protons are shown in cyan, γ photons are in yellow, neutrons in green and electrons are in red.

SIMULATION RESULTS

Semi-Analytical Computations

Before performing the beam tracking, the FE formalism is used, in combination with a python numerical solver (*numpy.optimise.solve*) to calculate the minimal Tantalum scatter thickness needed to get a flatness higher than 98% at the isocenter, as a function of the Source to Axis Distance (SAD). The SAD is the distance from the scatterer to the isocenter. Figure 4 gives the results obtained for three different beam energies (70, 75 and 82.5 MeV).

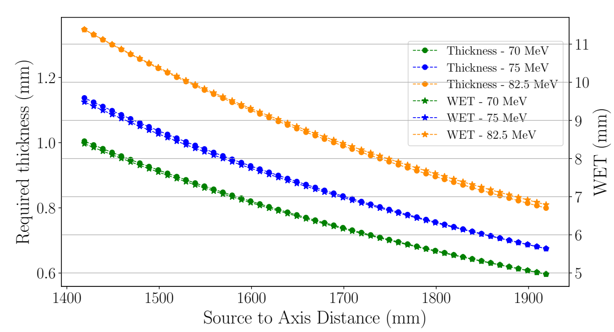

Figure 4: The required tantalum thickness as a function of the Source to Axis Distance (SAD).

As expected, we observe that the higher the SAD, the lower the required scatterer thickness. Regarding the energy dependence, we observe that a more energetic beam requires a thicker tantalum foil to be scattered up to the desired flatness at the isocenter.

We also show in Fig. 4 the induced range shifting for each tantalum scatterer thickness. This is indeed the scatterer WET. It is an important parameter for the nozzle design, as

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it will directly impact the in-depth dose deposition of the beam in the tumor.

The FE formalism also allows to derive the required aperture size as function of the SAD, for a fixed distance from the nozzle exit to the isocenter (7 cm in our case). The results of this computation are shown in Fig. 5.

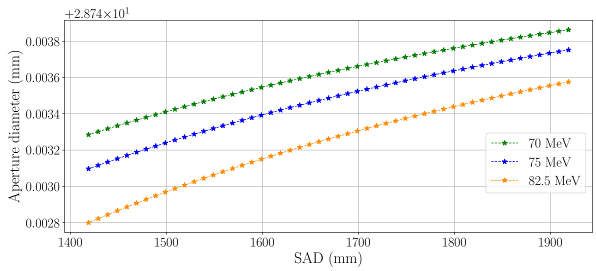

Figure 5: The required apertures sizes as a function of the scatterer position, for three different energies (70 MeV in green, 75 MeV in blue and 82.5 MeV in dark orange).

These aperture sizes and required tantalum thicknesses can now be used to perform the beam tracking using MANZONI and BDSIM.

Tracking with MANZONI

Figure 6 shows a comparison between the transverse profiles at the exit of the aperture and at the isocenter. The tracking was performed with 10^7 primary particles, for a 82.5 MeV beam energy.

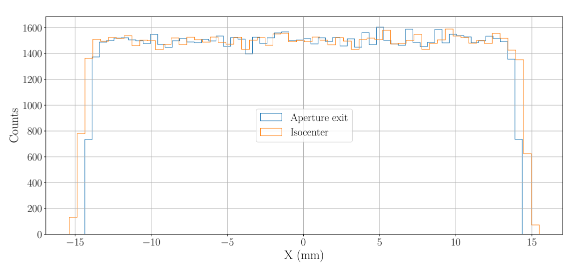

Figure 6: Comparison of the beam transverse profiles both at the aperture exit and at the isocenter.

The lateral penumbra increase due to the beam propagation after the aperture cut is clearly visible. We obtained a 97% flatness at the isocenter, with a 0.8 mm penumbra.

Simulations with BDSIM

For the BDSIM model, each simulation was performed with 10^7 primary protons, using the g4_QGSP_BIC_HP_EMZ physics list. The energy deposition was stored in a cubic 6 cm thick dose scorer mesh, and the resulting 3D histogram was post-processe to get the lateral profiles and the in-depth deposited doses.

The lateral profiles obtained for a scatterer tantalum foil respectively at 0, 40 and 50 cm from the nozzle entrance are shown in Fig. 7.

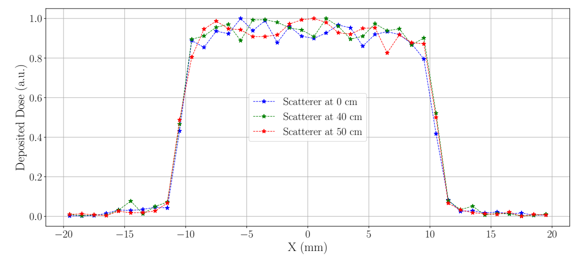

Figure 7: Lateral dose deposition profiles obtained with BDSIM for three different scatterer positions. Nozzle entrance in blue, 40 cm in green and 50 cm in red.

Figure 8 shows 4 Bragg Peaks obtained, for the same (82.5 MeV) energy at the nozzle entrance. For each simulation, the range shifter was a Lexan bloc, put 7 cm downstream of the Tantalum scatterer. The range shifting thicknesses simulated are 3, 9, 15 and 21 mm.

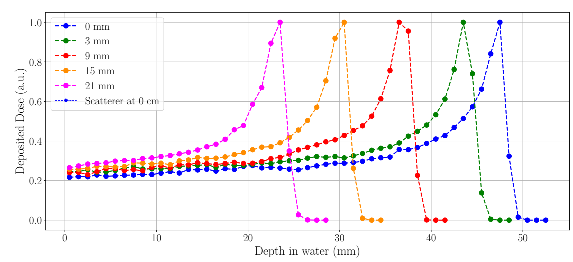

Figure 8: The in-depth dose distribution obtained with BDSIM, for 4 different thicknesses of a Lexan range shifter. A 1 mm step was chosen for the scorer mesh.

CONCLUSION AND OUTLOOK

In this work preliminary results obtained when modelling the IBA single-scattering eye treatment nozzle are presented and discussed. Consistent results are obtained for three different models: semi-analytical FE computations, first order tracking using Manzoni, and a Monte-Carlo code (BDSIM). Our computations showed that clinically accurate dosimetric performances can only be assessed by taking into account the full realistic geometry of the nozzle.

These simulations are a first step to investigate the nozzle design performances in greater details, including the formation of the Spread-Out Bragg Peak (SOBP), the evaluation of the dose distal fall-off and the optizmiation of the design to maximize the dose rate at isocenter, which will be reported later.

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