INCREASED DOSE RATE FOR A PROTON THERAPY EYE TREATMENT NOZZLE ON A MEDICAL GANTRY SYSTEM USING A DIAMOND DEGRADER

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Abstract

The Ion Beam Applications (IBA) ProteusOne (P1) system is suitable for treating ocular tumours and achieves efficient dose conformality using state-of-the-art pencil beam scanning techniques. Nevertheless, with the limited cyclotron current, clinically relevant irradiation times can hardly be achieved in eye tumours treatment cases with the baseline configuration of the system due to the significantly high energy degradation required (from 230 to around 70 MeV). One way to reduce the treatment time is to modify the degrader material and switch to another one that allows a smaller emittance increase, ultimately reducing the losses during the beam transport along the beamline. In this work, we evaluate the clinical performances of the P1 system when using a Diamond degrader instead of the Beryllium material for eye tumours treatment cases. First, we reoptimized the beamline by defining a novel configuration of the quadrupoles and the beam divergence slits so that the new beam obtained at the exit of the Diamond degrader can be guided to the isocenter with limited losses and clinically acceptable transverse sizes and symmetry. Then, using Beam Delivery SIMulation, we evaluated the new dosimetric properties of the system, namely the maximum dose rate, the distal fall-off and the lateral penumbra. The results highlight the fact that combining a Diamond degrader with an additional quadrupole increases the maximum dose rate by up to a factor 2 compared to the baseline configuration, without any clinically significant impact on the lateral penumbra and dose uniformity.

INTRODUCTION

The Ion Beam Applications (IBA) Proteus One (P1) system is a compact gantry, proton therapy facility which features a single treatment room to deliver treatment to cancer patients. Beam Delivery Simulation (BDSIM) [1] has been previously used to develop a realistic numerical model of the IBA P1 system [2]. BDSIM is a C++ particle tracking and beam-matter interaction code which uses tracking routines coupled with the Geant4 [3] Monte-Carlo library to simulate charged particles beams propagation through beam transport systems. The BDSIM model developed for the IBA P1 system is shown in Fig. 1.

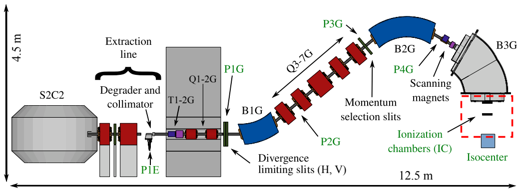

Figure 1: The IBA P1 system as modelled with Beam Delivery SIMulation (BDSIM). Reproduced with permission from Ref. [2]. The boxed region (dashed red) represents the treatment nozzle which has been designed to allow eye tumours treatment (see Fig. 2).

In a previous study, we adapted the nozzle of the P1 system to allow the treatment of cancerous ocular diseases. More specifically, we adequately positionned a Lexan range shifter and a circular aperture in the nozzle, and we performed Monte-Carlo simulations to define the required energy layers, spot spacing and range shifter thicknesses, in order to allow eye tumours treatment with a Distal Fall-Off (DFO) 90-10[1] of maximum 2 mm, a Lateral Penumbra (LP) of maximum 2 mm and an in-depth and transverse uniformities of maximum 2%. At the same time, we evaluated the instantaneous dose rate achieved by the system and found that it varies from 16 to 70 Gy/min over all the treatment range interval required for eye tumours treatment cases (from 5 to 35 mm). The configuration of the P1 nozzle as designed for eye tumours treatment is shown in Fig. 2.

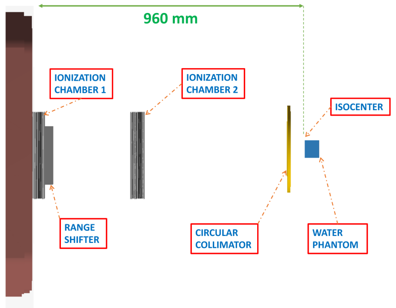

Figure 2: BDSIM model of the nozzle of the IBA P1 system with the range shifter and the aperture positionned to allow ocular tumours treatment.

However, when accounting for the additional time required to switch between the different energy layers and the different scanning magnets configurations in the pencil beam scanning (PBS) mode of the P1 system, the achieved instantaneous dose rate is not sufficient to guarantee the deliverability of a single treatment session within 60 sec-

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[1] The Distal Fall-Off (DFO) 90-10 is the difference between the 10 % and 90 % dose points downstream of the maximum of the Bragg peak: DFO = $R_{90} - R_{10}$.

onds. Therefore, as this time interval is the typical goal of physicians and medical physicists in eye tumours treatment centers [4], the configuration of the P1 system needs to be modified in order to obtain higher instantaneous dose rates, that would allow a single session delivery within one minute. The main reasons of the limitation on the dose rate are the limited beam current of 150 nA deliverable by the SuperConducting Synchro-Cyclotron (the S2C2) of the P1 system, the high energy degradation required not only in the beamline (from 230 to around 70-80 MeV for eye tumours treatment), but also inside of the nozzle, with the additional range shifter required to reach the treatment range interval of 5 to 35 mm.

In this paper, we propose to modify the degrader material from Beryllium to Diamond, a material that requires a reduced thickness and induces a smaller emittance increase during the beam matter interaction processes than Beryllium for an identical energy degradation [5]. As the properties of the degraded beam are completely different at the exit of the Diamond degrader from the beam obtained with Beryllium, a reoptimization of the beamline was required to allow the transport of this new lower emittance beam with minimal losses. Moreover, in order to compensate for the high divergence of the beam aft the exit of the Diamond degrader, we inserted an additional, 40 cm long, quadrupole just after the collimator, to directly focus the beam with a triplet instead of the doublet used in the baseline configuration upstream of the gantry system. The new configuration of the beamline at the exit of the degrader is shown in Fig. 3.

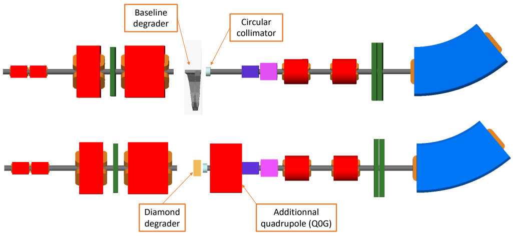

Figure 3: The energy degradation beamline of the IBA P1 system, from the exit of the accelerator to the first bending dipole (B1G). The baseline configuration in which a degrader wheel material made of Beryllium for clinical smaller than 11 cm is shown on top, while the new configuration proposed with a Diamond degrader coupled with an additionnal quadrupole is presented on bottom.

Based on the Python optimization package pymoo [6], we optimized the configuration of the quadrupoles and the divergence slits, to allow a symmetrical spot at the isocenter, with a beam size not larger than 11 mm along both transverse axes. The cost function of the optimization was the maximum of the transmission of the beamline. Then with the best solution found, we used Beam Delivery SIMulation (BDSIM) to simulate the dose deposition profiles induced at the isocenter in a cubic water phantom by the reoptimized clinical beam. The specific case of eye tumours treatment was studied, with an additional range shifter inserted in the nozzle, together with a circular, 15 mm radius and 1 cm thick, Brass aperture. Concerning the material of the range shifter, a comparison was done between Lexan and Polyethylen. For both range shifter materials, the gain in dose rate, the DFO and the Lateral Penumbra of the dose deposition profiles are assessed and compared with the baseline configuration.

BEAMLINE OPTIMIZATION

The algorithm used to recompute the configuration of the P1 system in order to efficiently transport the beam obtained with the Diamond degrader is based on the Python optimization library *pymoo*. The variables changed by the optimizer are the normalized gradients of all the quadrupoles located downstream of the degrader (including the additionnal quadrupole placed just after the collimator) and the opening of the horizontal and vertical divergence slits of the P1 system. The cost function is the transmission of the beamline, which must be maximized under the following two constraints:

1. a maximum beam size of 11 mm in the horizontal and vertical axes ($\sigma_x < 11$ mm and $\sigma_y < 11$ mm);
2. a beam symmetry (defined as $s = \frac{|\sigma_x - \sigma_y|}{\sigma_x + \sigma_y}$) of maximum 5% at the isocenter.

We present in Table 1 the final normalized gradients obtained at the end of the optimization and a comparison with the values used in the baseline configuration. The quadrupoles are numbered from 0 to 7, and the horizontal and vertical slits openings are respectively named SL2GX and SL2GY. The additional quadrupole is Q0G.

Table 2 shows the results obtained for the beam transverse sizes and the transmission of the beamline. We show both the transmission from the collimator exit (T_{col}) and from the accelerator exit (T_{acc}) to the isocenter.

The transverse beam size slightly increases from around 9 mm in the baseline configuration to around 10.8 mm with the Diamond degrader. As for eye treatment cases an aperture will be systematically used to define the transverse shape of the irradiation field, this increase is not expected to have a significant impact on the lateral penumbra. The simulations presented at the end of section will confirm this expectation.

MONTE-CARLO SIMULATIONS

After the beamline optimization, we simulated different Bragg peaks to investigate the impact of the new configuration that we defined on the DFO of the system for the minimum clinical range of 5 mm. This investigation is of great important as the optimization did not account for the DFO limitation of maximum 2 mm which is imposed in the context of eye tumours treatment. Figure 4 presents a few simulated Bragg peaks for different values of the horizontal opening of the momentum slits (SL3G). At the same time, the maximum dose obtained per primary particle launched at the exit of the S2C2 was also assessed in order to compute the *dose multiplication factor*, which is just the gain in dose compared to the baseline configuration with a Lexan range shifter. All these comparisons were done for both Lexan and Polyethylen range shifters in the nozzle, and the evolution

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Table 1: The values of the optimization variables obtained for the P1 system using a Diamond degrader coupled with an additional quadrupole, compared with the baseline configuration for which a Beryllium degrader is used.

Degrader Material	**Q0G (m^{-2})**	**Q1G (m^{-2})**	**Q2G (m^{-2})**	**Q3G (m^{-2})**	**Q4G (m^{-2})**	**Q5G (m^{-2})**	**Q6G (m^{-2})**	**Q7G (m^{-2})**	**SL1GX (mm)**	**SL2GY (mm)**
Beryllium	/	-5.67	4.49	3.50	-3.86	7.44	-7.16	5.24	27.50	14.50
Diamond	5.93	-6.41	3.90	5.03	-4.62	6.77	-7.63	7.82	27.45	27.39

Table 2: The values of the variables, the objective function and the constraints, obtained after the optimization of the P1 system using a Diamond degrader. The same parameters are also given for the baseline configuration for which a Beryllium degrader is used.

Degrader material	σ_x **(mm)**	σ_y **(mm)**	T_{col} **(%)**	T_{acc} **(%)**
Beryllium	8.1	9.0	2.4	0.79
Diamond	10.85	10.01	3.12	1.18

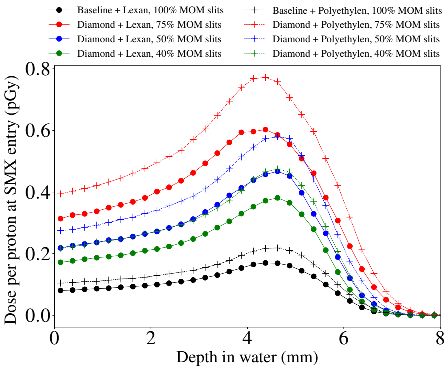

Figure 4: The depth dose profiles obtained for 3 different openings of the P1 momentum slits (75%, 50% and 40%). The results obtained with the new configuration are compared with the baseline results. The simulations are performed with a Lexan and a Polyethylen range shifters.

of the DFO and the dose multiplication factor as a function of the momentum slits opening are presented in Fig. 5.

The maximum DFO of 2 mm is exceeded with the new configuration when the momentum slits are let at the same opening as in the baseline configuration. Closing them up to 50% of their opening allows to restore the baseline DFO of 1.5 mm, while the dose multiplication factor decreases from around 5(resp. 4.2) to 2.1 (resp. 1.8) with the Polyethylen (resp. Lexan) range shifter. Therefore, combining the Diamond degrader with an additional quadrupole and a Polyethylen range shifter is the best solution to multiply the dose rate by a factor 2.

Finally we compare the impact of this new configuration on the lateral uniformity and on the lateral penumbra when considering only 1 energy layer of 70 MeV. The lateral profiles obtained with the baseline and the new configurations are compared in Fig. 6. As can be seen, there is no significant difference neither in terms of lateral uniformity nor in the values of the lateral penumbra.

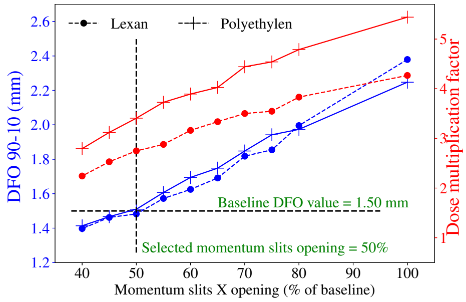

Figure 5: Evolution of the DFO and the dose multiplication factor as a function of the momentum slits opening (expressed as percentage of the baseline configuration). An opening of 50% allows to have a similar DFO as the baseline configuration, with a dose multiplication factor ranging from 2.5 to 3.5.

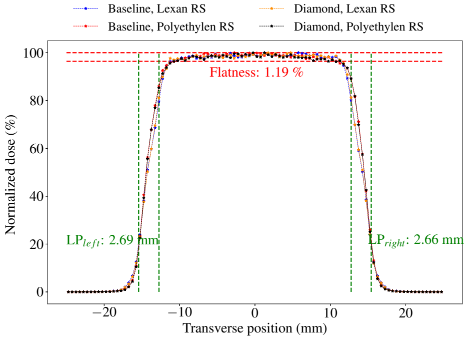

Figure 6: The lateral profiles obtained with the baseline configuration of the P1 system (Beryllium degrader), in comparison with the new configuration proposed (Diamond degrader with an additional quadrupole). For each configuration, Lexan and Polyethylen are simulated as a range shifter inserted in the nozzle, just downstream to IC1.

CONCLUSION

We propose in this paper a reoptimization the Ion Beam Applications (IBA) Proteus One (P1) system using the combination of a diamond degrader, an additional quadrupole and a Polyethylen range shifter to allow eye tumours treatment with significantly higher instantaneous dose rates compared to the baseline configuration. The Monte-Carlo simulations show that our new configuration can increase the instantaneous maximum dose rate by up to a factor 2, without having any clinically significant impact on the other dosimetric properties of the system.

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