NOZZLE DESIGN OPTIMIZATION FOR PROTON FLASH THERAPY

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Abstract

An increasing number of accelerators are pursuing FLASH radiotherapy, which promises to mitigate unwanted damage to healthy tissues by applying ultra-high dose rates. To reach this extreme intensity regime, it is necessary to maximize the transmission through the exit nozzle, apart from increasing the accelerator's output beam current. Simultaneously, the delivered beam properties must satisfy certain quality criteria that clinical applications require, such as transverse homogeneity.

For this reason, a Python-based software has been developed to optimize the design of double-scattering beam nozzles based on the construction of rings. For a user-defined set of incoming beam parameters, output field requirements and available materials, the tool searches for the most efficient scattering conditions using a graphical interface. These conditions are then translated into distances and shaping of the scatterers, involving a combination of high and low-density elements in a multiple-ring arrangement. A solution for the treatment of eye tumors has been successfully calculated, implemented, and tested with beam, in order to demonstrate the capabilities of this approach.

INTRODUCTION

The HZB Cyclotron [1] has been providing proton treatment of ocular tumors to more than 4600 patients since 1998 in collaboration with the Charité – Universitätsmedizin Berlin. Besides therapy, its versatile research and development program includes biomedical studies, especially in the field of FLASH radiation. The term FLASH has been established to describe irradiation with ultra-high rates (> 40 Gy/s), which has been shown to offer a better protection to healthy tissues without compromising the tumor control for the same dose [2]. Although the underlying mechanism of the FLASH effect is not fully understood yet, clinical trials on humans are already underway [3].

After the first FLASH experiments at HZB [4], various upgrades have improved the intensity, field size, depth modulation and repeatability of the delivered beam [5, 6]. The next goal was to reach for the clinical requirements of human eye treatment, which demand a higher beam transmission within a larger irradiation volume with sufficient homogeneity. For that reason, a four-ring double scattering system was implemented in the exit beam nozzle. Details of this setup, as well as its measured beam output will be presented in this paper.

The developed methodology and experience acquired through this process have been coded in a software tool, which is able to find the optimal scattering conditions for a set of input parameters and translate them to a nozzle design using common materials. Aspects and screenshots of this code together with some results will also be shown below.

TOOL FOR NOZZLE DESIGN

An efficient beam nozzle maximizes beam transmission within a certain field size at the sample location without compromising homogeneity. This task becomes considerably tedious or complicated when various parameters such as available length, scattering materials, and beam properties need to be adjusted — especially when choosing double scattering over single scattering for higher beam transmission, as explained below.

The traditional way of transforming the gaussian-like beam from the accelerator to a homogeneous transverse field needed for therapy is by simply introducing a thin scattering material and a collimator downstream the beam path. With this scheme, only the central part of the broadened beam propagates further, delivering a fairly flat distribution at the target. Although more than 90% of the beam gets discarded by this approach, its simplicity and robustness make it acceptable for the low dose rates employed in conventional radiotherapy. On the other side, a double-scattering nozzle combines multiple high and low-density materials in a way that the beam profile gets compressed and much higher transmission values are achieved for the same homogeneity, as demonstrated in Fig. 1.

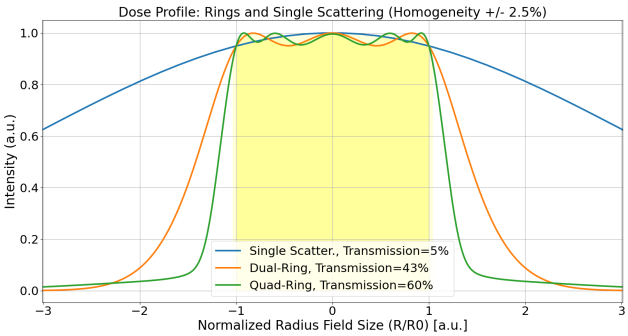

Figure 1: Beam profile and respective transmission of an arbitrary field with ±2.5% homogeneity deviation (yellow area) resulting from single scattering (blue) and double scattering arrangements with two (orange) and four (green) rings.

The latter scheme, initially introduced by Y. Takada for a two-ring system [7], has been extended to include three

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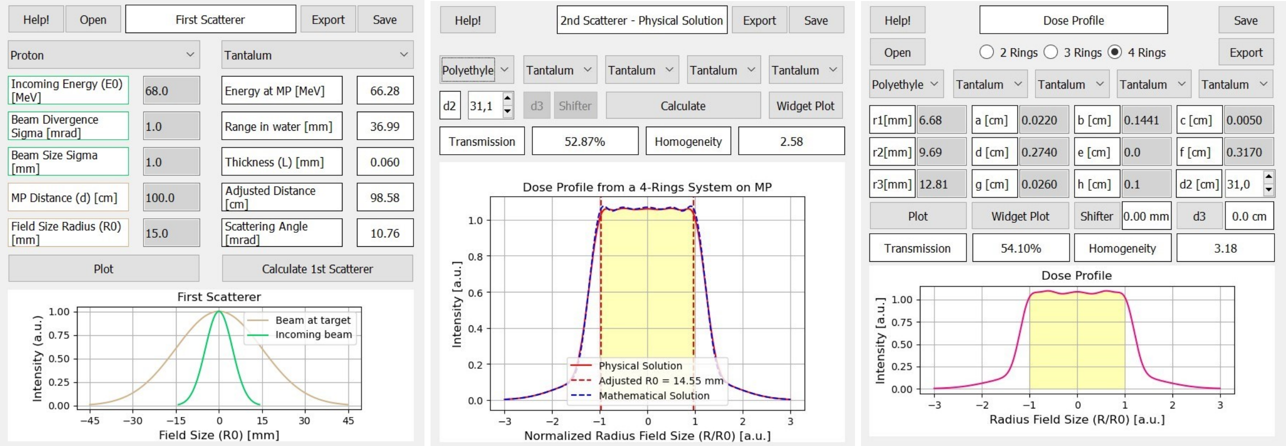

Proton · Tantalum

Incoming Energy (E0) [MeV]	68.0	Energy at MP [MeV]	66.28
Beam Divergence Sigma [mrad]	1.0	Range in water [mm]	36.99
Beam Size Sigma [mm]	1.0	Thickness (L) [mm]	0.060
MP Distance (d) [cm]	100.0	Adjusted Distance [cm]	98.58
Field Size Radius (R0) [mm]	15.0	Scattering Angle [mrad]	10.76

Polyethyle · Tantalum · Tantalum · Tantalum · Tantalum

d2	31,1		
Transmission	52.87%	Homogeneity	2.58

○ 2 Rings ○ 3 Rings ● 4 Rings

Polyethyle · Tantalum · Tantalum · Tantalum · Tantalum

r1[mm]	6.68	a [cm]	0.0220	b [cm]	0.1441	c [cm]	0.0050
r2[mm]	9.69	d [cm]	0.2740	e [cm]	0.0	f [cm]	0.3170
r3[mm]	12.81	g [cm]	0.0260	h [cm]	0.1	d2 [cm]	31,0
				Shifter	0.00 mm	d3	0.0 cm
Transmission	54.10%			Homogeneity	3.18		

Figure 2: Example screenshots from the optimizer tool: data for 1st scatterer (left), 2nd scatterer (middle) and final outcome (right). More details are given in the text body.

and four rings. The detailed mathematical modelling of this method is beyond the scope of this paper and will be published separately. Generally speaking, it involves complex equations for the matching of the scattering angles and the compensation of the energy loss along the process, which can only be solved numerically.

For all of the above reasons, an automated tool has been developed to design and optimize nozzles for positively charged particles. This software was created with Python [8] and offers a graphical interface, where the user can input the incoming beam properties (energy, size, divergence) together with the wished nozzle length, scattering materials and target outcome (beam energy, size, transmission, homogeneity), in order to get all necessary distances and dimensions of a double scattering nozzle with a dual-, triple- or quad-ring arrangement.

The user is guided through a sequence of pages that correspond to different steps of the design process, while observing all intermediate results in output values and plots, as demonstrated in Fig. 2. In the background, the program conducts the necessary mathematical and physical calculations, while running an optimization routine to meet the specified criteria within a given tolerance. Typically, a solution is reached within minutes; otherwise, the user receives a notification to adjust the requirements.

To ensure manufacturing simplicity, rounded values in micrometer increments are considered for the thickness and radii involved in the scattering objects depicted in Fig. 3. For the case of a FLASH nozzle for human eyes at the HZB Cyclotron, an efficient four-ring design was calculated and implemented for beam testing.

4-RING DOUBLE SCATTERING NOZZLE

The developed setup, shown in Fig. 4, has a total length of 98.5 cm and consists of a 60 μm aluminum stack for the first scattering 2 cm downstream the vacuum window (75 μm Kapton foil) and a four-ring second scatterer 31 cm upstream the target location. The latter is made of polyethylene and tantalum with varying thickness levels down to 50 μm, as shown in Fig. 3.

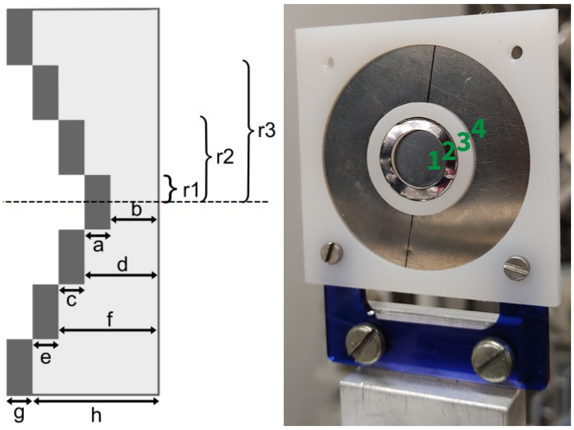

Figure 3: Schematic side view (left) and front view (right) of the designed four-ring scatterer.

The beam profile at the target position was captured by a monochrome CCD camera and is shown in Fig. 5 together with the simulated profile from the program. A field of 30 mm with a homogeneity deviation of around ±3% has been achieved. Despite the relatively approximate placing of all components by hand, a close agreement between simulation and measurement is observed, validating thus the employed physics models and the robustness of the design.

In order to evaluate the beam transmission through the nozzle, two air-filled ionization chambers with 75 μm Kapton foils each were installed at both edges. The first reference chamber was placed between the vacuum window and the aluminium foil, to capture the entire current from the accelerator, and the second one directly downstream a 30 mm collimating aperture at the target location, corresponding to the measured field. The signal ratio between the two chambers was measured to be 62%. Taking into account the maximum output current from the HZB Cyclotron [6], this demonstrated scattering efficiency is expected to provide

Figure 4: Nozzle setup: the beam travels from the end of the vacuum pipe (1) on the right toward the camera at the target position (4) on the left, undergoing double scattering from a thin aluminum foil (2) and a four-ring scatterer (3). A collimator aperture can be inserted at the position of the camera for the determination of the beam transmission using ionization chambers at both edges of the nozzle.

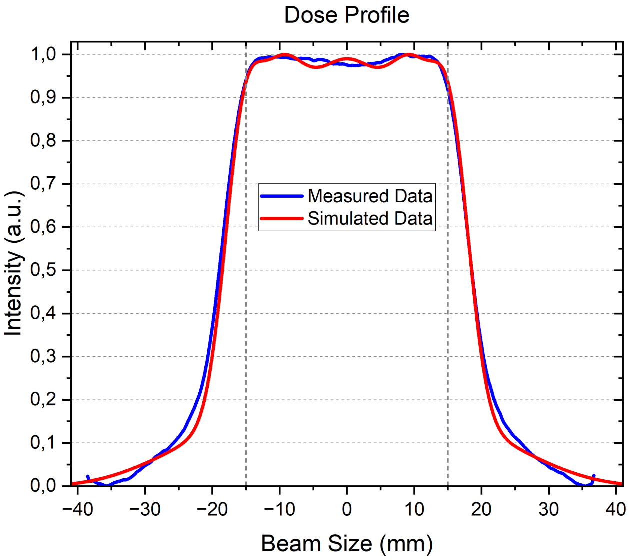

Figure 5: Simulated and measured transverse beam profile at the target plane.

dose rates greater than 100 Gy/s within the 30 mm field, also when the available modulator for a 27 mm spread-out Bragg peak [6] is included in the nozzle.

CONCLUSION

A nozzle optimizer software has been written in Python, which is able to quickly calculate double scattering designs with dual-, triple- or quad-ring arrangements according to the user demands using a graphical interface. Its performance has been demonstrated by the solution it provided for the FLASH requirements of HZB, namely a transverse field of 30 mm with a homogeneity deviation of around ±3% and a beam transmission in the order of 60%. The observed agreement between prediction and measurements verifies the validity of the employed physics models and manifests the robustness of the design, despite the rough manual placement of the involved components. This versatile nozzle can be paired with a modulator for a fully spread-out Bragg peak in order to deliver the clinical criteria for FLASH irradiation of human eyes with protons. Moreover, the developed code can be adjusted to the needs of other applications and institutes utilizing proton and helium beams, with the potential to extend it to heavier ions. Further details of the underlying model are beyond the scope of this paper and will be published separately in the near future.

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