A NOVEL METHOD OF EMITTANCE MATCHING TO INCREASE BEAM TRANSMISSION FOR CYCLOTRON BASED PROTON THERAPY FACILITIES: SIMULATION STUDY*

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Abstract

In proton therapy, high dose rates can reduce treatment delivery times, allowing for efficient mitigation of tumor motion and increased patient throughput. With cyclotrons however, high dose rates are difficult to achieve for low-energies as, typically, the emittance after the degrader is matched in both transversal planes using circular collimators, which does not provide an optimal matching to the acceptance of the following beamline. Transmission can however be substantially improved by transporting maximum acceptable emittances in both orthogonal planes, but at the cost of gantry angle-dependent beam shapes at isocenter. Here we demonstrate that equal emittances in both planes can be recovered at the gantry entrance using a thin scattering foil, thus ensuring gantry angle-independent beam shapes at the isocenter. We demonstrate in simulation that low-energy beam transmission can be increased by a factor of 3 using this approach compared to the currently used beam optics, whilst gantry angle-independent beam shapes are preserved. We expect that this universal approach could also bring a similar transmission improvement in other cyclotron-based proton therapy facilities.

INTRODUCTION

Brought into clinical practice at Paul Scherrer Institute (PSI) in the 1996, pencil beam scanning (PBS) is nowadays the standard beam delivery technique in proton therapy[1], [2]. However, current challenges of PBS particle therapy are the dosimetric uncertainties in treatment of moving targets and the relatively long treatment times involved. The dosimetric uncertainty can be minimized through the use of motion mitigation techniques, which aim to mitigate the interplay effect between the motions in the patient and the beam delivery; the most common motion mitigation techniques are breath-hold [3], rescanning [4], and gating [5]. For all these techniques, it is also desirable to have shorter treatment delivery times [6,7]. One way to reduce the treatment delivery time for PBS proton therapy is to increase the intensity of the low-energy beams by improving the transmission of the beam from the cyclotron to the isocenter (patient position), thereby reducing beam-on time (the time required to deliver the dose) during treatment delivery.

Most of the proton therapy facilities use a cyclotron. Since a cyclotron produces beams of a fixed energy, to modulate the energy of the beam, an energy selection system (ESS), consisting of a degrader with an adjustable thickness followed by momentum selection, is required. However, due to scattering in the degrader, for low-energy beams, the emittance after the degrader is in the range of a few hundreds of π*mm*mrad. Therefore, to minimize beam losses in the beamline, it is necessary to use beam emittance selection collimators after the degrader to restrict the emittance to the requirement of the following beamline or gantry. Currently, all cyclotron-based proton therapy facilities transport a maximum emittance of 30 π*mm*mrad through the beamline (in this work, beam sizes, divergences, and emittances are expressed as 2σ values), which limits the transmission of low-energy beams. At PSI for example, for the lowest energies (70-100 MeV), transmission through the beamline is below 0.1% [8]. Such low transmission for these low energies causes an increase in beam-on time.

One way to achieve higher intensity beams at the isocenter is to transport a higher emittance through the following beamline and gantry [8-11]. At our facility, we can transport a maximum of ~ 65 π*mm*mrad in X-plane and ~ 139 π*mm*mrad in Y-plane. These will increase the beam transmission significantly compared to conventional 30 π*mm*mrad emittance transport in both planes, at the cost of an asymmetric emittance at the gantry entrance, leading to gantry angle dependent beam shapes at the isocenter. To achieve gantry angle independent beam shape at the isocenter, it is necessary to have same emittance at the entrances of the gantry.

In this study, we report on the use of a thin scattering foil, placed in the beamline between the ESS and gantry coupling point, to achieve equal emittances in both planes, whilst maintaining a high transmission through the beamline and gantry, a method also used in several synchrotron-based ion beam therapy facilities [12,13]. In this work, all simulation investigations were performed with 70 MeV beam as our goal was to increase the transmission for low energy beams.

METHODS AND MATERIALS

Emittance Matching with Scattering Foil

To increase the emittance in the X-plane to a similar value as the Y-plane emittance, but with minimally effect on the emittance in the Y-plane, the following boundary conditions have been applied: (as expressed schematically in Fig. 1).

13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOMS025

- Beam waist is at the location of the scattering foil ($R_{12} = 0$ and $R_{34} = 0$).
- No dispersion at the scattering foil location ($R_{16} = R_{26} = 0$).
- Optimized focusing parameters based on twiss-scattering formula for the thin scattering foil.
- The divergence ratio between X-plane and Y-plane must be smaller than the emittance ratio between X-plane and Y-plane at the entrance of scattering foil.
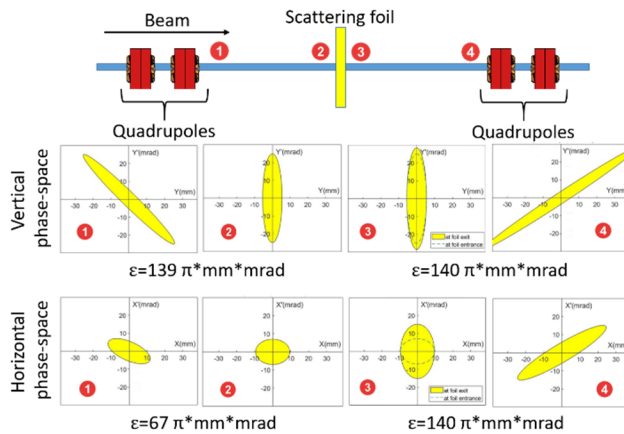

Figure 1: Schematic of the function of scattering foil. Both the horizontal and vertical phase-space ellipses and profiles at different location along the beamline (before and after the scattering foil).

Specification of Scattering Foil

A tantalum (Ta) scattering foil 30 µm thick, assuming a density of 16.69 g/cm^3, is placed in the beam line as shown in Fig. 2.
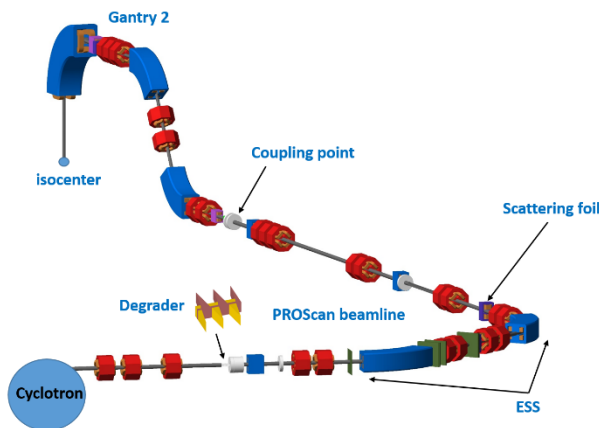

Figure 2: BDSIM model of PROSCAN beam line and Gantry 2.

Monte Carlo Simulation with New Beam-Optics Design

The matrix formalism code TRANSPORT has been used to design new beam optics to include the above described scattering foil. However, TRANSPORT cannot predict the scattering effect and beam losses along the beamline. To simulate the scattering effect and to calculate the transmission of the new beam optics and the beam size at isocenter, Monte Carlo simulations, based on beamline settings optimized with TRANSPORT, are required. These have been performed using the BDSIM 1.4.133 Monte Carlo simulation toolkit [14]. Based on initial TRANSPORT beam optics, we did the BDSIM simulation up to scattering foil and calculated the beam parameters after the scattering foil. With these new parameters from BDSIM simulation, we redesign the beam optics in TRANSPORT from scattering foil to isocenter. After that, we did a BDSIM simulation for the full PROSCAN beamline and calculate the transmission along the beamline and beam size at the isocenter.
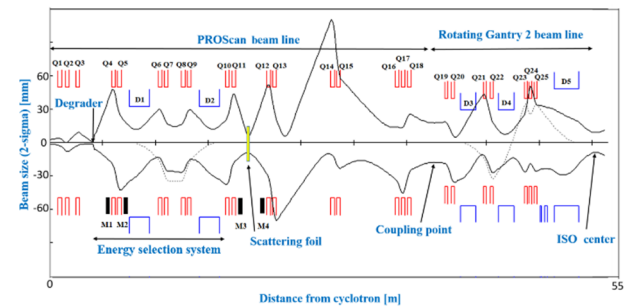

Figure 3: The new beam optics including a scattering foil transports 67 π*mm*mrad in X-plane and 139 π*mm*mrad in Y-plane up to scattering foil location and transports almost 140 π*mm*mrad (in both planes) from scattering foil to isocenter. The beam envelopes show the beam size in 2-sigma values and the dispersion (dashed line) along PSI's ESS beam line (The lower half of figure shows beam envelope in X-plane (bending plane) and the upper half shows envelope in Y-plane).

RESULTS

Emittance Simulation with Scattering Foil

The beam optics from cyclotron exit to the scattering foil location (position 2 in Fig 1) have been designed such that we get a beam size of 9.5 mm and 7 mrad divergence in the X-plane, and 5.5 mm and 25 mrad in the Y-plane.

Table 1: Simulated Beam Parameters After Scattering Foil

	Beam size (mm)	Beam Divergence (mrad)
X-plane	9.5	14.7
Y-plane	5.5	25.5

With BDSIM simulation, we predict the beam parameters after the scattering foil. As shown in Table 1, in X-plane, we achieved 9.5 mm beam size and 14.7 mrad divergence and in Y-plane, we achieved 5.5 mm beam size and 25.5 mm divergence. After the scattering foil, we get 140 π*mm*mrad emittance in both planes (Table 2).

13th Int. Particle Acc. Conf.
ISBN: 978-3-95450-227-1

IPAC2022, Bangkok, Thailand
ISSN: 2673-5490

JACoW Publishing
doi:10.18429/JACoW-IPAC2022-THPOMS025

Table 2: Simulated Emittance Value Just Before and After the Scattering Foil

	Emittance before scattering foil (π*mm*mrad)	Emittance after scattering foil (π*mm*mrad)
X-plane	67	140
Y-plane	139	140

Transmission Improvements with Scattering Foil

We have compared the transmission at different locations along the beamline for the reference beam optics transporting 30 π*mm*mrad (as in clinical use) and the new beam optics with scattering foil.

Table 3: Simulated transmission using reference beam optics and new beam optics with scattering foil. Transmission values are from cyclotron to different locations along the beamline.

Location along beamline	Reference beam optics	New beam optics with scattering foil
M2	1.5%	5%
M3	0.23%	1.26%
Coupling point	0.22%	0.96%
Isocenter	0.14%	0.42%

As we are transporting higher emittance, at the monitor M2 location (shown in Fig 3), we get almost 5% transmission for new beam optics while only 1.5% transmission with reference beam optics. While passing through the ESS, we lose the beam in momentum selection slits in both cases. For reference beam optics, from the end of ESS to coupling, we do not lose the beam. However, when introducing the scattering foil, divergence increases in both planes, and the next quadrupole magnet is almost 2 m away. Therefore, losses between quadrupoles Q12 to Q15 are unavoidable, and another 25% of the beam is therefore lost in the new beam optics. For the scattering foil case, the gantry beam optics was designed with 2:1 imaging which allows transporting high emittance through the gantry while having minimum losses [9]. Overall then, with the use of asymmetric optics, 2:1 imaging in the gantry, and the introduction of the scattering foil, we predict an overall transmission of 0.42% from the cyclotron to the isocenter, which can be compared to the only 0.14% transmission for the reference beam optics.

However, transmission improvements come at the cost of an increased beam size. For the reference beam optics, the beam size at the isocenter is 10.5 mm whereas with the high transmission and scattering foil beam optics, this increases to 18.5 mm, representing a 76% increase in beam size.

CONCLUSION

In this work, in simulation, we have demonstrated that by using a thin scattering foil placed in the beamline, we can match the emittance in both transverse planes by increasing the divergence in the low emittance-transporting plane (in our case X-plane). As this approach allows for transport of maximum acceptable emittance in both planes, this method substantially increases the low energy beam transmission through the beamline, while achieving gantry angle independent beam sizes at the isocenter. The obtained higher intensities (dose rates) could reduce treatment delivery times to aid motion mitigation techniques such as breath-hold, gating, and rescanning. In addition, shorter treatment delivery times may increase patient throughput, lowering the cost of proton therapy treatment.

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