ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-FRBI01

DIFFERENT METHODS TO INCREASE THE TRANSMISSION IN CYCLOTRON-BASED PROTON THERAPY FACILITIES*

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Abstract

In proton therapy (PT), high dose rates could allow efficient utilization of motion mitigation techniques for moving targets, and potentially enhance normal tissue sparing due to the FLASH effect. Cyclotrons are currently the most common accelerator for PT, accounting for two-thirds of the total installations. However, for cyclotron-based facilities, high dose rates are difficult to reach for low-energy beams, which are generated by passing a high-energy beam through an energy degrader and an energy selection system (ESS); due to scattering and range straggling in the degrader, the emittance and energy/momentum spread increase significantly, incurring large losses from the cyclotron to the patient position. To solve these problems, we propose different options to transport the maximum acceptable emittance in both transverse planes (using new gantry beam optics, asymmetric collimators and/or scattering foil). We demonstrate in simulation that low-energy beam transmission can be increased up to a factor of 6 using these approaches compared to the currently used beamline and ESS. This concept is key to enhance the potential of PT by increasing the possibilities to treat new indications in current and future PT facilities while reducing the cost.

INTRODUCTION

The most advanced, and nowadays the most used method to deliver the dose is spot scanning or pencil beam scanning (PBS) [1]. Treatment delivery time with PBS PT depends both on the beam-on time and the dead time (the time required to change energy layers and/or lateral position) between pencil beams [2,3]. As such, PBS irradiation with high-intensity beams will reduce beam-on time and thus shorten total delivery times, making motion mitigation techniques such as breath-hold or gating more efficient and patient-friendly [4].

Most of the PT facilities use a cyclotron, which extracts proton beams at fixed energy (at PSI, we extract 250 MeV beam). However, to spread the dose over the depth of the tumor, different beam energies are needed for the treatment (70-230 MeV). In a cyclotron-based facility, the energy is lowered by passing the beam through energy-degrading material(s) (so-called energy degraders). However, due to scattering in the degrader, for low energy beams, the emittance after the degrader is in the range of a few hundred of π*mm*mrad. Additionally, due to range straggling in the degrader, the momentum spread of the beam will also increase. Therefore, to minimize beam losses in the beamline, it is necessary to use beam emittance selection collimators after the degrader and momentum selection slits in the energy selection system (ESS) to restrict the emittance and momentum spread to the requirement of the following beamline or gantry. Currently, all cyclotron-based PT facilities transport a maximum emittance of 30 π*mm*mrad through the beamline, which limits the transmission of low-energy beams. For example, for the lower energies transported by the Gantry 2 at our institute (70-100 MeV), transmission from the cyclotron to the isocenter is of the order of only 0.1% [5,6,7,8].

Therefore, to limit the losses in the beamline, in this paper, we are providing a summary of different ways to efficiently transport higher emittance through the beamline.

First, we propose the use of a large beam size and low divergence beam at the coupling point (CP) along with an imaging factor of 0.5 (2:1) in a new design of gantry beam optics to transport higher emittance through gantry while achieving higher transmission and thus increase beam intensity at the isocenter. Secondly, we propose the use of scattering foil to achieve the same emittance in both planes at the entrance of the gantry while transporting maximum acceptable emittance in both planes from the degrader, thus ensuring gantry angle-independent beam shape at the isocenter. In the end, to maximize the emittance transport through both transverse planes, we propose to use a collimation system, asymmetric in both beam size and divergence, resulting in symmetric emittance in both beam transverse planes as required for a gantry system.

This study was performed as a collaborative doctoral project between the center for proton therapy and a large accelerator facility group at PSI and published in [5,6,7,9,10,11]. In the following, all beam sizes, divergences, and emittances are expressed as 2-sigma values.

TRANSMISSION OPTIMIZATION THROUGH GANTRY

Conventional beam optics of cyclotron-based proton gantries were designed to provide point-to-point focusing in both planes, with an imaging factor of between 1 to 2 from

* THIS WORK IS SUPPORTED BY A PSI INTER-DEPARTMENTAL FUNDING INITIATIVE (CROSS)
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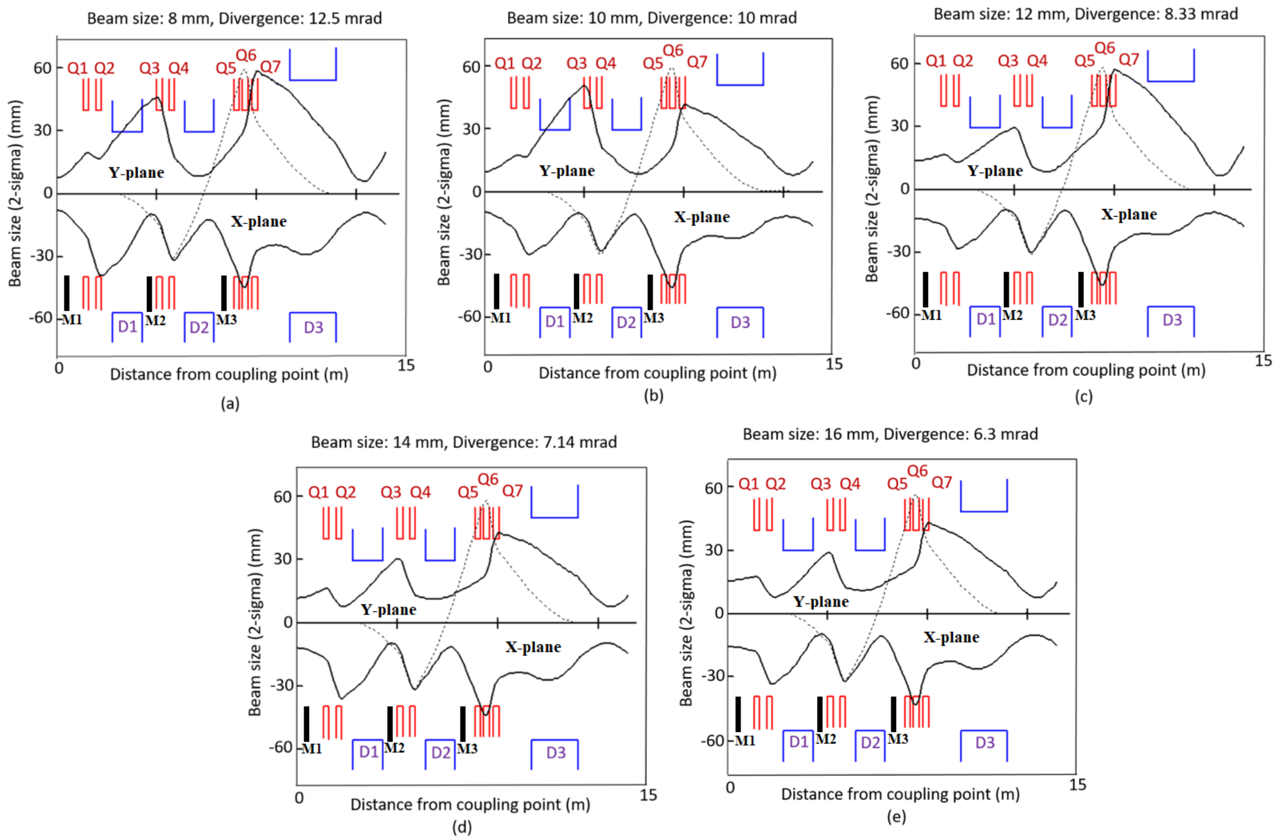

Figure 1: Gantry beam optics to transport 100 π*mm*mrad with different beam phase space at the CP. The beam envelopes show the beam size in 2-sigma values and the dispersion (dashed line) along PSI's Gantry 2 beamline (The lower half of each figure shows the beam envelope in the X-plane (bending plane) and the upper half shows the envelope in Y-plane). Figure (a), (b), (c), (d), and (e) represents 1:1, 1.25:1, 1.5:1, 1.75:1, and 2:1 imaging respectively. Elements D = dipole magnets and elements Q = quadrupole magnets. The dispersion only occurs in the bending plane (in our case, X-plane) [9].

the CP to the isocenter [6,7]. These increase the possibility of beam losses along the gantry as the beam envelope approaches the beam pipe. For instance, for PSI's Gantry 2, by transporting 30 π*mm*mrad emittance (3 mm beam size and 10 mrad divergence at the CP) with 1:1 imaging, the transmission of 57 % is achieved for lower energies (70-100 MeV). However, to achieve higher intensity for lower energy beams, it is desirable to transport a higher emittance through both the beamline and gantry. Here, we report on a new beam optics approach, which transports higher emittances through the gantry.

To study the effect of beam phase space at CP on gantry transmission, we chose five different phase space orientations of which each had the same 100 π*mm*mrad emittance. The gantry beam optics were then modified for all five cases to transport this same emittance through the gantry. In order to achieve the same beam size at the isocenter, however, beam optics with different magnification factors, depending on the beam size at CP, were designed. Figure 1 shows the selected beam size and divergence at CP, together with the resulting imaging factor for five different beam widths and their beam envelopes through the gantry.

A ±1% momentum spread (Δ p/p) was assumed for all cases. Due to the large dispersion, some beam is inevitably lost in the quadrupole triplet in all cases [9].

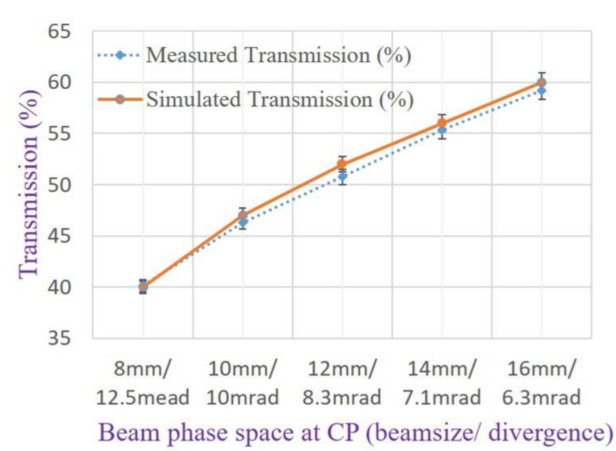

Figure 2: Beam transmission through gantry (simulation and measured) for transporting 100 π*mm*mrad through gantry with different beam parameters at the CP [9].

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When transporting beams with 100 π*mm*mrad emittance through the gantry, we get a minimum transmission of about 40% for a beam size of 8 mm and large divergence (12.5 mrad) (Figure 2 (a)). By increasing the beam size and decreasing the divergence, however, one can see a gradual increase in transmission through the gantry, reaching a maximum transmission of about 60%, for the largest beam size at CP (16 mm), corresponding to the smallest divergence. This matches expectations as can be observed in Figure 1 and Figure 2. This improvement in transmission results from substantially less beam loss in the first two quadrupole and dipole magnets as the beam envelopes are now far from the apertures of these magnets for cases (d) and (e) compared to cases (a), (b) and (c). As such, and combined with 2:1 imaging, we get a maximum transmission through the gantry. Nevertheless, due to the maximal effect of the dispersion in the quadrupole triplet, it is still unavoidable to have some beam losses due to the 1% momentum spread [9].

TRANSMISSION OPTIMIZATION THROUGH FIXED BEAMLINE

As demonstrated in the previous section, the use of large beam sizes and low divergence at the CP allows the transport of larger emittances through the gantry while achieving reasonable transmission (>50%) through the gantry. Therefore, in this section, the aim is to find a way to transport about 100 π*mm*mrad or more emittance from the degrader exit to the gantry entrance (CP).

Use of scattering foil

The resulting proton beam from the energy degrader has a symmetric, but large phase space distribution in both transverse planes. This symmetry however is not fully compatible with an optimal transport through the first quadrupole magnet, which is either horizontally or vertically focusing. By modifying the emittance after the degrader such that it is asymmetric, transmission through the subsequent beam line can be substantially improved. For instance, after focusing the beam in the Y-plane using the first quadrupole after the degrader, the vertical beam size behind the second quadrupole is small enough to pass the following bending magnet of the ESS, thus allowing to select higher divergence acceptance in the Y-plane compared to the X-plane. Such an optimized beamline at our facility transports a maximum of 65 π*mm*mrad in X-plane (using beam size selection collimator radius of 6.5 mm and beam divergence collimator of 14.4 mm) and 139 π*mm*mrad in Y-plane (using beam size selection collimator radius of 6.5 mm and beam divergence collimator of 33.3 mm), but at the cost of an elliptical beam shape at the gantry entrance, leading to gantry angle dependent beam shapes at the isocenter [10,11].

However, in order to simplify beam commissioning and quality assurance, it is desirable to have gantry angle-independent beam optics and beam sizes at the isocenter. To achieve gantry angle independence, it is ideally required to have the same emittance in both planes by the time the beam gets to the gantry entrance.

Here, we report on the use of a thin scattering foil (made of tantalum (Ta) with a thickness of 30 µm and density of 16.69 g/cm^3), placed in the beamline between the ESS and gantry CP ((Figure 3(a)), to achieve equal emittances in both planes, whilst maintaining a high transmission through the beamline and gantry.

To achieve a similar emittance in both planes after the scattering foil, the beam optics from the degrader exit to the scattering foil (Figure 3(a)) have been redesigned, while still transporting the maximum emittances accepted by the beamline in both planes: 67 π*mm*mrad in X-plane and 139 π*mm*mrad in Y-plane. This results in almost equal emittances after the scattering foil of 148 π*mm*mrad in the X-plane and 145 π*mm*mrad in the Y-plane. With the use of the scattering foil, we measured an overall transmission of 0.4% from the cyclotron to the isocenter, which can be compared to only 0.13% transmission for the reference beam optics (clinically used beam optics at PSI). This comes at the cost of increased beam size. For the reference beam optics , the beam size at the isocenter is (11.2±0.6) mm whereas, with the high transmission and scattering foil beam optics, this increases to (20.2±0.8) mm, representing an 80% increase in beam size.

Table 1: Measured transmission using reference beam optics and new beam optics with scattering foil (measured) and asymmetric collimators (simulation). Transmission values are from the cyclotron to different locations along the beamline [5,10,11].

	coupling point (%)	isocenter (%)
Reference optics	0.22 ± 0.007	0.13 ± 0.004
New optics with scattering foil	0.93 ± 0.03	0.40 ± 0.012
New optics with asymmetric collimator	1.2 ± 0.036	0.72 ± 0.036

Use of asymmetric collimator

In this subsection, the main aim is to find an alternative solution to transport higher emittance through the fixed beamline without increasing the emittance.

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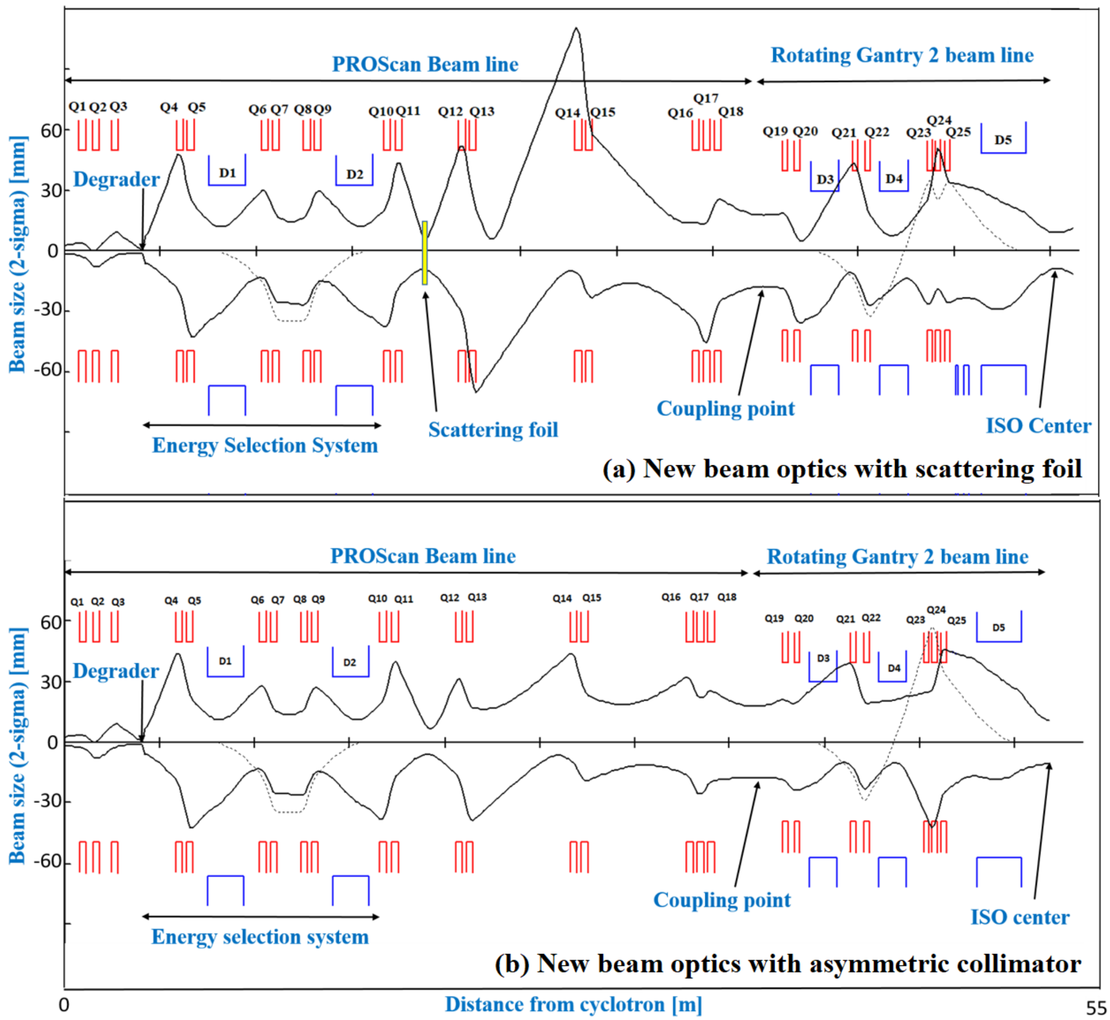

Figure 3: (a) shows the new beam optics with scattering foil transporting 67 *mm*mrad in X-plane and 139 π*mm*mrad in Y-plane up to scattering foil location and transporting almost 145 π*mm*mrad (in both planes) from scattering foil to isocenter. (b) shows the new beam optics with two asymmetric phase space selection collimators transporting 100 π*mm*mrad in both planes. [5,10]

As mentioned before, for proton beam delivery with a gantry, it is required to have the same beam properties at the isocenter for all gantry angles. The most straightforward method to achieve this is to have the same emittance (same beam size and divergence) in both planes at the entrance of the gantry. In general, in most cyclotron-based gantry facilities, two round-shaped collimators, positioned after the degrader, are used which then provide the same beam size and divergence in both planes, which is then symmetrically imaged to the gantry entrance point. Due to the alternating focusing signs of quadrupole lenses and bending magnets, the requirements for beam size and beam divergence at the start of the beam transport after the degrader can be quite different for obtaining a maximum transmission and symmetric emittance. A round-shaped collimator limits the emittance in both planes in the same way, to achieve the symmetric emittance requirement, but at the same time, it limits the emittance in one plane more than necessary.

As the PSI Gantry 2 can transport 100 π*mm*mrad emittance, we have designed the collimator system C1–C2 to select 100 π*mm*mrad in both planes too. We, therefore, selected the beam divergence selection collimator (C2) aperture such, to have the maximum acceptable divergences in both planes, being 10 mrad and 27 mrad in the X and Y-plane, respectively. To also obtain equal emittance in both planes, the beam size in the Y-plane must be three times smaller than the beam size in the X-plane. For this, we design collimator C1 such that it selects a 10 mm beam size in the X-plane, and a 3.7 mm beam size in the Y-plane.

Figure 3(b) shows the beam optics using elliptically shaped asymmetric collimators transporting 100 π*mm*mrad. Although this new beam optics was designed with TRANSPORT [12], BDSIM [13] has been used to

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estimate the transmission along the beamline. With an asymmetric collimation system, we thus predict an overall transmission from the cyclotron to the isocenter for 70 MeV beam of 0.72%, compared to 0.13% in the reference beam optics, corresponding to an increase of almost a factor of 6 in beam current reaching the patient.

However, this comes at a cost on beam size with the simulated beam size in the air for the reference optics at isocenter being 11.2 ± 0.6 mm, whereas for the asymmetric beam optics, beam size at isocenter is 17.2 ± 0.7 mm, representing an increase of about 50%. With the new system, we could achieve a maximum of 6 nA beam current at the isocenter for 70 MeV beam compared to 1 nA with the reference beam optics [5].

CONCLUSION

In summary, we have shown that for a fixed emittance value, it is possible to maximize proton beam transmission through a gantry by using a small divergence value and large beam size at the CP, together with de-magnifying beam optics imaging from CP to the isocenter. Additionally, we have shown that the use of scattering foil or asymmetric collimator allows transporting 100 π*mm*mrad emittance through fixed beamline while achieving an overall transmission gain of factor 3 or factor 6 respectively. We expect that our proposals for transmission improvement will be applicable in other cyclotron-based facilities to increase the transmission for low-energy beams. However, the magnitude of the transmission increase will be facility dependent due to differences in distances, apertures, materials, and cyclotron energies.

ACKNOWLEDGEMENTS

We thank Dr. Rudolf Doelling for his support in the measurements. We acknowledge the help of the PSI cyclotron operation group, PSI vacuum group, and PSI radiation protection group. This work is funded by PSI's CROSS funding scheme.

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