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Author(s):
Maradia, Vivek; Meer, David; Giovannelli, Anna C.; Lomax, Antony J.; Weber, Damien C.; Schippers, Jacobus M.; Psoroulas, Serena

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A NOVEL BEAM OPTICS CONCEPT TO MAXIMIZE THE TRANSMISSION THROUGH CYCLOTRON-BASED PROTON THERAPY GANTRIES *

V. Maradia[1,†], D. Meer, H. A. C. Giovannelli[1], A. J. Lomax[1], D. C. Weber[2], J. M. Schippers, S. Psoroulas, Paul Scherrer Institute, Villigen, Switzerland
[1]also at ETH Zurich, Switzerland
[2]also at University Hospital Zurich, Switzerland
[2]also at University Hospital Bern, Switzerland

Abstract

In proton therapy, most of the conventional beam optics of cyclotron-based proton gantries were designed to provide point-to-point focus in both planes with an imaging factor between 1 and 2 from the entrance of the gantry to the isocenter (patient location). This means that a small beam size at the gantry entrance is required to achieve the required small beam size at the isocenter. Due to the typically used beam emittance, this in turn results in large beam divergence at the gantry entrance, increasing the possibility of beam losses along the gantry when the beam envelope is close to any apertures.

To maximize transmission through gantries, we investigate a novel beam optics concept that instead uses 3:1 imaging. This reduces the beam divergence at the gantry entrance by a factor 3, whilst maintaining a small beam size at the isocenter. Such a beam envelope is easier to control and intersects less with apertures compared to 1:1 or 1:2 imaging. For PSI Gantry 2, beam optics based on 3:1 imaging increases proton beam transmissions for lower energies by 40% compared to 1:1 imaging beam optics.

Non-standard imaging factors such as 3:1 can help maximize transmission for different gantry lattices, thus reducing treatment delivery times.

INTRODUCTION

A typical proton therapy facility can be divided into three different parts. The first is an accelerator, which produces high-energy protons. This is followed by a fixed beamline, which transports the beam from the accelerator exit to the third part, the gantry (rotating beamline), which delivers beam to the target (isocenter) from different directions.

Based on the size and location of the tumor, particle beams with different energies are required to cover all possible beam penetration depths in the human body. For proton therapy, the energy required for patient treatments is typically in the range of 70-230 MeV.

Most of the proton therapy facilities use a cyclotron [1]. 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, is required. This however results in an energy-dependent beam transmission due to the increased energy spread resulting from the degrading process and multiple scattering in the degrader. At PSI for example, for the lowest energies (70-100 MeV), transmission through the beamline is below 0.1% [2]. In addition, there are beam losses in the gantry due to beam scraping at different locations. Such losses for these low energies cause an undesirable increase in treatment delivery time.

In this article, we propose a new beam optics scheme aimed at reducing losses in the gantry, which has been tested at PSI's Gantry 2.

CONVENTIONAL GANTRY OPTICS

PSI's Gantry 2 uses 1:1 imaging from the gantry entrance to the isocenter and transports a 30 π*mm*mrad emittance [3] (in this work beam sizes, divergences and emittances are expressed as 2-sigma values). Since this is comparable to other gantries, the here presented improvement could also be of advantage in other gantries. For example, one of the major commercial companies in the proton therapy field, IBA, uses 1:2.5 imaging for their one-room compact gantry solution, transporting an emittance of 30 π*mm *mrad [4].

As clinically, a small beam size at the isocenter is required, for most gantries, the beam optics design goal is to have 3-8 mm beam size at the isocenter, neglecting scattering in the nozzle and in air. For 1:1 or 1:2.5 imaging therefore, this requires a small beam size at the gantry entrance. Due to multiple Coulomb scattering in the vacuum window at the nozzle entrance, in the air gap, and in materials present in the nozzle however, one usually ends up having 10 to 15 mm beam size at the isocenter for low energies [5, 6].

Given a 30 π*mm*mrad emittance therefore, a beam size of 5-3 mm will have a 6-10 mrad divergence at the entrance of the gantry. With the beam optics shown in Fig. 1(a), with an initial beam size of 3 mm, 10 mrad divergence in both transverse planes and a dp/p = 0.7%, we measured, for PSI's Gantry-2, a transmission of only ~ 57% for the low energy beams (70-100 MeV). As can be seen in Fig. 1(b), which shows the beam envelope in this gantry, the major beam losses with this set-up occur in the quadrupole magnets Q2, Q4, Q6, and Q7.

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† vivek.maradia@psi.ch

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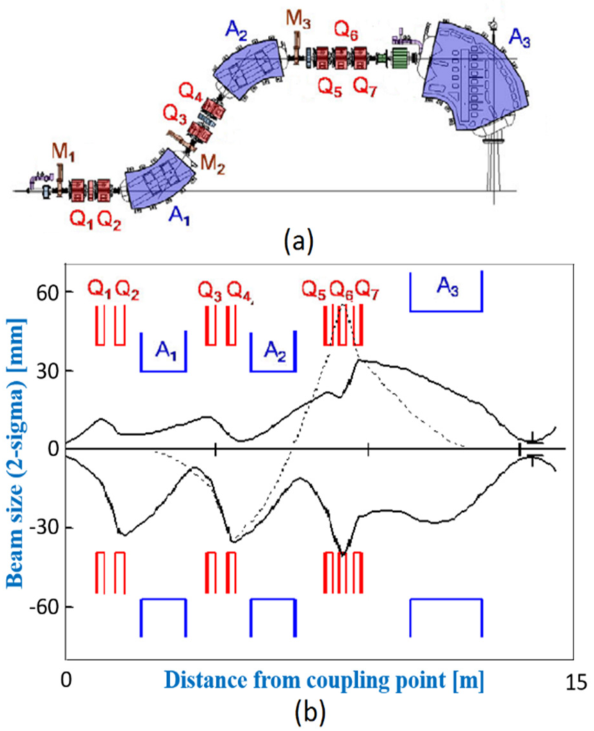

Figure 1: (a) Shows the PSI's Gantry 2 layout, with three dipoles (elements A) and seven quadrupoles (elements Q). (b) Shows the 2-sigma beam envelope and the dispersion (dashed line, dp/p = 0.7%) along the gantry with 1:1 imaging (The lower half shows beam envelope in X-plane (bending plane) and the upper half shows envelope in Y-plane).

PROPOSED GANTRY OPTICS

To avoid influence of the beam energy and gantry rotation angle on both the beam size at the isocenter and beam transmission through the gantry, requirements for beam optics between gantry entrance and isocenter location can be defined as follows:

- Same beam size and same divergence at the entrance of the gantry in both transverse planes (in terms of the sigma matrix describing the beam properties in a matrix formalism, $\sigma 11 = \sigma 33$ and $\sigma 22 = \sigma 44$).
- Focus-to-focus transport system (in terms of transfer matrix $R12 = 0$ and $R34 = 0$).
- Imaging between gantry entrance and isocenter ($R11 = R33$ and $R22 = R44$).
- Full achromaticity of the transport system ($R16 = R26 = 0$).

As such, here we describe a modification of the Gantry 2 optics, to reduce transmission losses substantially.

Due to the large dispersion at the location of Q6 in Gantry 2, the beam size is mostly determined by the momentum spread in the beam, which we do not want to reduce. As such, to avoid beam scraping in Q2 and Q4 of the gantry, we modified the incoming beam to have a smaller divergence at the gantry entrance. To decrease divergence for a given emittance, the beam size at the gantry entrance needs to be increased. To maintain a small beam size at the isocenter however, we also modified the imaging to demagnify the beam width by factors of 2:1 and 3:1. In this work, we modified the Gantry 2 beam optics in this way and adjusted the incoming beam parameters such that the 30 π*mm*mrad emittance was preserved.

SIMULATION

First order gantry beam optics have been calculated using the PSI's graphic TRANSPORT framework [7]. Figure 2 (a) shows the beam envelopes for 2:1 imaging assuming a 10 mm beam size and 3 mrad divergence at the entrance of the gantry in both planes. The simulation was performed for 70 MeV. Compared to the original optics, the strengths of Q1 and Q2 needed to be adjusted, whereas to preserve achromaticity, the strengths of the other quadrupoles remained unchanged.

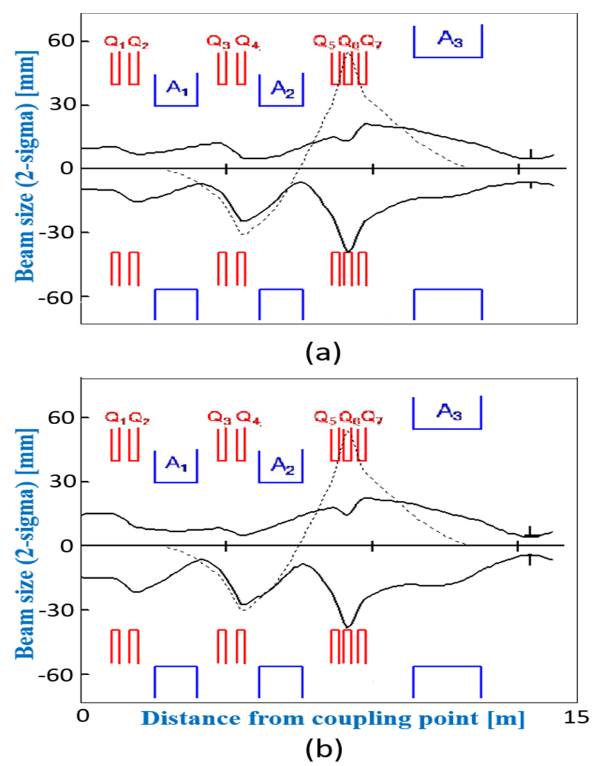

Figure 2: (a) Gantry beam optics with 2:1 imaging. (b) Gantry beam optics with 3:1 imaging.

For the 3:1 imaging beam optics (Fig. 2(b)) we chose a 15 mm beam size and 2 mrad divergence in both planes at the entrance of the gantry. For all beam optics, the transmission through the gantry (see table 1) has been estimated using an in-house developed Transport matrix-based particle tracking program MINT [8]. As can be seen, moving from 1:1 to 3:1 imaging, MINT predicts that transmission of 70 Mev protons can be increased from 60-84%.

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Table 1: Transmission Estimated by MINT for Different Imaging Factors

Imaging factor	Beam size at gantry entrance (mm)	Beam divergence at gantry entrance (mrad)	Transmission from MINT simulation (%)
1:1	3	10	60
2:1	10	3	77
3:1	15	2	84

EXPERIMENTAL SETUP

Experimental verification of the proposed beam optics have been performed at PSI's Gantry 2. The beam size entering the gantry was selected by a fixed aperture collimator positioned at the gantry entrance. For this experiment, we used different collimator apertures to achieve different beam sizes. Since the incoming emittance from the fixed beamline to the gantry entrance is fixed at 30 π*mm*mrad, we used a last quadrupole triplet before the gantry entrance (not shown in Fig. 1) to achieve a particular beam size at the gantry entrance collimator.

Three current monitors on the gantry (M1-3, see Fig. 1) measured the transmission through the gantry. To measure the beam current at the isocenter, a clinically used monitor (ionization chamber) positioned before the isocenter at the gantry exit, was used. The beam intensity from the collimator was measured with monitor M1 in the fixed beamline (see Fig. 1).

RESULTS

For the 70 MeV beam, transmission results from the simulation showed good agreement with the experimental results. Figure 3 shows that for 1:1 imaging there are more losses in the first magnets of the beamline, between M1 and M2. This matches the expectation, since, as shown in Fig. 1, the beam envelope is very close to the magnet apertures of Q2 and Q4.

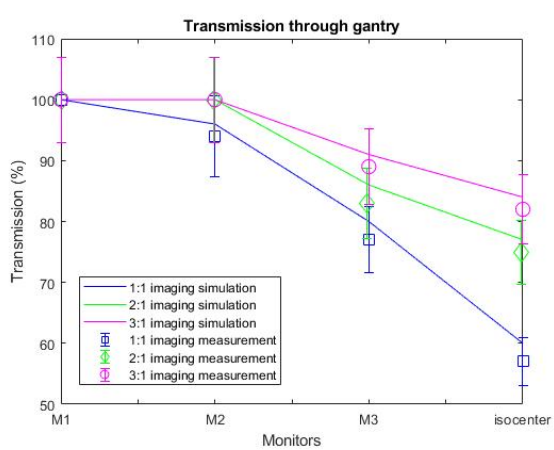

Figure 3: Simulated (line) and measured (data points) transmissions along the gantry (monitor position) with different imaging schemes.

For 2:1 and 3:1 imaging, there is almost 100% transmission through the first two quadrupoles and the first dipole magnet, as the beam envelope is far from the magnet aperture, as shown in Fig. 2. The losses observed between M2 and isocenter location are expected to be in Q6 and Q7, which are unavoidable for all imaging cases in order to achieve achromaticity (R16 = R26 = 0). 3:1 imaging however minimizes losses between monitor 2 and isocenter. As such, 1:1 imaging restricts the transmission to ~ 57%, whilst demagnification increases the transmission by 30-40%, resp 75% for 2:1 imaging and ~ 82% for 3:1 imaging.

CONCLUSION

We have shown that the transmission of the beam through PSI's Gantry 2 can be increased by 30-40% using alternative beam optics imaging. This has been achieved by increasing the beam size and decreasing the beam divergence at the gantry entrance, in combination with novel beam optics, which de-magnifies the image of the beam entry at the isocenter by a factor of 2 to 3. Since the optics of PSI's Gantry 2 are comparable to other gantries, the here presented improvement could also be of advantage in other gantries. We expect therefore that this transmission improvement will be possible in more gantry types, opening the option of faster treatments in proton therapy generally.

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