A DESIGN OF A ROTATING GANTRY WITH EASY STEERING FOR PROTON THERAPY

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Abstract

We propose a rotating gantry with easy trajectory correction which is needed when we change the gantry rotational angle for proton therapy. The gantry is a standard type with 5.0 m rotating radius, and delivers proton beam with maximum energy of 250 MeV. The beam from the transport course is deflected by an upsream bending magnet BM1 and finally deflected by two bending magnets BM2 and BM3 to the irradiation nozzle. The radii and maximum field strengths of these bending magnets are 1.5 m and 1.6 T. Five quadrupole magnets are installed between BM1 and BM2. The dispersion function at the irradiation nozzle can be tuned to be zero by two steering magnets used in the gantry and two beam position monitor in the nozzle.

The beam trajectory in the nozzle is easily and quickly corrected by using two beam position monitors in the nozzle. This present trajectory correction keeps higher treatment efficiency when it is necessary to correct the trajectory differently for each rotating angle.

1 INTRODUCTION

In recent years, proton therapy has been successfully applied to cancer treatments. The characteristic that dose distribution of proton shows Bragg-peak. This effect of protons makes it possible to irradiate tumors with higher doses than other healthy tissues surrounding them.

In order to use this effect, rotating gantries which can deliver the proton beam from any angle in a plane have been used in proton therapy.

Many treatments require large uniform radiation fields, often as large as 30cm×30cm [1]. Since the size of the beam which is extracted from an accelerator is small, it is required to be spread. Usually, beam spreading is performed in a nozzle installed downstream of the gantry.

To obtain a large uniform irradiation field, various radiation field spreading methods have been used in nozzles. These methods are categorized intos passive and active beam delivery systems [1].

Passive beam delivery systems employ single or double scatterers to spread the beam and flatten the beam intensity [2]. And the lateral part of the spread beam is cut off by the collimator along the shape of tumour.

In active beam delivery systems, two scanning magnets are placed in a nozzle. They are set in tandem with their magnetic field directions orthogonal to one another and to the beam direction in order to irradiate 2-dimensional regions.

In order to accomplish the beam flattening in passive or active methods described above, it is needed to keep the trajectory of beam center in a nozzle.

Quadrupole and bending magnets in a gantry beam line are supported by a gantry frame. When the gantry is rotated, the frame is distorted because of these magnets weights. Then it makes magnets alignment error on a gantry frame. And it makes trajectory distortion.

In order to correct a trajectory distortion, correction field strength of steering magnets must be chosen adequately for every different rotating angle.

We present a compact rotating gantry and also a trajectory correction method easy steering for rotating gantry.

2 AN OPTICAL DESIGN OF GANTRY

An optics for the gantry using double scattering method has been designed on condition that the extracted proton beam from a synchrotron has characteristics as shown in Table 1.

Table 1: Beam Parameters

Beam Energy	70- 250 MeV
Momentum Spread	below ±0.2%
Magnetic Rigidity	1.23- 2.43 Tm

The gantry has three bending and six quadrupole magnets. Bending magnets are 60 degrees upward and downward ones and a 90 degrees downward one. Radius of bending magnets is 1.5m, rotating radius is 5.0m. The maximum magnetic field of the bending magnets is 1.6T.

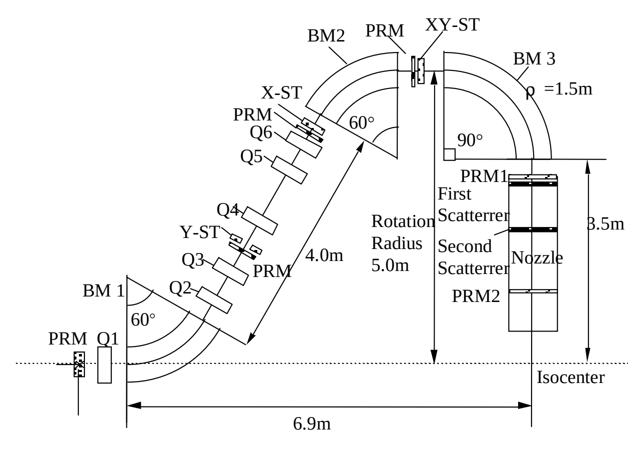

Figure 1: An Example of the Presented Gantry

Optical design conditions are (i) βx=βy=5m, αx=αy=0 at the entrance of the gantry, (ii) dispersion functions η_x =0, and their gradients η'_x=0 at the entrance of the gantry, (iii) $\eta_x = \eta'_x$=0 at the exit of BM3 and (iv) αx=αy=0 at the first scatterer. Figure 2 shows betatron functions of the present gantry.

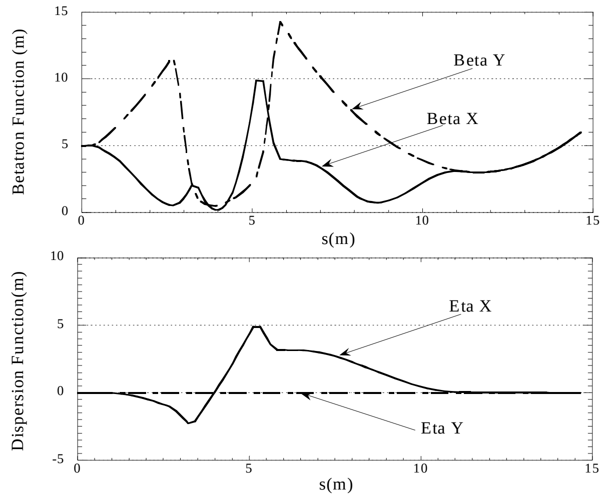

Figure 2: Betatron and Dispersion function of the gantry

3 A SCHEME OF TRAJECTORY CORRECTION

A beam position and a slope of a beam trajectory at an element in a gantry beam line are calculated by transfer matrix.

If there are alignment errors of quadrupoles or bending magnets, beam trajectories are distorted by extra magnetic field which made by them.

We show transfer matrix for bending magnet when there is an error of roll angle. In the case that roll angles of bending magnets and alignment errors of quadrupole magnets are small, it is possible to divide the effects of error.

In the bending plane

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cos\theta & \rho\sin\theta \\ -\dfrac{\sin\theta}{\rho} & \cos\theta \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} \qquad (1)$$

Perpendicular to the bending plane

$$\begin{pmatrix} y \\ y' \end{pmatrix} = \begin{pmatrix} 1 & \rho\theta \\ 0 & 1 \end{pmatrix} \begin{pmatrix} y_0 \\ y'_0 \end{pmatrix} + \begin{pmatrix} \dfrac{\rho\sin\phi\times\theta^2}{2} \\ \sin\phi\times\theta \end{pmatrix} \qquad (2)$$

where ρ and θ are a radius and a deflection angle of a bending magnet. Where ϕ is roll angle of bending magnet. Where ϕ = 0 is no roll angle alignment error case.

Then, we represent a transfer matrix and alignment error effects terms for quadrupoles as follows:

Where K is value of magnetic gradient divided by magnetic rigidity, and L is an effective length of quadrupole, ξ is a length of alignment error.

Focusing type:

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cos(\sqrt{K}L) & \dfrac{1}{\sqrt{K}}\sin(\sqrt{K}L) \\ -\sqrt{K}\sin(\sqrt{K}L) & \cos(\sqrt{K}L) \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} + \begin{pmatrix} \left(1-\cos(\sqrt{K}L)\right)\xi \\ \sqrt{K}\sin(\sqrt{K}L)\,\xi \end{pmatrix} \qquad (3)$$

Defocusing type:

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cosh(\sqrt{K}L) & \dfrac{1}{\sqrt{K}}\sinh(\sqrt{K}L) \\ \sqrt{K}\sinh(\sqrt{K}L) & \cosh(\sqrt{K}L) \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} + \begin{pmatrix} \left(1-\cosh(\sqrt{K}L)\right)\xi \\ \left(-\sqrt{K}\sinh(\sqrt{K}L)\right)\xi \end{pmatrix} \qquad (4)$$

In equation (1)-(4), first terms are products of ideal transfer matrices without alignment error and vectors which components are beam position and its slope. Second terms are displacement vector which components are beam position and its slope owing to magnet's alignment error. We describe A_i as i-th ideal transfer matrix and δ_i as i-th displacement vector.

Above eqs.(1) – (4)represents $A_i + \delta_i$ and we represents drift space as Di , we can show transfer matrix from start points to n-th element exit with alignment error as :

$$\mathbf{X}_n = M_i = D_i\,(A_i + \delta_i)\,D_{i-1}\,(A_{i-1} + \delta_{i-1})\cdots(A_1 + \delta_1)\,D_0 \qquad (5)$$

Because elements for dose flattening in a nozzle are settled by design trajectory, it is needed that beam position and its slope of trajectory are settled zeros. In order to satisfy above condition, two steering magnets are needed for one direction.

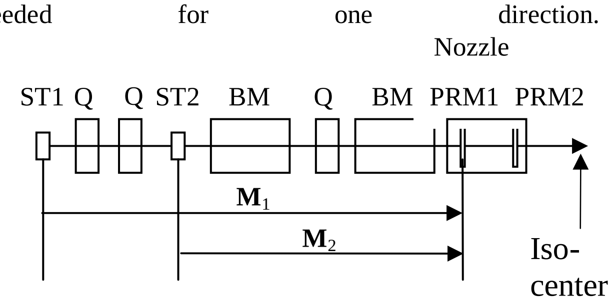

Figure3: a configuration of beam line in a gantry with two steering magnets and transfer matrices for a beam trajectory correction.

Figure 3 shows a configuration of this scheme , where

$\mathbf{M}_1$: Transfer matrix from ST1 to PRM1 (without error)

$\mathbf{M}_2$: Transfer matrix from ST2 to PRM1 (without error)

$\mathbf{k}_1$: Correction kick at ST1

$\mathbf{k}_2$: Correction kick at ST2

$\mathbf{x}_{err}$:Trajectory error observed at PRM1 using with PRM2

$$M_1 = \begin{pmatrix} a_1 & b_1 \\ c_1 & d_1 \end{pmatrix},\ M_2 = \begin{pmatrix} a_2 & b_2 \\ c_2 & d_2 \end{pmatrix},$$

$$k_1 = \begin{pmatrix} 0 \\ k_1 \end{pmatrix},\ k_2 = \begin{pmatrix} 0 \\ k_2 \end{pmatrix},\ x_{err} = \begin{pmatrix} x_{err} \\ x'_{err} \end{pmatrix}$$

If we give a kick k_1, k_2 for trajectory correction at steering magnets ST1 and ST2, these kick effects are observed $x_1=M_1$, $x_2=M_2$ at PRM1. In order to correct trajectory error at PRM1, $k_1$and k_2 must be satisfy an equation as follows;

$\mathbf{x}_1+\mathbf{x}_2+\mathbf{x}_{err}=0$ (6)

Eqation(6) are transformed as follows;

$$\begin{pmatrix} a_1 & b_1 \\ c_1 & d_1 \end{pmatrix}\begin{pmatrix} 0 \\ k_1 \end{pmatrix} + \begin{pmatrix} a_2 & b_2 \\ c_2 & d_2 \end{pmatrix}\begin{pmatrix} 0 \\ k_2 \end{pmatrix} + \begin{pmatrix} x_{err} \\ x'_{err} \end{pmatrix} = \begin{pmatrix} b_1 & b_2 \\ d_1 & d_2 \end{pmatrix}\begin{pmatrix} k_1 \\ k_2 \end{pmatrix} + \begin{pmatrix} x_{err} \\ x'_{err} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad (7)$$

Then, we summarize the required conditions in order to use this method is as follows;

(i)There is no optical equipment between PRM1 and PRM2.

(ii)Two steering magnets are installed upstream of PRM1.

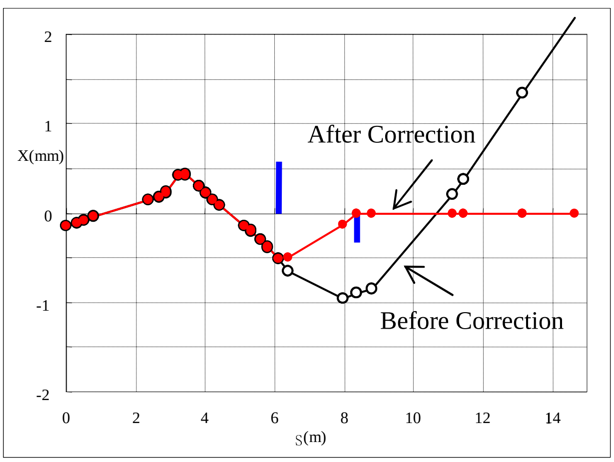

Figure4: Trajectories in the bending plane of gantry.

4 SUMMARY

We propose a rotating gantry with easy trajectory correction which is needed when we change the gantry rotational angle for proton therapy.

The gantry rotating radius is 5.0 m and it delivers the proton beam with maximum energy of 250 MeV. The radii and maximum field strength of these three bending magnets are 1.5 m and 1.6 T.

We also proposed a trajectory correction method suitable for rotating gantry. In this method, field strength of steering magnets for trajectory correction are obtained easily by using two beam position monitors in the nozzle and transfer matrices of the gantry beam line without knowing alignment errors of magnets.

This trajectory correction keeps higher treatment efficiency when it is necessary to correct the trajectory differently for each rotating angle.

5 REFERENCES

[1]W. T. Chu et al. “Instrumentation for treatment of cancer using proton and light-ion beams”, Rev. Sci. Instrum., Vol. (8), pp.2055-2122, 1993

[2]Y. Takada “Dual-Ring Double Scattering Method for Proton Beam Spreading”, Jpn. J. Appl. Phys. VOl.33 pp. 353-359,199