Physical design of scanning gantry for proton therapy facility*

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Abstract A proton therapy facility based on a linac injector and a slow cycling synchrotron is proposed. To achieve effective treatment of cancer, a scanning gantry is required. The flexible transmission of beam and high beam position accuracy are the most basic requirements for a gantry. The designed gantry optics and scanning system are presented. Great efforts are put into studying the sensitivity of the beam position in the isocenter to the element misalignments. It shows that quadrupole shift makes the largest contribution and special attention should be paid to it.

Key words proton therapy, gantry, optics, scanning system

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1 Introduction

Therapy with proton or carbon has showed essential advantages compared with conventional X-ray therapy [1]. More and more hadron therapy facilities based on linac, cyclotron or synchrotron are running or being built nowadays. To achieve effective treatment of cancer, scanning gantry and pencil beam scanning technique have been proposed and exploited from the middle of 1990s [2]. The Advanced Proton Therapy Facility (APTF) based on a linac injector and a slow cycling synchrotron is proposed, with detailed introduction in Ref. [3]. As an important part of the facility, a scanning gantry is designed to provide a size-adjustable beam with any direction to the patient and sub-millimeter position accuracy in the isocenter.

This paper is arranged as follows. The overall requirements for the gantry are discussed in Section 2; the designed gantry optics, scanning system and beam position accuracy analysis are presented successively; some conclusive remarks are given at last.

2 Considerations for gantry design

The optics matching between the fixed transport line and the gantry is the primary requirement for the gantry design. Until now, there have been roughly four kinds of matching methods, i.e., “symmetric-beam method”, “round beam method”, “equivalent beam divergence method” and “rotator method”. The first method suits the beam with equivalent emittances, e.g., the beam extracted from cyclotron. The other three methods accommodate for the beam with unequal emittances, as in our case, the beam from slow cycling synchrotrons by resonance extraction.

It becomes difficult to match the optics with the second and third method in case that large difference exists between the horizontal and vertical emittance. The fourth method based on the “empty ellipse” approach can completely solve the non-symmetrical beam transfer problem, however, the additional “rotator” increases the length of transfer line and thus the cost significantly (For more detail, see Refs. [4] and [5]). On the other hand, one can change the non-

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symmetrical beam to be symmetrical with solenoids [6] or thin scatter [7] in the fixed transport line, thus the first method can also be used for the non-symmetrical beam. We use solenoids to balance the beam emittance and "symmetric-beam method" for optics matching, i.e.

$$\begin{aligned} E_x &= E_y, \\ \beta_x &= \beta_y;\ \alpha_x=\alpha_y;\ \gamma_x=\gamma_y, \\ D_x &= D_z=0;\ D'_x=D'_z=0, \end{aligned} \tag{1}$$

where E_x and E_y are the horizontal and vertical emittance, α,β,γ, are the Twiss functions, D_x and D'_x are the horizontal dispersion and its derivative.

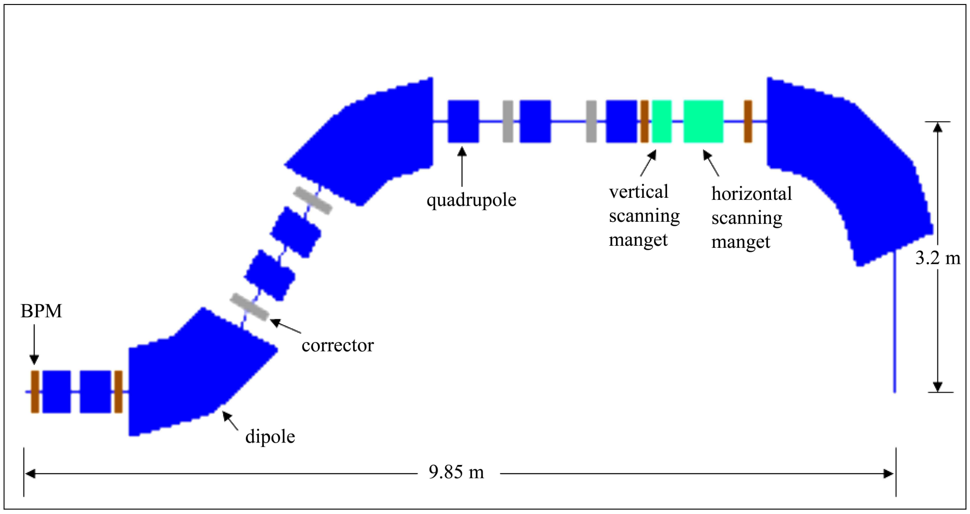

Fig. 1. Layout of the scanning gantry.

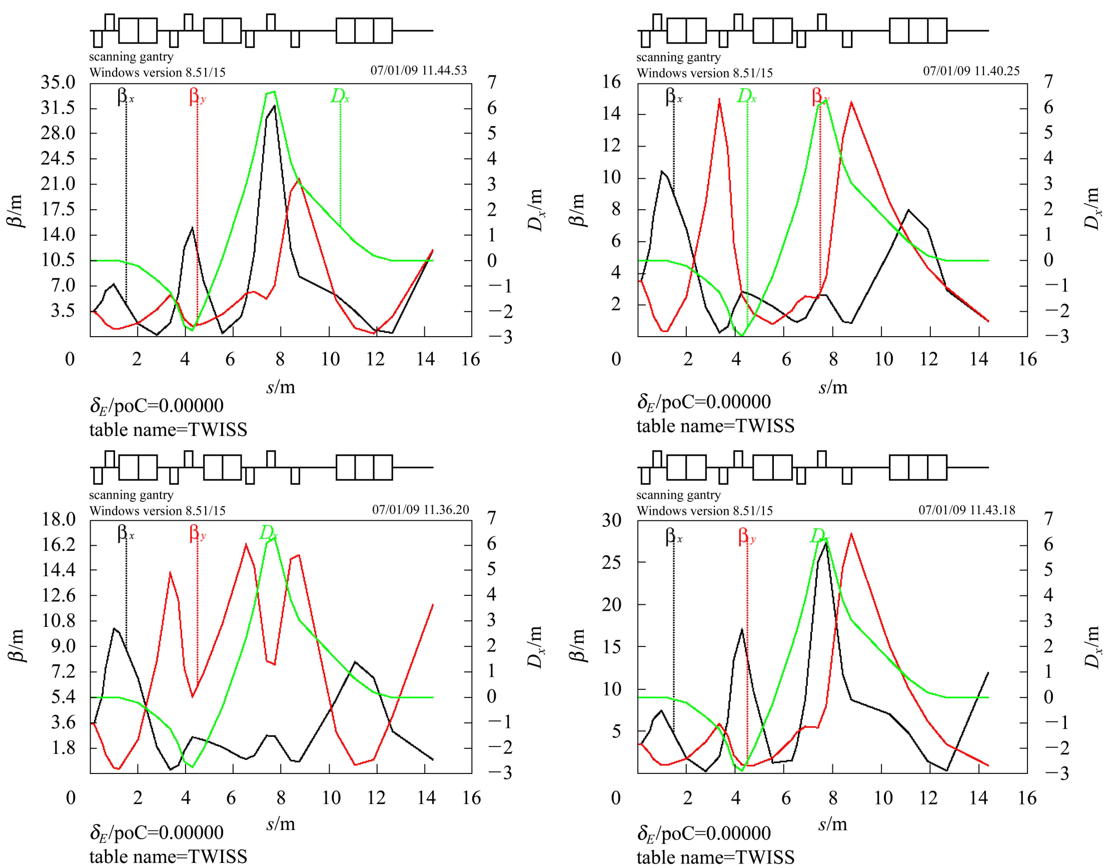

Fig. 2. Four extreme cases of the Twiss functions along the gantry.

There are some other conditions the gantry optics should obey. The optics should be achromatic so as to minimize the effect of energy spread. It is required that the beam size should be variable from 4 to 10 mm and the beam position from −10 to 10 cm in the isocenter.

3 Gantry optics

Thanks to the “symmetric-beam method”, the optics will not vary with rotation angle, thus we can design the lattice with only one specific rotation angle, like zero degree. The layout of the iso-centric and cylindrical gantry is illustrated in Fig. 1. Three dipoles are used for bending up and then bending down the beam. Seven quadrupoles are adopted to satisfy the achromatic condition and to control the beta functions along the gantry. Keep the Twiss functions at the entrance of the gantry constant, and make sure the beat function at the exit of the gantry is able to be changeable by 12.5 times. Fig. 2 shows four extreme cases of Twiss functions along the gantry. To save space, we would like to reduce the radius rather than reduce the length, thus we place the scanning system in the upper straight section (1.56 m) of the gantry. For the beam should be scanning in the region of ±10 cm, the last dipole should have a large gap, thus the vertical beta function at the exit of the last dipole is strictly controlled.

4 Scanning system

Two scanning magnets are applied to vary the beam position in the isocenter. The scanning system has nearly no influence on the optics properties of the gantry, dispersion is low because of low deflecting angle [5]. The action of the last dipole's fringe field plays a small role in the gantry optics, but it is important to produce an approximate parallel beam. The parallelism of the beam should bring a lot of practical advantages: for therapy planning, for patching fields techniques, to provide lower skin dose, etc.

The scanning magnets' strengths are calculated. The transfer matrixes from the horizontal and vertical scanning magnet to the exit of the last dipole $M_{\rm H}$ and $M_{\rm V}$ are obtained by multiplying the matrixes together, with the fringe angle of the last dipole as variables. Then the relationship of the beam coordinates at the exit and entrance of the scanning system can be written as

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{\rm ExitDipole} = M_H(\theta_1,\theta_2)\begin{pmatrix} x \\ x' \end{pmatrix}_{\rm InHScan}, \qquad (2)$$

$$\begin{pmatrix} y \\ y' \end{pmatrix}_{\rm ExitDipole} = M_V(\theta_1,\theta_2)\begin{pmatrix} y \\ y' \end{pmatrix}_{\rm InVScan}, \qquad (3)$$

where θ_1 and θ_2 are the rotation angle for the entrance and exit pole face of the last dipole, respectively.

It is reasonable to assume that the incident beam is ideally along the axis in the scanning system, i.e., $x_{\rm InHScan}=0$, $y_{\rm InVScan}=0$, then we have

$$x'_{\rm ExitDipole} = M_H(2,2)\, x'_{\rm InHScan}, \qquad (4)$$

$$y'_{\rm ExitDipole} = M_V(2,2)\, y'_{\rm InVScan}. \qquad (5)$$

To produce a parallel beam, it requires $x'_{\rm ExitDipole} = y'_{\rm ExitDipole} = 0$, M_H(2,2) and M_V(2,2) should be zero. There is no positive real solution, however, we can plot the variations of M_H(2,2) and M_V(2,2) with the rotation angle θ_1 and θ_2 (Fig. 3) and find the optimal solution which minimizes both the target values. From Fig. 3, one can see that $\theta_1=0°$ and $\theta_2=24.2°$ give the best result.

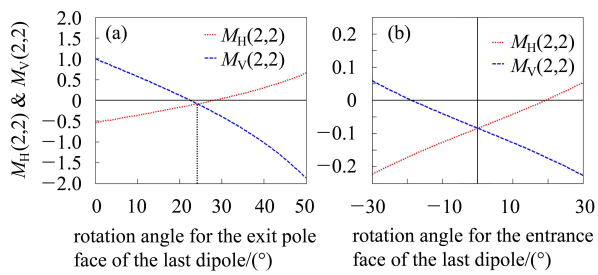

Fig. 3. M_H(2,2) and M_V(2,2) variation with θ_2 while $\theta_1=0°$ (a) and with θ_1 while $\theta_2=24.2°$ (b).

The first order estimation is direct and intuitive but rather rough, for it neglects high order effects of dipole fringe fields [8]. A geometrical optical tracking code is programmed to simulate the concrete beam

Table 1. Scanner strength first order estimation and correction.

position (H/V)/cm	Hor. scanner strength estimation/mrad	Ver. scanner strength estimation/mrad	corrected Hor. scanner strength/mrad	corrected Ver. scanner strength/mrad
10/−10	73.67	28.78	67.0	30
10/10	73.67	−28.78	67.0	−30
−10/10	−73.67	28.78	−70.65	27.3
−10/−10	−73.67	−28.78	−70.65	−27.3

trajectory, and the scanner strengths are corrected. Several characteristic cases are listed in Table 1. One can see that the difference of scanner strength calculation with two approaches can be up to 3 mrad.

5 Beam position accuracy analysis

To achieve sub-millimeter positioning precision, it is necessary to investigate the sensitivity of the beam position accuracy to the misalignments of gantry elements. The misalignments can be classified into two kinds, systematical and random. Systematical misalignments are reproducible, like the elastic deformations as a function of gantry angle. Random misalignments represent errors caused by uncertain and non- reproducible factors, typically temperature fluctuation [9].

The systematical misalignments can be compensated by an orbit correction system in advance. But the beam position divergence in the isocenter caused by random misalignments which have gaussian distribution in theory, is inevitable. So we study the effects of the element position random displacements in the gantry beam transport system. The action of the scanning magnet is not taken into account. It is assumed that the monitors and steering units in the upstream line will guide the beam into the gantry perfectly on axis, i.e., no error is transmitted from the upstream line to the gantry. The magnets are considered to have ideal field quality as well. Four effects, i.e., the quadrupole shift, the qudrupole tilt, the dipole shift and the dipole tilt are considered. Turn on and off the errors respectively, and calculate the beam position in the isocenter by tracking the beam through the misaligned transport line with computer code AT.

The “reference” random errors set for all elements are, $3\sigma_{\rm shift} = 0.1$ mm, $3\sigma_{\rm tilt} = 0.1$ mrad. The simulation shows that the beam position possible displacement is a little bigger in the case of 0° than the case of 90° gantry angle, and in the former case, the maximum overall beam position distribution $3\sigma_{\rm total}$ in the iso-center is 0.57 mm and 1.52 mm (horizontal and vertical plane respectively, see Fig. 4). Quadrupole shifts make the largest contribution to the beam position deviation. The sub-millimeter beam position precision can be achieved only if the quadrupole shift limit is changed to 0.06 mm. For the dipole, the tilt angle misalignment is more critical than the shift. Controlling the dipole tilt misalignment, e.g., 0.05 mrad, will benefit the release of the quadrupole shift limit.

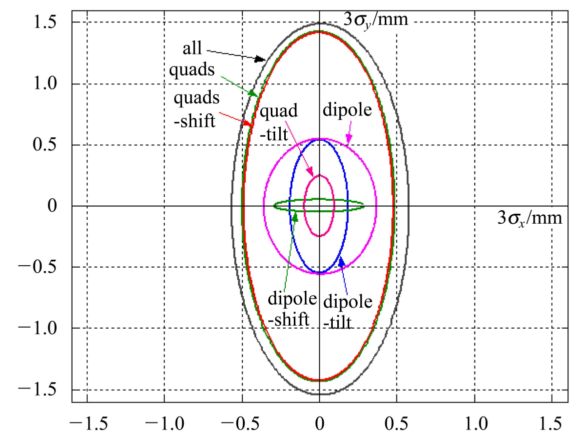

Fig. 4. Beam position uncertainty 3σ due to reference random misalignments.

It should be mentioned that the analysis is done using the lattice with small beta functions in the isocenter (up right in Fig. 2), corresponding to the beam scanning with the smallest beam size. Similar results are obtained with the other cases.

6 Conclusion

We present the physical design of scanning gantry for APTF, including the gantry optics, the scanning system and the beam position accuracy analysis. The designed gantry satisfies the requirements for the active scanning treatment. The scanning magnets with optimal dipole fringe angle lead to approximate parallel beam scanning, and the correction of the scanner strength from the first order calculation is described. The beam position accuracy in the isocenter is analyzed at last. Special attention should be paid to controlling the most critical error-quadrupole shift.

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