Evaluation of the effect of mechanical deformation on beam isocenter properties of the SC200 scanning beam delivery system

Ming Wang, Jinxing Zheng, Yuntao Song, Ming Li, Xianhu Zeng

Abstract

For proton pencil beam scanning (PBS) technology, the accuracy of the dose distribution in a patient is sensitive to the properties of the incident beam. However, mechanical deformation of the proton therapy facility may occur, and this could be an important factor affecting the proton dose distribution in patients. In this paper, we investigated the effect of deformation on an SC200 proton facility’s beam isocenter properties. First, mechanical deformation of the PBS nozzle, L-shape plate, and gantry were simulated using a Finite Element code, ANSYS. Then, the impact of the mechanical deformation on the beam’s isocenter properties was evaluated using empirical formulas. In addition, we considered the simplest case that could affect the properties of the incident beam (i.e., only the bending magnet (BG3) has an error in its mounting alignment), and the effect of the beam optics offset on the isocenter characteristics was evaluated. The results showed that the deformation of the beam position in the X and Y direction was less than 0.27 mm, which meets the structural design requirements. Compared to the mechanical deformation of the L-shape plate, the deformation of the gantry had more influence on the beam’s isocenter properties. When the error in the mounting alignment of the BG3 is equal to or more than 0.3 mm, the beam deformation at the isocenter exceeds the maximum accepted deformation limits. Generally speaking, for the current design of the SC200 scanning beam delivery system, the effects of mechanical deformation meet the maximum accepted beam deformation limits. In order to further study the effect of the incident beam optics on the isocenter properties, a fine-scale Monte Carlo model including factors relating to the PBS nozzle and the BG3 should be developed in future research.

1. Introduction

The main reason for the increased interest in proton therapy is because it is clean and precise. In terms of the efficiency of the high beam used and the flexibility to achieve conformal treatment, various implementations of pencil beam scanning are in use or under development [6]. The most established technique is discrete spot scanning, or “point-and-shoot”, where the pencil-beam is applied to a particular spot until the accumulated dose reaches the set value. The beam is then turned off while the current to the scanning magnets is changed for the next spot and the process continues, cycling through the spots one at a time. A complete layer is painted at a set beam energy, and then the energy is reduced layer by layer [7]. The other possible modes being researched include continuous beam motion combined with velocity and/or beam current modulation, spot by spot energy variation, multiple paintings of the whole target and many others. In all cases, all PBS technologies require accurate control of the beam dose, the beam position, and the beam’s isocenter properties (beam size, position accuracy, and energy spread), which directly affect the uniformity of the dose distribution [8–12].

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In previous studies, several attempts have been made to understand the factors affecting the beam’s isocenter properties. In order to reduce the effect of the nozzle on a beam’s characteristics, an IBA team uses two quadrupoles to focus the beam’s transverse size into the entrance of the nozzle, and design the vacuum chamber to reduce the air length [13,14]. Shen et al. investigated the effect of range shifter material on proton pencil beam characteristics [15]. Lin et al. investigated the effect of gantry angle-dependent scanning beam properties on proton scanning treatment [16]. In addition, Li et al. used the Finite Element method to investigate the effects of electromagnetic load on mechanical deformation of the gantry [17]. However, there is no article discussing in detail the effects of mechanical deformation on the beam’s isocenter properties, especially for the pencil beam scanning nozzle. However, for a proton therapy facility, the mechanical deformation of the facility is an important factor that affects proton therapy accuracy.

In this paper, in order to evaluate the effect of mechanical deformation on the beam’s isocenter characteristics of an SC200 scanning beam delivery system, the Finite Element method was used. First, the deformation of the nozzle baseplate, L-shape plate and gantry were obtained using the Finite Element code, ANSYS. Then, the impact of this mechanical deformation on the beam’s isocenter properties was evaluated using empirical formulas. In addition, the effect of the mounting alignment error of the last bending magnet (BG3) on the beam optics was investigated based on beam optics theory [18].

2. Materials and methods

2.1. Description of the proton therapy gantry of the SC200

The superconducting isochronous cyclotron SC200, designed by the Institute of Plasma Physics at the Chinese Academy of Sciences (ASIPP) and the Joint Institute for Nuclear Research (JINR) in Hefei, can accelerate protons to 200 MeV with a maximum beam current of 1 µA [19]. There are two treatment rooms in the SC200; one is a gantry treatment room and the other is a fixed treatment room.

For the physical design of the gantry treatment room with the PBS nozzle, the location of the scanning magnets has significant implications for nozzle commissioning. As shown in Ref. [20], there are two main methods: 1) down-stream scanning; 2) up-stream scanning. For down-stream scanning, the beam direction is divergent while the beam scans laterally. A parallel beam (infinite SAD) can be obtained by properly optimizing the beam optics and the last bending dipole using the up-stream scanning method. However, there are other technical challenges that need further investigation, such as the beam energy-dependent inhomogeneities and the fringe fields of the dipoles, which require higher-order corrections for position-to-current conversions. For the down-stream scanning methods, one of the advantages is that for the first-order beam there is a linear correlation between the spot position at the isocenter and the scanner magnet current. Another advantage is that the spot shape is unaffected by different scan positions [20].

The layout of the physical design of the gantry treatment room for the SC200 is as shown in Fig. 1. The accelerator system, the energy degrader system, and the beam transport system in Fig. 1 are all simplified. For the gantry beamline transport system, three bending magnets (BG1-60°, BG2-60°, BG3-90°) were used to deflect the proton beam, and seven quadrupoles (QG1- QG 7) were used to focus the beam in the transverse direction. By correctly matching the currents in the bending magnets and quadrupoles, the beam shape can be focused and the minimum full width at half maxima (FWHM) in the vacuum is 4 mm at the isocenter. Table 1 lists the main parameters of the gantry beamline for the SC200.

2.2. Description of the PBS nozzle

The PBS nozzle is the last component along the treatment beamlines. Devices in the nozzle and the associated control and safety components are used to control and monitor various physical parameters of the nozzle, and to control treatment delivery by the nozzle. Fig. 2 shows a layout of the spot scanning nozzle system for the SC200 [21]. After the beam exits the gantry beamline system, it passes through a vacuum window and enters the nozzle. As the proton beam passes through the PBS nozzle, it primarily interacts with the following components: beam profile monitor (IC3), scanning magnets (SMX and SMY), beam position monitor/dose monitor (IC2), beam position monitor/dose monitor (IC1). In addition, a helium chamber is inserted into the nozzle to reduce the effects of lateral scatter and energy loss on the beam [21].

The detectors IC1, IC2 and IC3 are multiwire ionization chambers. The strip pitch of the IC1 and IC2 is 2.0 mm and the position resolution of the peak is much less than one strip width, typically 10% of the strip width or less for normal beam currents and noise levels.

Fig. 3 (a) shows a photo of a gantry with beamline magnets. With a diameter of 10 m, the gantry of the SC200 is capable of high-precision dynamic speed control of 0.1–1 rpm with a maneuver range of ±185°. Fig. 3 (b) shows the integrated model of the PBS nozzle with the gantry. The nozzle is connected to the gantry using an L-shape plate. The L-shape plate is mainly composed of a gantry mounting plate (horizontal direction), a nozzle mounting plate (vertical direction), a reinforcing rib and a position adjusting

![Fig. 1. Layout of the physical design of the gantry treatment room for SC200.](image-url)
device. The nozzle component (scanning magnets, gas chamber and ionization chamber) are installed on a precision aluminum baseplate. The precision aluminum baseplate is installed on the L-shape plate, which is used to install the nozzle on the gantry datum plane with bolts and dowels. Lx and Ly ($L_x = 1020 ~\text{mm}, \quad L_y = 1100 ~\text{mm}$) are the dimensions of the nozzle installation plate on the gantry in the X and Y directions, respectively.

2.3. Theoretical analysis of the effect of deformation on beam isocenter properties

The nozzle accepts a beam from the high energy beam transfer line directed along the Z axis and deflects it through small angles so that it reaches the isocenter plane in the desired X, Y transverse position, as shown in Fig. 4. This deflection is monitored by the ionization chambers IC1 and IC2. A third chamber, IC3, checks the beam's position entering the scanning magnets. The distance from the measurement plane of the ionization chamber, SID, is well-known and stable because the components are mounted on a precision machined plate. The distance, SAD, depends on more physical relationships and will vary slightly with the gantry angle. In practice, it is more convenient to use beam measurements to determine the magnification ratio of SAD/SID.

$$X\text{-Magnification} = X_{\text{iso}}/X_m = \frac{\text{SAD}_X}{\text{SID}_X}$$
$$Y\text{-Magnification} = Y_{\text{iso}}/Y_m = \frac{\text{SAD}_Y}{\text{SID}_Y}$$

(1)

Unlike the ionization chamber position, the position of the scanning magnets has not been so carefully defined. Because the magnetic field between the scanning magnet poles is quite uniform across the width of the poles and the deflection angles are small, the magnets are quite tolerant of small position errors. In other words, if the scanning magnets are slightly shifted or rotated from their nominal position, the deflection of the beam due to a particular magnet field is hardly affected. A precision adjustment system for the magnets is not therefore necessary. It is more important that the positions are rigid and stable, especially in the gantry system.

Fig. 5 shows the effect of mechanical deformation on the ionization chamber. Fig. 5 (a) shows the ideal case, where the PBS nozzle has no deformation. Fig. 5 (b) and (c) show the beam trajectory with deformation in the X(Y) or Z direction, respectively. Fig. 5 (d) shows the beam trajectory with rotation in the X–Z(Y–Z) plane.

Given that a typical purely mechanical accuracy requirement for spot dose delivery accuracy at the isocenter plane is ±0.5 mm, a typical safe factor of 1.5 was considered. Table 2 lists the accepted limits for mechanical deformation of the PBS nozzle at the isocenter of the SC200. The scan system baseplate should be maintained in a position relative to the nominal beam trajectory that is within 0.35 mm of X and Y. The rotation in the planes X–Z and Y–Z should be kept below 0.15 mrad.

3. Results and discussion

3.1. Structural deformation analysis

3.1.1. Structural deformation of the nozzle’s precision aluminum baseplate

As shown in Fig. 3 (b), the scanning magnets and ionization chambers are mounted rigidly on a precision aluminum baseplate. Errors in the positioning of this plate thus determine errors in the positions of the scanning magnets and ionization chamber. In this simulation, the L-shaped plate is assumed to be solid, and without deflection. The simulation was done using a load of 25 kg uniformly distributed over the last 220 mm of the baseplate. This 220 mm is the length used by the mounting plates of the ionization chambers and range-shifter, which attach to the beam. As you can see in Fig. 6, it showed a maximum deflection of 0.047 mm at the right-hand end of the beam, and approximately 0.035 mm at the position of IC1. This result indicates that the design of the precision aluminum baseplate satisfies the requirements of the structural design.
3.1.2. Structural deformation of the L-shape plate

The L-shaped plate shows deformation when integrated with the whole PBS nozzle. In order to study the effect of an emergency stop on mechanical deformation, a dynamic analysis with a 0.08 rad/s² acceleration was considered for the L-shape plate. Table 3 lists the mechanical deformation of the L-shape plate under static and dynamic analyses. The results show that the deformations under static and dynamic analyses are basically the same. Both conditions indicate that the deformation in the Y direction exceeds that of the other two directions. However, the maximum amount of deformation does not exceed 0.02 mm.

Table 2
Specifications for the accepted limits of mechanical deformation for the PBS nozzle at the isocenter.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Item</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>X &amp; Y axes</td>
<td>Offset</td>
<td>≤ ±0.35 mm</td>
</tr>
<tr>
<td>X &amp; Y axes</td>
<td>Angle</td>
<td>≤ ±0.15 mrad</td>
</tr>
</tbody>
</table>

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Fig. 3. The gantry treatment room of the SC200 (a: photo of the gantry with beamline magnets; b: an integrated model of the PBS nozzle with gantry).

Fig. 4. Schematic of the pencil beam scanning nozzle.

Fig. 5. Effect of mechanical deformation on detector detection: (a) normal condition; (b) shift in the Z direction; (c) shift in the X(Y) direction; (d) rotation in the X–Z(Y–Z) plane.
3.1.3 Structural deformation of the gantry

For the structural analysis of the nozzle’s precision aluminum baseplate or L-shape plate, it was assumed that the gantry was solid, and that it did not deform. As shown in Fig. 3(a), bending magnets and quadrupoles need to be installed on the gantry. In particular, the bending magnets are very heavy, which is a challenge for the mechanical deformation control of the gantry. During the operation of the proton therapy facility, the bending magnets or quadrupoles on the gantry generate an electromagnetic force, which could affect the mechanical deformation. However, according to the study in Ref. [16], when the electromagnetic force is, or is not considered, the deformation values of the gantry remain almost identical. Therefore, the effect of the electromagnetic force on the mechanical deformation will not be considered in this analysis.

Fig. 7 shows the mechanical deformation of the L-shape considering the gantry effect. Fig. 7 (a) shows the maximum deformation on the L-shape plate and Fig. 7 (b) shows the maximum rotation on the L-shape plate. The rotation angle in the X-Z (Y-Z) plane is calculated with equation (2), where \( z_{\text{max}} \) and \( z_{\text{min}} \) represent the maximum and minimum deformation in the Z direction, respectively. The results show that the maximum displacement occurs in the Y direction, similar to the results listed in Table 3. The maximum amount of deformation does not exceed the design reference value of 0.02 mm and the maximum rotation of the L-shape plate also does not exceed the upper limit of 0.15 mrad.

\[
\theta(xz)_{\text{max}} = \frac{z_{\text{max}} - z_{\text{min}}}{l_x} \\
\theta(yz)_{\text{max}} = \frac{z_{\text{max}} - z_{\text{min}}}{l_y}
\]  

(2)

3.2. The effect of mechanical deformation on the beam’s isocenter position

In practice, the deformation and the rotation of the L-plate plate combine together to affect the beam’s properties. Equations (3) and (4) list two methods for converting beam deformation on the L-shape plate to isocenter position. Equation (3) considers the rotation of the L-shape plate on the XZ (YZ) plane, while \( l \) is the distance from the end of the L-shape plate to the isocenter. Equation (4) shows another method. This method directly multiplies the deformation value of the L-shape plate by a gain factor \( a \), which is the ratio of the length of the L-shape plate and the length of the gantry mounting plate to the isocenter. In this calculation, \( a \) was set to 1.4.

Fig. 8 shows the maximum beam position deformation at the isocenter using equations (3) and (4). For the X direction, the displacement of the proton beam at the isocenter calculated by the two methods, is basically the same. However, for the Y direction, the result calculated using equation (4) is larger than the result calculated using equation (3). In general, however, the maximum mechanical deformation in the Y direction does not exceed the design value.

\[
x_{\text{iso}} = x_{\text{max}} \pm \theta(xz) \\
y_{\text{iso}} = y_{\text{max}} \pm \theta(yz)
\]  

(3)

\[
x_{\text{iso}} = x_{\text{max}} \ast a \\
y_{\text{iso}} = y_{\text{max}} \ast a
\]  

(4)

As shown in Fig. 9, three cases of mechanical deformation were investigated to analyze their effects on the beam’s isocenter position. The three cases were as follows: case1: just considered the mechanical deformation of the L-shape plate under static conditions; case2: just considered the mechanical deformation of the L-shape plate under dynamic conditions; case3: considered the

---

Table 3

<table>
<thead>
<tr>
<th>Degrees</th>
<th>X Static</th>
<th>X Dynamic</th>
<th>Y Static</th>
<th>Y Dynamic</th>
<th>Z Static</th>
<th>Z Dynamic</th>
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<td>0.0016</td>
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<td>0.008</td>
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<td>0.085</td>
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<tr>
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<td>0.0005</td>
<td>0.0008</td>
<td>0.125</td>
<td>0.121</td>
<td>0.187</td>
<td>0.016</td>
</tr>
<tr>
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<td>0.0008</td>
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<td>0.183</td>
<td>0.0014</td>
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<td>0.0015</td>
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<td>0.008</td>
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<td>0.085</td>
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<tr>
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<td>0.0016</td>
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<td>0.097</td>
<td>0.004</td>
<td>0.0043</td>
</tr>
<tr>
<td>90</td>
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<td>0.0008</td>
<td>0.181</td>
<td>0.181</td>
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<td>0.0014</td>
</tr>
<tr>
<td>135</td>
<td>0.0005</td>
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<tr>
<td>180</td>
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<td>0.007</td>
<td>0.008</td>
<td>0.084</td>
<td>0.085</td>
</tr>
</tbody>
</table>

Fig. 6. Mechanical deformation on nozzle’s precision aluminum baseplate.
mechanical deformation of the L-shape plate, taking into account the effect of the gantry. The deformation of the beam at the isocenter shown in Fig. 9 is calculated using Equation (5).

For the X direction, it can be seen that the most influential effect on the isocenter properties of the proton beam is due to deformation by the gantry. For the Y direction, the beam deformation values are basically the same in all three cases. However, in all three cases, it was demonstrated that the beam deformation does not exceed the set design limits.

3.3. The effect of shifts in beam optics on the isocenter beam position

The ideal beam passes exactly along the nominal beam axis through the isocenter, position (0, 0) on the isocenter plane. However, the beam trajectory can vary in practice, due to slight field errors or drift in transfer line magnets when the beam energy is changed. In practice, the beam trajectory error combines with errors from mechanical deformation. For the down-stream scanning dose delivery system, both the mounting error and magnetic field fluctuation of the last bending magnet located in the front of the nozzle directly affect the incident beam trajectory. So, in this section, we discuss deformations caused just by the mounting alignment errors in BG3, assuming that the beam entering the BG3 is in an ideal orbit.

The transport matrix of the dipole magnet can be express by equation (5). Where $\alpha$ is the deflection angle, and $\rho$ is the deflection radius. The last bending magnet of the SC200 beam delivery system is BG3, as shown in Fig. 1. For the BG3, $\alpha = \pi/2$ and $\rho = 1.5$ m.

$$\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = \begin{bmatrix} \cos \alpha & \rho \sin \alpha \\ -\rho \sin \alpha & \cos \alpha \end{bmatrix} \cdot \begin{bmatrix} x_0 \\ y_0 \end{bmatrix}$$

We will briefly introduce the beam transfer matrix for considering mounting error. If you want to get more detailed knowledge on these equations, you can find details on their derivation in Ref. [18]. Equation (6) describes the theoretical transformation matrix when a small shift in the X direction is introduced. For equation (6), there is an implicit assumption that the small offset in the X direction does not affect the magnetic field values, so the deflection radius does not change.

Due to the magnetic field being almost unchanged, when a small shift in the Y direction occurs, the particle trajectory will not be changed, so the transport matrix of the magnet is the same as for equation (5). Equation (8) describes the transformation matrix when there is a shift introduced in the Z direction. $\Delta s$ represents the shift values.

$$\theta = \frac{\Delta x \sin \alpha}{\rho - \Delta x \cos \alpha}$$ (7)
![Image](image_url)

**Table 4** Beam trajectory shift values due to mounting alignment errors in BG3.

<table>
<thead>
<tr>
<th>X DS (mm)</th>
<th>Y DS (mm)</th>
<th>Z DS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

\[
\begin{bmatrix}
X_1 \\
X_2
\end{bmatrix} =
\begin{bmatrix}
\cos \alpha & \rho \sin \alpha \\
-\sin \alpha / \rho & \cos \alpha
\end{bmatrix}
\begin{bmatrix}
X_0 \\
X_0
\end{bmatrix} + \begin{bmatrix}
\Delta s \sin \alpha \\
0
\end{bmatrix} \tag{8}
\]

**Fig. 9.** Beam position deformation at the isocenter (a: In the X direction; b: In the Y direction).

**Fig. 10.** Beam position deformation at the isocenter combining shifts in the beam optics and mechanical deformation.

Table 4 shows the beam trajectory shift values due to mounting alignment errors in BG3. It can be seen from the results that the offset generated in the Z direction has the most serious effect on the beam trajectory. We can consider that the incoming trajectory simply adds to the scanning magnet's deflection to produce an error in the spot position at the isocenter plane that is independent of the spot's position.

**Fig. 10** shows the beam deformation at the isocenter, combining variation in the beam optics and mechanical deformation, using Equation (4). There are two cases considered, case 1 is where the shift in all three directions is 0.3 mm, while case 2 considered a shift of 0.1 mm. When the offset of the BG3 alignment error is 0.3 mm, the scanning accuracy in the X direction will be above 0.5 mm, which is at the limit of the irradiation accuracy for the PBS nozzle. For case 2, we can see that the maximum deformation at the isocenter is still lower than the safety margin of 0.35 mm.

Of course, the above discussion simply considers errors in the mounting alignment of the BG3 bending magnet. While in reality, there are other factors that will affect the beam trajectory after the beam enters the BG3, such as shifts in the alignment angle, non-uniformity in the magnetic field, the Hysteresis effect and so on. Additionally, the beam on entering the BG3 may not be in an ideal orbit. In order to better study the influence of the above factors on the scanning accuracy, a complete Monte Carlo model including the PBS nozzle and bending magnets should be developed using TOPAS simulation, to which a three-dimensional magnetic field can be introduced using the software OPERA, to analyze the effects of a non-uniform magnetic field on the beam's isocenter properties.

**4. Conclusion**

In this study, the effect of mechanical deformation on the beam's isocenter properties were evaluated in detail. It can be seen from the results that the largest effect was caused by deformation of the gantry, when compared with deformation of the L-shape plate. For the current design of the SC200 scanning beam delivery system, the effects of mechanical deformation meet the maximum beam deformation limits. Compared with mechanical deformation, we find that the deviation of the incident beam has a more severe effect on the isocenter properties. In following studies, we will conduct more detailed Monte Carlo models to further research in this area.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have
appeared to influence the work reported in this paper.

Acknowledgement

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.02.012.

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