COMPACT BEAM DELIVERY SYSTEMS FOR ION BEAM THERAPY*

C. Sun[†], D. Arbelaez, S. Caspi, D. Robin, A. Sessler, W. Wan, LBNL, CA 94706, USA

M. Yoon, POSTECH, Pohang, Kyungbuk, Korea

Abstract

In this paper we present a coil winding concept for a large aperture, combined-function 90° magnet that allows for a significantly more compact carbon ion gantry. The winding concept enables the reduction in the size and weight of the magnet without compromising the important beam transport properties. Alternatively, a small aperture gantry requires a post-gantry scanner. We present a compact design for a post-gantry point-to-parallel scanning system.

INTRODUCTION

In an accelerator based ion-beam particle therapy (IBT) facility, ions (typically protons and carbon ions) are accelerated and injected into patients' bodies to treat deep-seated cancer tumors. Many IBT facilities use rotatable gantry beamlines to direct the ion-beam at the patient from different angles. Gantries, however, are expensive, requiring large (4 to 7 meter radius) structures enclosed in large, heavily shielded rooms. This is particularly true for carbon treatment facilities that require beams of higher magnetic rigidity. At present there are many proton beam gantries in operation, however there exists only one gantry for carbon beams. This is at the newly built Heidelberg Ion Therapy (HIT) facility [1]. As compared with an equivalent proton gantry (for example, the Gantry-II at the Paul Sherrer Institute (PSI)), the HIT gantry is roughly 50% larger and 5 times heavier. It is unlikely that many facilities will be able to afford multiple carbon gantries of the size and weight of the HIT gantry.

For both the HIT gantry and PSI Gantry-II, scanning magnets are placed upstream of the final 90° bending magnet. To achieve a point-to-parallel scanning, a large aperture of this bend is required. As as a result, the size and weight of the whole gantry is driven by this large aperture magnet. In this paper we present a coil winding concept for a large aperture, combined-function 90° magnet that allows for a significantly more compact carbon ion gantry [2, 3]. The winding concept enables the reduction in the size and weight of the magnet without compromising the important beam transport properties. With this superconducting bending magnet, it may be possible to realize a carbon gantry with comparable size and weight as that of PSI Gantry-II.

To reduce aperture of the final bending magnet, it is necessary to place the scanning mangets downstream of the
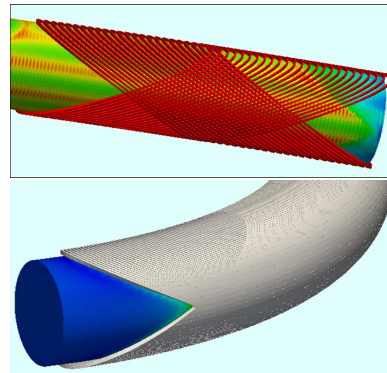
Figure 1: Superposition of two alternating skewed solenoids on a straight cylinder (Top) and a torus (Bottom).

bend. In this paper, we also present a compact design for a post-gantry point-to-parallel scanning system.

PART A: LARGE APERTURE MAGNET

Superposing two solenoid-like thin windings that are oppositely skewed (tilted) with respect to a cylindrical axis (Fig. 1), the combined current density on the surface of the cylinder is $\cos\theta$-like and the resulting magnetic field in the bore is a pure dipole [4]. Applying this winding concept to the construction of toroidal coils (Fig. 1) has the benefit of eliminating difficulties in placing windings under tension over a concave surface [2, 3]. As a result, the magnet is more compact, cost effective and better positioned to handle the large Lorentz forces that develop during operation. We show in particular that it is possible to arrive at a combined-function winding geometry where the resulting multipole field content can satisfy all the aperture and field constraints of the final bend of a carbon ion gantry.

The magnetic field and beam dynamics of the curved superconducting magnet above have been first studied using the Differential Algebra (DA) code COSY INFINITY. To achieve point-to-parallel scanning of 400 MeV carbon beam, it is found that the required dipole field B_0 is about 5.0 T in the middle of the torus, and required quadrupole B_1 and sextupole B_2 gradients are -2.26 T/m and 1.30 T/m^2, respectively. The small, but non-zero, sextupole was found to help balance out the sextupole terms arising from the fringe field. To generate such required magnetic fields, Genetic Algorithm (GA) has been applied to find the optimal winding solutions.

First, we need to parameterize the winding path of the coil on the surface of torus. To simplify the description of the winding, the simple toroidal coordinate system
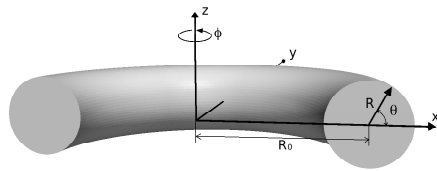
Figure 2: Simple toroidal coordinate system.

Figure 3: Vertical magnetic fields (B_z). Left: the contour of the vertical field across the bore; Right: the profile of the vertical field on the mid-plane.

(R, ϕ, θ) is used, where R is the radius of the torus bore, ϕ is the toroidal angle and θ is the poloidal angle shown in Fig. 2. Given the bore radius R, the relationship between ϕ and θ, i.e, $\phi = f(\theta)$, will determines the winding path of the coil on the surface of the torus. To generate multipole field components, we propose the following winding relation for torus

$$\phi = \theta/n + a_0 \sin\theta + a_1 \sin 2\theta + a_2 \sin 3\theta + \cdots, \quad (1)$$

where n is the coefficient determining the number of turn of the coil on a 2π torus, and $a_0, a_1, a_2, \cdots$ determine the multipole field components.

To calculate the magnetic field due to the winding path given by Eq. (1), however, it is convenient to transform the winding description from the toroidal coordinate system (R, θ, ϕ) to Cartesian coordinates (x, y, z). The coordinate transformation between them is given as follows:

$$
\begin{aligned}
x &= (R_0 + R\cos\theta)\cos\phi, \\
y &= (R_0 + R\cos\theta)\sin\phi, \\
z &= R\sin\theta, \quad (2)
\end{aligned}
$$

where R_0 is the radius of the spine of torus (Fig. 2). Thus, for given coefficients $n, a_0, a_1, a_2, \cdots$ as well as the coil current I, the magnetic field inside the torus can be numerically evaluated using Biot-Savart law.

Now, the question is what values the coefficients $n, a_0, a_1, a_2, \cdots$ and current I should be in order to generate required magnetic field. To answer this question, Genetic Algorithm is applied to solve this winding problem. Multiple solutions are found. One of these solutions is: I= 18 kA, n=864, a_0=0.168, a_1= -5.74×10^{-3}, a_2=2.345×10^{-4}. The magnetic field of this winding across the bore of the torus is shown in Fig. 3, which clearly meets the requirements. The solution presented is only one possible solution that meets the field requirements. There are many others with different combination of (I, n, a_0, a_1, a_2) values. This allows us to explore different options and choose those which are most practical (i.e., easier to wind, lower tolerances, lower stress and stored energy, etc.).

To evaluate the effect of scanning and beam distortion of this magnet, simulations were carried out where particles were tracked from the entrance of the gantry to the patient position for different settings of the scanning magnets.

The beam is deflected at various angles at the position of steering magnets before the gantry as shown in Fig. 4 (Left). So, ideally the beam centroids must show a linear dependence on kick angles while at the same time the
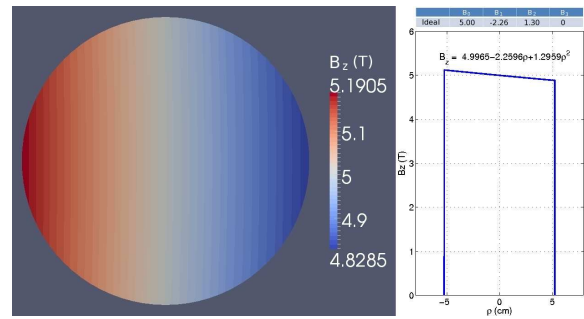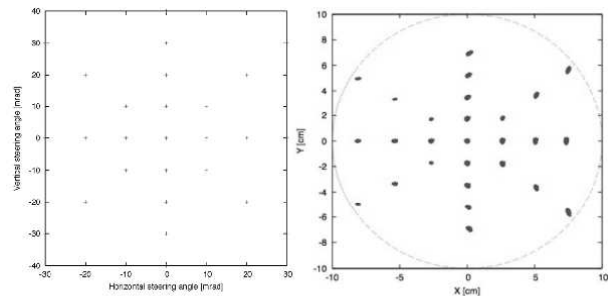

Figure 4: (Left) Horizontal and vertical scanning magnet settings. (Right) Beam shapes at the patient position with optimized winding.

shape of the beam should not change. Fig. 4 (Right) shows the beam spots in the transverse plane at the patient position. One can see that a nearly point-to-parallel scanning is achieved.

PART B: POST-GANTRY SCANNER

To reduce aperture of the final 90° bending magnet, however it is necessary to place the scanning mangets downstream of the bend. In this section, we present a compact design of a post-gantry point-to-parallel scanning system.
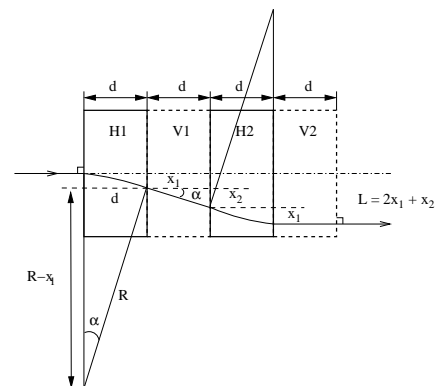

Figure 5: Layout of post-gantry scanning magnets.

08 Applications of Accelerators, Technology Transfer and Industrial Relations

The layout of this system is shown in Fig. 5. The system consists of two horizontal (H1 and H2) and two vertical (V1 and V2) rectangular bending magnets which are arranged alternatively in a row. All the magnets have the same length of d. To achieve point-to-parallel scanning, the two horizontal and two vertical bends need to be ramped with the same field strength (B_0), but in an opposite direction. Only considering the horizontal trajectory, the particle is displaced x_1 after the first horizontal bend (H1), and drifted x_2 in the first vertical bend (V1), and displaced again x_1 in the second horizontal bend (H2). So the overall displacement after the scanner is

$$L = 2x_1 + x_2 = 2R - 2\sqrt{R^2 - d^2} + d^2/\sqrt{R^2 - d^2}, \quad (3)$$

where R is the bending radius of the magnets, and $R = B\rho/B_0$ ($B\rho$ is the magnetic rigidity of particle).

To cover the scanning region $L = \pm 0.1$ m using a 400 MeV carbon beam ($B\rho = 6.466$ Tm) with the magnetic field $B_0=2$ T, the bending radius R is 3.183 m and the required length d of the bends is 0.398 m according to Eq. (3). The total length of the scanning system is about 1.6 m. Based upon these parameters, we carried out particle tracking study of this scanning system. First, one-dimensional horizontal and vertical scannings are simulated by tracking a single particle through the scanner with different magnetic fields. The tracking results are shown in Fig. 6. Then, a 2D scanning simulation is carried out. The result is shown in the Fig. 7. In the simulation, 1000 Gaussian distributed particles are tracked. The Twiss parameters and emittance of the beam at the entrance of the scanner are taken from the NS-FFAG gantry design [5], and $\beta_x = \beta_y = 1$ m, $\alpha_x=\alpha_y=0$, and $\epsilon_x=\epsilon_x=1$ mm-mrad. The tracking result shows that the beam spot size (RMS) is about 4 mm at tumor location, 1.25 m downstream from the scanner (1 m from the scanner to patient plus 0.25 m tumor depth). By adding several focusing quadrupoles in front of the scanner, we are able to reduce the beam spot size to about 1 mm, which might be attractive for tumor treatments at edges. However, it requires extra space of 2 m long. Further study is required to optimize the focusing quad beamline. In these tracking studies, a hard-edge model is assumed for the bending magnets and fringe field effects are not taken into account. These effects may distort beam scannings at the edge, which could be corrected by changing the magnetic field at the scanning edge.

Assuming 4 mm beam spot size at the patient, to cover the scanning region of 20 cm requires 50 horizontal spots and 50 vertical rows. Assuming that the maximum magnetic field of the scanner is ± 2 T and the ramping rate is 100 T/s, one horizontal sweep requires 4 T field change and takes 0.04 seconds. 50 of such sweeps in vertical takes 2 seconds. The vertical scan from -2 T to +2T also takes 0.04 seconds. So, one complete transverse scan takes 2.04 second. Assuming that 10 transverse scans are needed to treat tumor at different depth, the total time for a treatment would be 20.4 seconds.
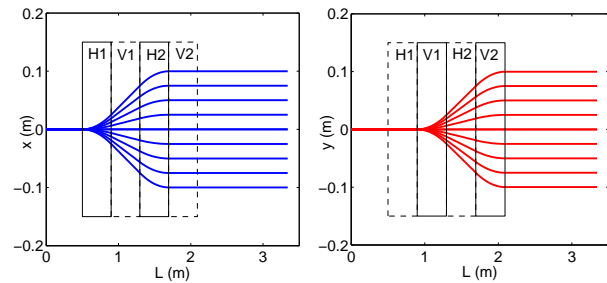

Figure 6: Horizontal (left) and vertical (right) scannings.
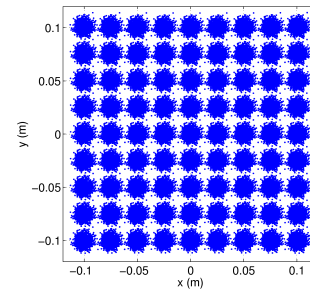

Figure 7: 2D Beam scanning. The beam spots are taken at 1.25 m downstream of the scanner.

CONCLUSIONS

In the paper we demonstrated that it is possible to optimize the coil winding path for a tilted solenoidal pair wound on a toroid that will produce the fields required for point-to-parallel beam scanning. This winding concept enables a reduction in the size and weight of the final $90°$ bending magnet without compromising the important beam transport properties of the ion beam gantry. Further studies will be carried out to evaluate the stored energy, stresses, inductance, fast ramping and cryogenic systems of this bending magnet.

A compact design of a post-gantry scanning system is also presented in this paper. Simulations shows that a point-to-parallel scanning can be achieved. Further evaluations of this system, such as alternative focusing quadrupoles to obtain smaller beam spot size, and simulations with a more accurate field model will be performed in the near future.

REFERENCES

[1] U. Weinrich, Proceedings of the 2006 European Particle Accelerator Conference, Edinburgh, Scotland (2006) 964-968.

[2] D. Robin et al., Nucl. Instr. Meth. Phys. A, in press (2011).

[3] S. Caspi et al, 22nd International Conference on Magnet Technology (MT-22), France, 2011, to be published.

[4] D. I. Meyer and R. Flasck, Nucl. Instr. Meth. **80** (1970) 339.

[5] D. Trbojevic et al., Phys. Rev. ST Accel. Beams **10**, 053503 (2007).

08 Applications of Accelerators, Technology Transfer and Industrial Relations