COMPACT GANTRY WITH LARGE ENERGY ACCEPTANCE*

Weishi Wan#, David Robin, Andrew Sessler, and Changchun Sun, LBNL, Berkeley, CA 94720, USA

Abstract

Existing proton beam therapy gantries weight 100+ tons and require large (three stories) heavily shielded rooms to house them. Pioneering work by Trbojevic et al [1] using fixed field alternating gradient (FFAG) gantry concept demonstrated the potential of both reducing the size of the gantry as well as increasing the energy acceptance. In this paper we present a new variation of a compact superconducting FFAG gantry. The gantry consists of three, small aperture, 7-bend achromat sections followed by transverse scanning magnets. The 7-bend achromat contains high field superconducting combined-function bending magnets. This gantry provides a large (+/-20%) energy acceptance for fast depth scanning. We present the analysis of the beam tracking and show that it is possible to scan the ion beam over a large volume of roughly 1 cubic liter, with minimal distortion in the beam shape without changing the fields of the superconducting magnets.

INTRODUCTION

Rotatable gantries are needed to optimize the delivery of ion beams in an ion beam therapy facility. Existing gantries using resistive magnets, such as the PSI-II gantry, already deliver impressive performance. They allow for fast 3D pencil beam scanning over a wide field region. However these gantries are large, heavy, and expensive. Existing proton gantries are several stories high and weigh more than 100 tons. Reducing the size and weight of the gantry will have a large impact on the construction and operational cost, as well as the reliability of such a facility. Various groups have been working on this problem lately and the common theme is the application of superconducting magnet technology to reduce the size and weight simultaneously. Another consideration is that the gantry should be able to allow for rapid energy changes for fast depth scanning. This is particularly advantageous for treating moving tumors and repainting.

In this paper, we present a preliminary design of a compact gantry with large energy acceptance that transports beams with different energy without ramping the magnets in the gantry for any given position of the gantry.

DESIGN AND LAYOUT

Generally speaking, the concept of the design grew out of that of the fix field alternating gradient (FFAG) accelerator that originated in the 50s and was revived in the late 90s [3]. Specifically, our concept is a variation of the scheme developed recently by Trbojevic et. al. [1,2]. The differences are two folds. First, instead of a continuous chain of magnets, three identical groups of 7 magnets each are used for the bending, which makes room available for beam diagnostics and might even make it easier to manufacture the device (see Fig. 1). Second, sextupole and octupole components are introduced in the middle 5 magnets of each group to reduce nonlinear aberrations that are results of strong focusing and the lumping of the magnets. The example here is designed for 190 MeV protons and energy acceptance of +-21% (150 MeV to 230 MeV). The bending field on the optical axis is around 3.2 T and the maximum field is kept below 6.2 T. The bore radius of the magnets is 3.25 cm. The details of the parameters are listed in Table 1.

Table 1: Parameter list of the 7-bend achromat. The lengths of the magnets are those of the effective field boundary and the fields are effective field within the boundary. The peak field will change somewhat for real magnets with soft edge fringe field.

Type	L (m)	B_0 (T)	B_1 (T/m)	B_2 (T/m^2)	B_3 (T/m^3)
Drift	0.734	---	---	---	---
Bend	0.103	3.2	79.9	0	0
Drift	0.15	---	---	---	---
Bend	0.162	3.2	-84.3	-432	4067
Drift	0.15	---	---	---	---
Bend	0.156	3.2	84.1	216	1168
Drift	0.15	---	---	---	---
Bend	0.185	3.2	-84.0	-311	-3795
Drift	0.15	---	---	---	---
Bend	0.156	3.2	84.1	216	1168
Drift	0.15	---	---	---	---
Bend	0.162	3.2	-84.3	-432	4067
Drift	0.15	---	---	---	---
Bend	0.103	3.2	79.9	0	0
Drift	0.734	---	---	---	---

From the beam optics point of view, each magnet group, which bends the beam 90 degrees, is mirror symmetric about the center, achromatic, point to parallel and parallel to point (Fig. 2). Furthermore, the focal lengths of the two transverse planes of each magnet group are equal, making the beam independent of the angular position of the gantry to the leading order. The scanner is located after the third group, which is followed by a 2 m long drift (see Fig. 1). The source to axis distance (SAD)

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#wwan@lbl.gov

of this gantry is 2.3 m, which is short but acceptable [4]. The two advantages of not placing magnets after the scanner are that there is no concern of the distortion of the beam after the kicker and that the large free space between the kicker and the patient allows access of diagnostics equipment while treatment is underway [4].

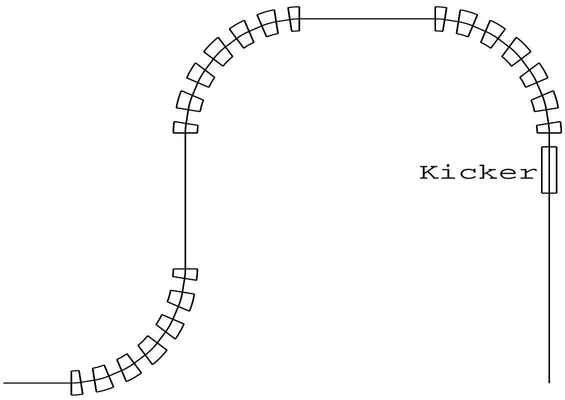

Figure 1: Layout of the compact gantry. The Kicker (transverse scanning magnets) is located after the last 7 bend achromat. The radius is roughly 4 m and the distance between the first magnet to the isocenter is around 5.2 m.

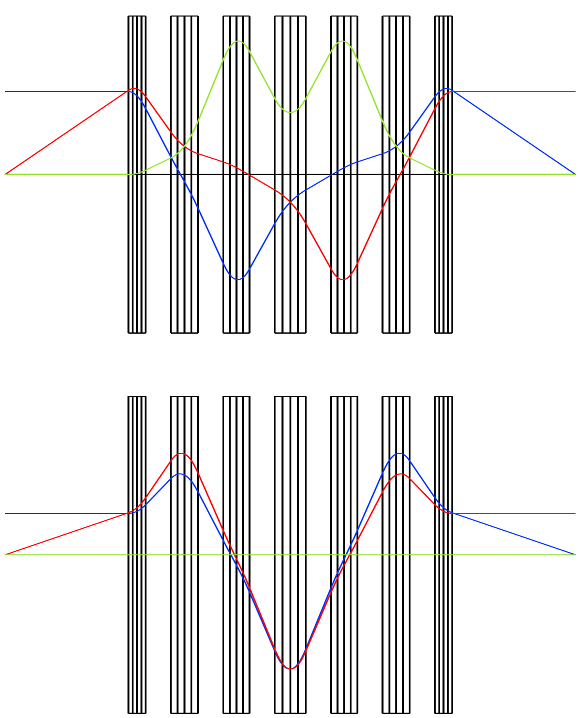

Figure 2: Principal rays of the compact gantry. Top: plot of the rays in the x-z plane; Bottom: plot of the rays in the y-z plane. Green: off-momentum ray; Blue: cosine-like ray; Red: sine-like ray.

TRACKING RESULTS

In order to get the nonlinear aberrations under control, sextupole and octupole components are introduced in the middle 5 magnets of the 7 bend achromat, where dispersion is reasonably large. Due to mirror symmetry, there are 6 independent knobs in each achromat, which are used to minimize the sum of the absolute values of all aberrations up to the third order (Table 1). The magnets are modeled with the default soft edge fringe field in the code COSY INFINITY [5], which is based on measurement of the PEP II magnets [6]. The protons are tracked through the 5th order Taylor map of each magnet, taking into account higher order effect due to the combination of the magnets. The result is shown in Fig. 3 for the case of no kick from the scanner. It is obvious that the nonlinear multipoles are able to keep the aberrations small and thus maintain the quality of the beam at the patient. As stated above, there is no need to show the plots for the kicked beam since the kicker and the drift space downstream don't generate significant aberrations.

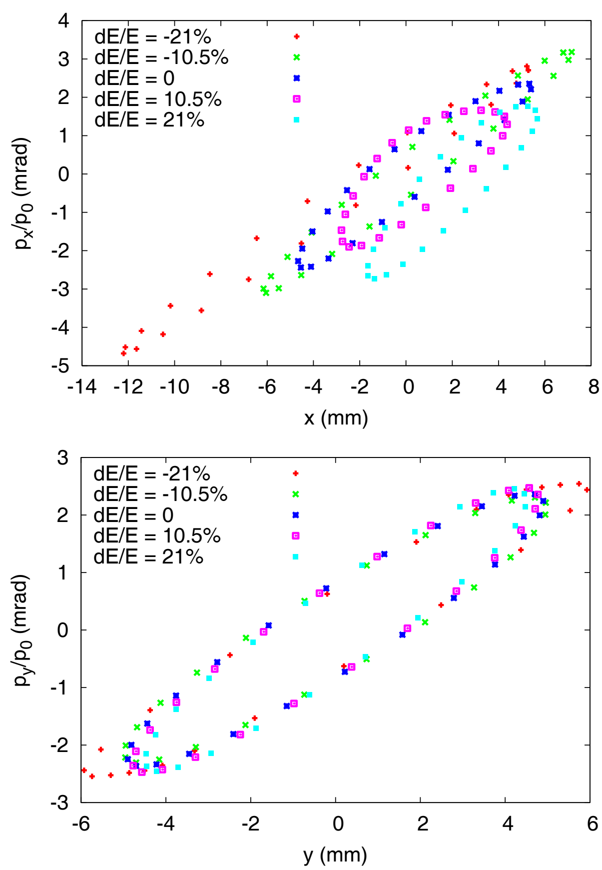

Figure 3: Phase space plots of the gantry. The emittance is 4 mm mrad in both planes. Top: the horizontal plane. Bottom: the vertical plane.

The single kicker and drift is the simplest post gantry scanning scheme. There are other possible schemes to transport the beam from the kicker to the isocenter that have some potential advantages yet will add complexity and add weight. The first scheme is using a pair of kickers (see Sun et al [7]). Such a scheme could achieve infinite

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SAD. A second scheme, using a number of larger aperture quads, could also achieve larger SADs as well as smaller beam at patient. This second scheme, initially proposed by Trbojevic et al [1], uses a fixed field quad triplet and showed good performance when the kicker is off. No data of the kicked beam has been published. We have studied a similar scheme using a symmetric quad quintuplet. With this arrangement, we can achieve half the size at the patient and double the SAD (at the cost 30% increase in kicker strength). The kicked beam maintains good quality when the sharp cut off (SCOFF) model is used. Yet we found, to our dismay, that the extended fringe field causes significant degradation of the quality of the beam. The variation of the vertical beam size is on the order of 10, even with sextupole and octupole components introduced to correction the aberrations. At least for the present design, we haven't found a way to overcome this difficulty and favor the option of the drift space.

CONCLUSIONS AND DISCUSSIONS

A preliminary design of a compact gantry with large energy acceptance is presented. Like other proposed FFAG type gantries [1], it has the potential of greatly reducing the weight, thus lowering the cost of construction and operation, and increasing the speed of energy scanning, thus deceasing treatment time. Unlike the previous FFAG designs, the present design utilizes 7 bend achromatic modules, as opposed to FODO cells, making available room for diagnostics. Furthermore, nonlinear multipole components are used to minimize the impact of aberrations, which in turn allows us to preserve the quality of the beam through the long drift space between the end of the last achromat and the isocenter.

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