SUPERCONDUCTING NON-SCALING FFAG GANTRY FOR CARBON/PROTON CANCER THERAPY*

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Abstract

We report on improvements in the non-scaling Fixed Field Alternating Gradient (FFAG) gantry design. As we previously reported [1], a major challenge of the carbon/proton cancer therapy facilities is in the isocentric gantry design. The weight of the isocentric gantry transport elements in the latest Heidelberg carbon/proton facility is 135 tons [4]. In this report we detail improvements to the previous non-scaling gantry design. We estimate that this non-scaling FFAG gantry would be almost a hundred times lighter than traditional heavy ion gantries. Very strong focusing with small dispersion permits passage of different energies of carbon beams through the gantry's fixed magnetic field.

1. INTRODUCTION

The number of cancer hadron therapy facilities is rapidly growing all around the world. Many more are being commissioned or in process of being built (Germany, Italy, Japan, USA, etc.). This progress is mostly due to the multiple advantages of hadron cancer therapy with respect to any other radiation methods [2]. A major challenge in present and future hadron therapy facilities is the beam delivery system. An isocentric gantry system is becoming a necessity for each facility. The request comes mostly from hard to reach tumors especially around the spine (chordomas, low grade chondro-sarcomas, unresectable sacral chordomas). The hadron therapy treatment requires different incident angles to avoid damage to sensitive areas (such as spine) by radiation. The gantry must deliver a precise ion dose to the patients with very good reliability and stability. Larger cancerous tumors require transverse position scanning at different beam energies and an angle variation around the patient provided by gantry rotation. The non-scaling FFAG (NS-FFAG) concept should dramatically reduce the overall weight [4] of a carbon gantry made of warm magnets. The fixed field magnets have transversely linear variation of the magnetic field and they could be made of superconducting or high temperature superconductors.

Study of a Gantry with Smaller Energy Range

This report is an update on the previous carbon/proton design [1]. Design differences in this study come mostly due to the possibility of fast magnetic field variation with a different superconductor.

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The superconductor wire is comprised of a multiplicity of filaments of niobium/titanium superconductor alloy disposed within a matrix of copper. The “eddy” current problem of the superconducting cables is significantly reduced and a current variation of 30 A/s has been achieved.

In addition to the advantage of dramatically smaller weight of the NS-FFAG magnets we have previously emphasized an ability of operating the gantry at a fixed magnetic field for the whole range of carbon/proton energies required for the patient treatment. Our latest report [1] has the NS-FFAG gantry with 150-400 MeV range, with a fixed magnet current. This corresponds to the momentum range of $\delta p/p$=–25% up to 30%. In the present report the momentum range is reduced to $\delta p/p$=+–15%. This corresponds to the kinetic energy between 235-400 MeV/u with the value of $B_{max}\rho$=5.5192819 Tm. A switch from $B_{max}\ \rho$ to the new value of $B_{new}\ \rho$=4.079469 Tm can be done as fast as the present warm temperature magnets can do (30 A/s). The patient treatment with a range in kinetic energy of 135-400 MeV is now provided with two current settings.

2. THE NON-SCALING FFAG

The non-scaling FFAG is made of fixed field combined function magnets with a linear transverse variation of magnetic field [5].

The Basic Cell of the Gantry

An example a gantry basic cell with betatron functions is shown in Figure 1.

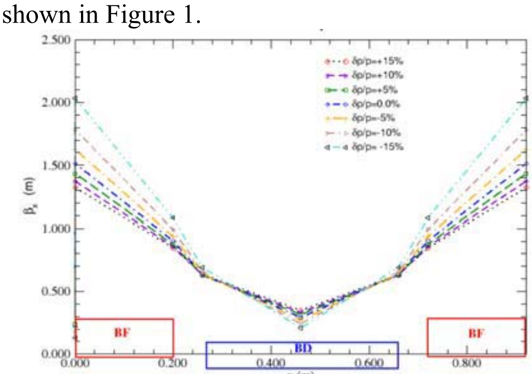

Figure 1: Betatron functions in one gantry cell.

The central magnet is a defocusing combined function magnet with a minimum of dispersion and horizontal β_x function at the middle. The dispersion function throughout FFAG lattice retains very small values. The large momentum acceptance and small orbit offsets are a consequence of the small dispersion. The gantry, made of the non-scaling FFAG cells, accepts and propagates different energies ions with very small variation of the orbit. The combined function magnets of the basic cell with bending angles are presented in Figure 2. The middle of the dipole is selected as a place for the input and output of the gantry.

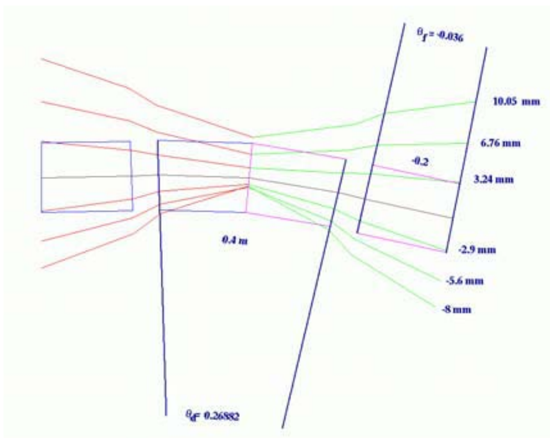

Figure 2: The basic cell of the gantry made of non-scaling FFAG combined function magnets.

The offsets at the end of the cell are obtained from the Polymorphic Tracking Code (PTC) [6] in a range off momentum $\delta p/p < \pm 15$ %, or in kinetic energy a range of 235-400 MeV/n.

Gantry Design

A design of the gantry requires a ring with zero dispersion and slopes at the middle of the major combined function dipoles as presented in Figure 3.

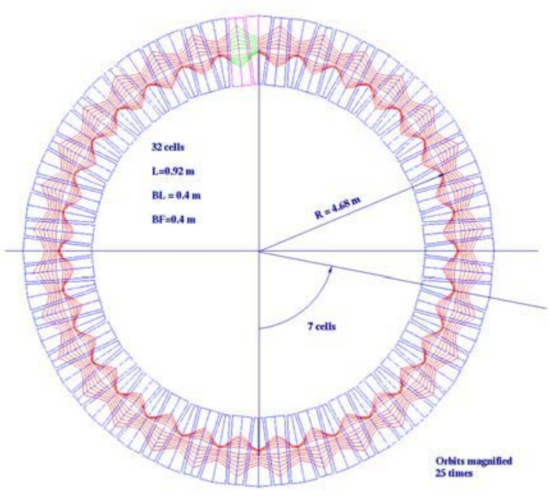

Figure 3: Non-scaling FFAG ring to be used for the gantry design. Orbit offsets are magnified 25 times.

Stable orbits for carbon ions are found within $\delta p/p = \pm 15\%$. The radial scanning and orbit correction is provided at the end of the gantry. A construction of the gantry follows the ring solution and 7 cells of the ring are used in the first example for the beginning of the gantry, as presented in Figure 4.

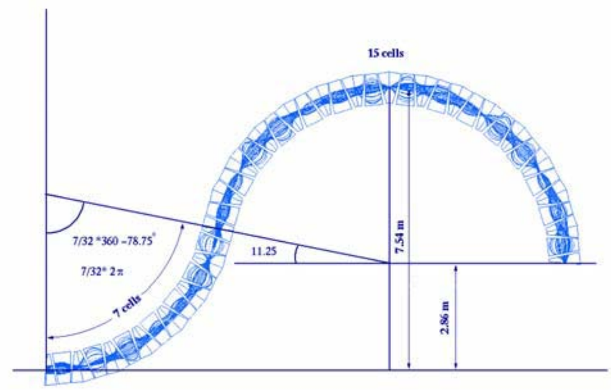

Figure 4: A gantry made of 7 and 15 cells of the ring presented in previous figure. Orbit offsets are magnified 25 times. Tracking is performed with the PTC program.

Particle Tracking in the Gantry

Beam amplitudes within ellipses with maximum values for the horizontal axis of x_{max}=3 mm and y_{max}=3 mm are used as initial conditions for particle tracking through the gantry. Tracking results are shown in Figures 5 and 6 for the x , x' and x, y phase space.

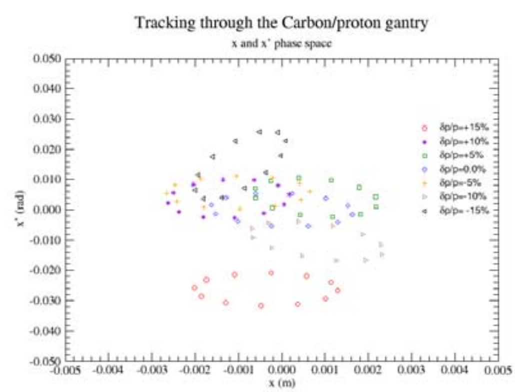

Figure 5: Tracking results in the *x* and *x'* phase space.

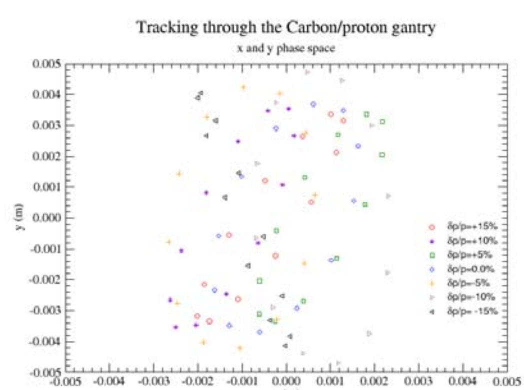

Figure 6: Tracking results in the x-y plane.

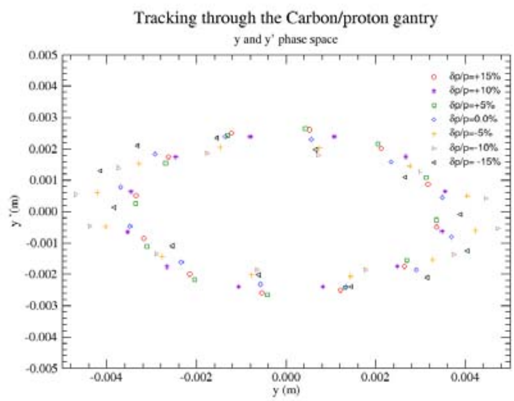

Figure 7: Tracking results in the y,y' phase space.

Beam Scanning

The beam scanning should be of a rate of the order of 100 Hz. The superconducting cables combined with the copper matrix could be used in the beam scanning a rough estimate is 50 Hz.

The Size of the Gantry's Magnets

There are about 24 to 30 non-scaling FFAG cells (0.92 meters long) used in the gantry design. The same number of major bends-combined function magnets is required. Magnet dimensions, field *B,* gradients *G,* and maximum aperture A_p, are summarized in Table 1.

Table 1: Magnet properties

	L(m)	B(T)	G(T/m)	A_p(m)	B_{max}(T)
BD	0.40	3.7-4.3	-68.5	± .008	4.24
BF	0.40	1.00	71	± .010	1.8

The 40 cm long magnets of this size do not have excessive field requirements for superconducting magnets and could be built as a coil dominated magnetic field operating at lower temperatures (2-4K). A configuration has a simple inner quadrupole surrounded by a thicker outer dipole coil and a very thin dipole coil (active shield) at much larger radius.

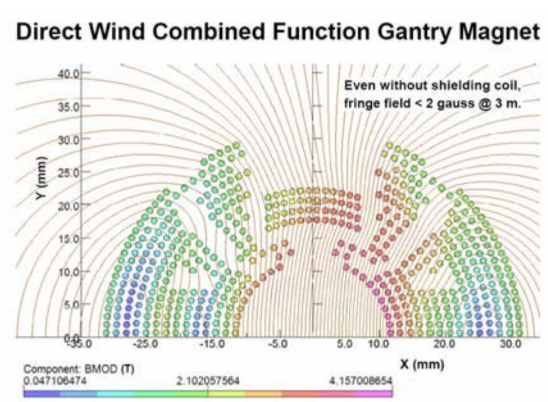

Figure 8: Preliminary superconducting combined function magnet design.

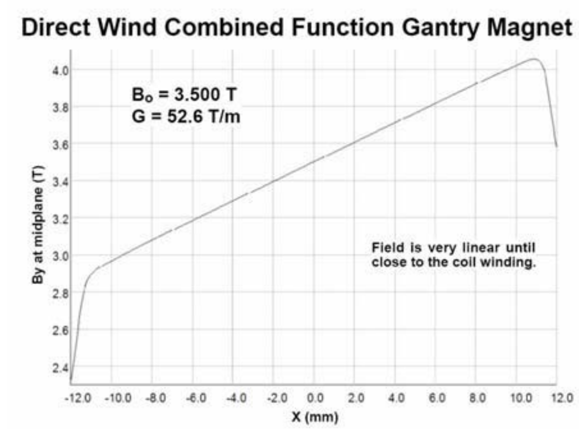

Figure 9: Magnetic field along the transverse axis.

The cryostat has an *OD~170* mm. A thin warm iron shell around the whole magnet to reduce the fringe field is not necessary. The magnetic field of less than 2 Gauss was calculated at a distance of 2 meters (as shown in Figure 8). The estimated weight of the magnets is in the range 45-75 kg/m or average ~50 kg/m. For ~20 meter long gantry beam line is ~1400 kg. This does not include the weight of the support system, but it is to be compared to the 135 tons of the "transport components" [4].

3. SUMMARY

An update on the non-scaling FFAG gantry is presented. Two settings of the fixed magnetic field provide an energy range of 135-400 MeV/u for the carbon-proton cancer treatment. Small magnet sizes should reduce the cost and weight of the gantry, and ease gantry operation. The transverse and final focus scanning system is assumed to be at end of the gantry transport above the patient. The carbon gantry size has been reduced from the previous [1] radius of 5.85 m to 4.6, or the length of the transport system is reduced from 25.7 m to 20.2 m (number of cells is reduced from 28 to 22). The vertical distance from the end of the gantry to the patient bed is 2.86 m.

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