UPDATE ON THE INNOVATIVE CARBON/PROTON NON-SCALING FFAG ISOCENTRIC GANTRIES FOR CANCER THERAPY*

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Abstract

There is a dramatic increase in numbers of proton/carbon cancer therapy facilities in recent years due to a clear advantage with respect to the other radiation therapy treatments. Cost of the ion cancer therapy is still to high for most of the hospitals and a dominating part comes from the delivery systems. We had previously presented design of the carbon and proton isocentric gantries [1] using the principle of the non-scaling alternating gradient fixed field magnets (NS-FFAG), where a size and weight of the magnets should be dramatically reduced. The weight of the transport elements of the carbon isocentric gantry is estimated to be 1.5 tons compared to the 130 tons a weight of the Heidelberg gantry. The similar claim of 500 kg comes for the transport elements of the proton permanent magnet gantry. We present an update on these designs.

INTRODUCTION

The main motivation for applying the NS-FFAG concept to the isocentric gantries is to reduce the enormous weight of the transport elements and to make the operation easier. The reduction in size and weight at the same time simplifies construction and reduces the weight of the supporting structure. Two NS-FFAG designs for the isocentric gantry are presented: one with separated function permanent Halbach magnets, to be used for the proton cancer therapy facility, and the other with superconducting combined function magnets, to allow carbon and proton ion transport and delivery.

The beam size and scanning system of the gantry have to include effects of the beam straggling and multiple Coulomb scattering during the propagation of ions inside the patient. The size of the beam grows along its way to the tumor. The size at the Bragg peak, where most of energy is deposited, rises with input beam energy. For a 200 MeV proton energy a position of the Bragg peak is at ~26 cm. The beam size due to multiple Coulomb scattering reaches a value of σ_{MC} = 6.5 mm, while due to beam straggling the beam size is σ_{ST} = 7.6 mm. They contribute to the total beam size as $\sigma^2_T = \sigma^2_{OPT} + \sigma^2_{MC} + \sigma^2_{STR}$, where σ_{OPT} is the beam size defined by the optics of the transport. It becomes evident that the beam size at the tumor could be adjusted even though there is an angle of the beam with respect to the patient skin. It could be adjusted as well as if the beam would arrive with 90° t\with respect to the skin. Optical elements and scanning system can be programmed in advance in such a way to produce very similar skin radiation to the one produced by

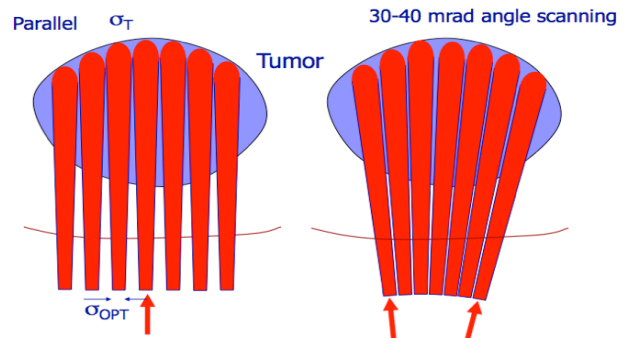the "parallel" scanning technique. To explain this argument more clearly a sketch is made in Fig. 1.

Fig.1: Parallel and angle scanning.

PERMANENT HALBACH MAGNET PROTON GANTRY

The proton cancer facilities could use permanent Halbach separated function magnets. Fig. 2 shows the magnetic field distribution along the transverse axis, while the gantry magnet is sketched at Fig. 3. The maximum magnetic field in the center of the Halbach dipole magnet is: $B_g = B_r \ln(OD/ID)$, where B_r is the material permanent magnetic field value, while OD and ID are the outside and inside diameters of the material modules.
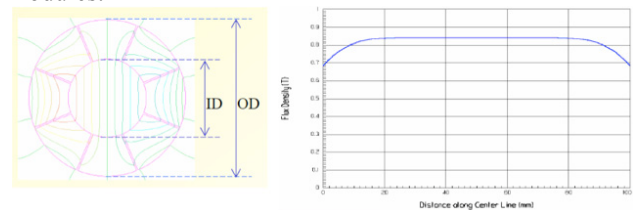

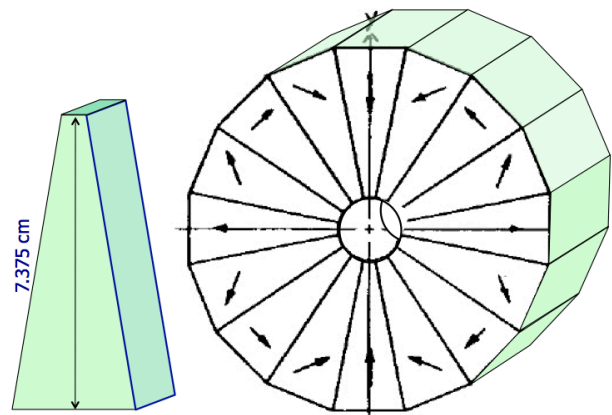Fig. 2: Halbach magnet - magnetic field distribution.

Fig. 3: Halbach magnet applied for the proton gantry with 7.375 cm length of each slice.

Magnets are made of (Nd–Fe–B) neodymium–iron–boron compounds assuming the maximum operating temperature of 70° C and with the magnetic field of $B_r = 1.35$ T. The NS-FFAG isocentric gantries would provide a simple solution as they are easy to operate and the field is fixed for all treatment energies. This should reduce the cost as well. The total weight of the permanent proton gantry is estimated to be about~500 kg. In addition there is no power consumption.

Basic Cell

The basic cell is only 29 cm long. Very short permanent magnet blocks are put close together creating a very strong focusing. Fig. 4 shows magnet lengths and proton orbits in a cell, for the kinetic energy range between 51-250 MeV. The maximum orbit offsets are $x_{max}=-6.5$ and $x_{max} =+11$ mm, for energies of 51 and 250 MeV, respectively. The gradients of the two Halbach quadrupoles made of 16 modules are $G_F=160$ T/m and $G_D =-175$ T/m with corresponding diameters of 3 and 2.6 cm, ($G_F=2.4/0.015=160$ T/m and $G_D= 2.4/0.0137=175$ T/m).
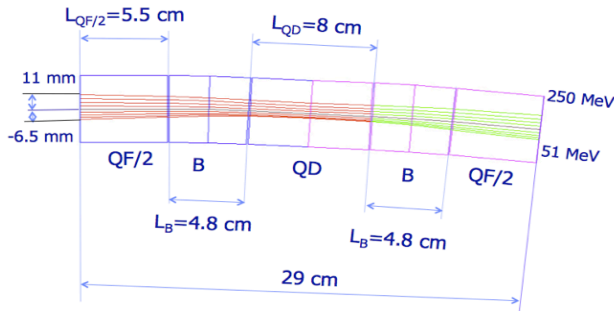

Fig. 4: Basic cell of the proton gantry made of Halbach permanent separated magnets for energy range 51-250 MeV.

Fig. 5 shows the betatron function dependence on energy with small amplitude and dispersion functions.
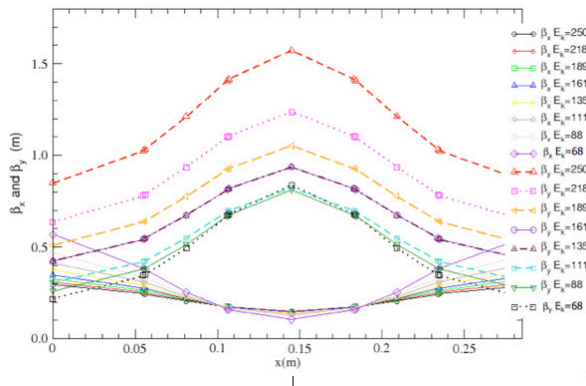

Fig. 5: Betatron functions in a cell dependence on energy.

Fig. 6 shows the permanent function isocentric gantry where orbits with kinetic energies between 68 -250 MeV are magnified 20 times. Protons were tracked through the gantry with the Polymorphic Tracking Code (PTC),

developed by E. Forest [2]. The initial normalized emittance of ε_n=0.5 mm mrad with beam size of ±3 mm.

BRHO = 1.7372345376900 Tm   ANG=2π/120 = 0.05235987755982988
BYD=   2.0214 T   KF =160.0 T/m   KD=   -175.0 T/m
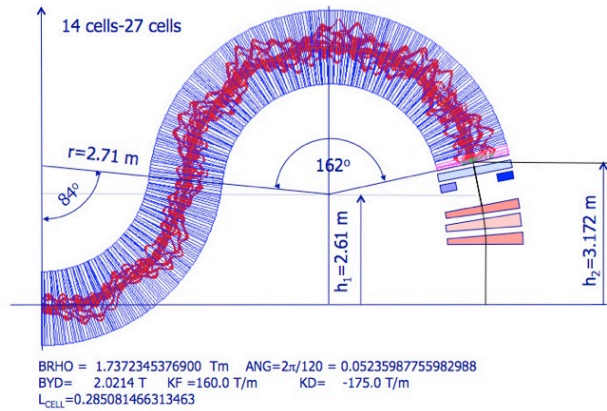L_{CELL}=0.285081466313463

Fig. 6: Isocentric gantry for proton cancer therapy made with permanent Halbach magnets.

Results of the proton distributions, for different energies, of the x-y, and x-x_p, phase spaces at the end of the gantry, are shown in Fig. 7, and Fig. 8, respectively.
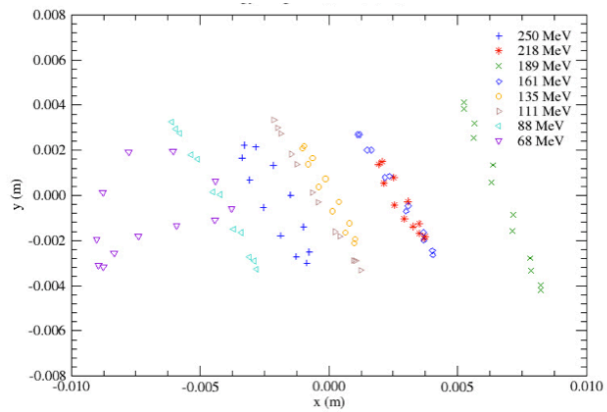
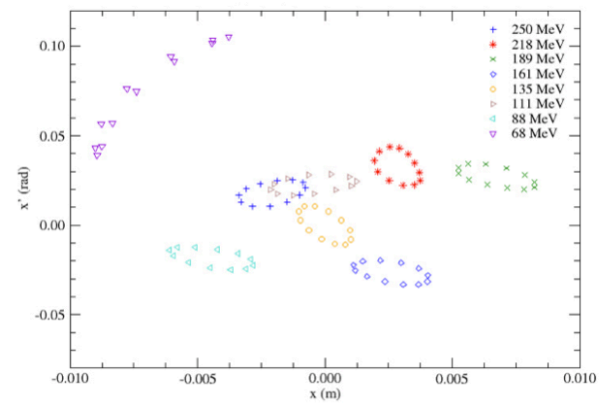

Fig. 7: X-Y phase space at the end of the gantry.

Fig. 8: X-X_p phase space at the end of the gantry.

The focal source point is at the end of the gantry and the scanning magnets are placed close to it. Fig. 9 shows the spot scanning, focusing and beam-positioning system. It follows with a source to axis distance (S.A.D.) of 3.17 m. There are two scanning magnets for the opposite planes, while the combined function magnets adjust the

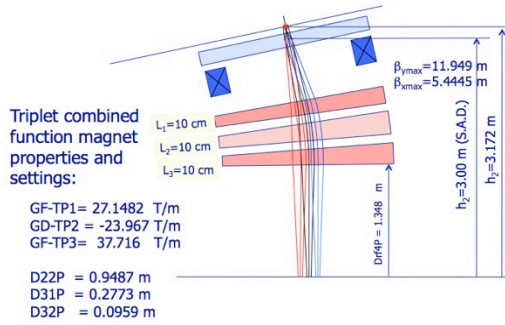required beam size at the tumor. Properties of the magnets are shown in Fig. 9.

Fig. 9: Scanning and final focusing system at the end of the proton isocentric gantry made of permanent Halbach magnets.

NEW VERY SMALL CARBON/PROTON SUPERCONDUCTING GANTRY

The present world-class facility at Heidelberg for carbon/proton and other ion cancer treatments is already operating with a 630-ton isocentric gantry, where the transport element weight is 135 tons [1]. The NS-FFAG concept should provide a weight reduction to about 1.5 tons. The NS-FFAG combined function magnet carbon isocentric gantry, presented in Ref. [3] and in Fig. 14, allows transfer of the carbon $^{12}C^{6+}$ ions or protons in the momentum range of $\delta p/p = \pm 30\%$ or in the kinetic energy range of 150–400 MeV/u for carbon ions or 78-250 MeV for protons. Ions of different energies reach the end of the gantry have offsets within $\pm$ 6mm and the position at the patient is adjusted with the scanning and triplet focusing magnets for each energy separately. The small size and strong focusing of the NS-FFAG reduces the size of betatron functions and dispersion, allowing large momentum acceptance with small orbit offsets. Fig. 10 shows preliminary design by B. Parket (BNL) of the gantry superconducting combined function magnet.
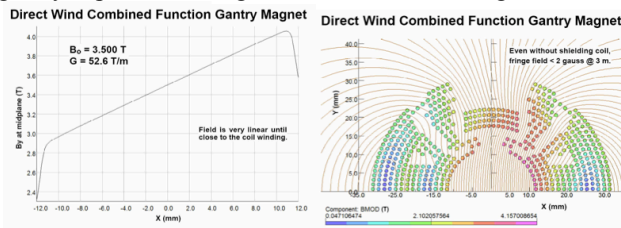

Fig. 10: Superconducting combined function magnet for the carbon/proton gantry (B. Parker, BNL).

In a Table 1 combined function magnet properties, designed by B. Parker from BNL, are shown.

Table 1: Superconducting Combined Function Magnet

Magnet	L(m)	B(T)	G(T/m)	A_p(m)	B_{max}
BD	0.40	3.7-4.3	-68.5	±0.008	4.24
BF	0.40	1.0	71	±0.010	1.8

The orbit offsets and the magnet size are reduced even more if the magnetic field is adjusted for each energy. The gantry design is shown in Fig. 11 and it has been submitted for as an addendum to the existing NS-FFAG gantry patent.
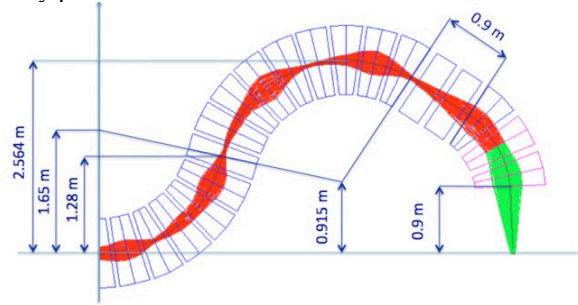

Fig. 11: Small carbon/proton gantry with superconducting magnets. Orbits are magnified 20 times. The scanning magnets are above the final triplet.

The new NS-FFAG design is very compact as the small superconducting magnets keep tight control of the beam. A focal point of the gantry is set to be at the end of it by the quadrupole gradients. Focusing of the beam to the patient is adjustable. The strength of the scanning magnets is B_{max}=0.93 T for the energy of 400 MeV/u, and the lengths of combined function magnet triplets are 0.3m, 0.32 m, and 0.3m.

SUMMARY

The proton isocentric gantry made of permanent magnets shows that might be possible to reduce the cost of the gantry, to simplify the operation procedures (as no adjustments are required through the gantry for the energies 68-250 GeV), and to lower operation cost. Real application would require a study of possible degradation of the magnetic field with time, or due to proximity of other Halbach magnets. The carbon gantry or carbon/proton combination has to be done with the superconducting magnets. The carbon/proton gantry could be built with the superconducting magnets of significantly smaller size if their magnetic field is adjusted per energies. The overall size would be even smaller than the new isochronous proton gantry at the PSI. EMMA experiment at the STFC Daresbury Laboratory in the UK has just started and it is a proof of principle of the non-scaling FFAG gantry.

REFERENCES

[1] U. Weinrich, Poc. EPAC'06 [Edinburgh, UK, 2006], 964.

[2] E. Forest, E. Mcintosh and F. Schmidt. KEK Report 2002–3, CERN-SL-2002-044 (AP) 44, 3 (2002).

[3] D. Trbojevic, B. Parker, E. Keil and A. M. Sessler, *Phys. Rev. S.T. Accel. Beams* **10**, 053503 (2007).