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SUPERB FIXED FIELD PERMANENT MAGNET PROTON THERAPY GANTRY*

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Abstract

We present the top-notch design of the proton therapy gantry made of permanent magnets with very strong focusing. This is a superb solution fulfilling all cancer treatment requirements for all energies without changing any parameters. The proton energy range is between 60-250 MeV. The beam arrives to the patient focused on each required treatment energy. The scanning system is place between the end of the gantry and the patient. There are multiple advantages of this design: easy operation, no significant electrical power - just for the correction system, low weight, low cost. The design is based on the recent very successful commissioning of the permanent magnet 'Cornell University and Brookhaven National Laboratory Energy Recovery Linac Test Accelerator 'CBETA' project [1-3].

INTRODUCTION

We present a permanent magnet proton gantry with large enough momentum acceptance to cover all required treatment beam energies without having to change the magnetic fields. New *"FLASH" and "mini-beams"* developments required this type of gantry.

The effect called *"FLASH"* is based on very high dose-rate irradiation (pulse amplitude $\geq 10^6$ Gy/s), short beam-on times (≤100 ms) and large single doses (≥10 Gy). The second effect relies on the use of arrays of *mini-beams* (0.5–1 mm, spaced 1–3.5 mm). Both approaches have been shown to protect healthy tissues [4].

A superconducting magnet gantry could be built on the same principle for use with Carbon ion beams. The gantry is:

1. Less massive and more compact beam delivery systems capable of delivering ion beams by protons the permanent magnets of the proposed gantry design are 1/10 the size of corresponding iron magnets and the gantry radius is smaller. This reduces the overall gantry weight very significantly. The same would be true for a carbon ion gantry built with constant field superconducting magnets.
2. Technology that can provide for rapid (seconds) scanning of the beam over a tumour volume in three dimensions (that is: both transversely and longitudinally)": the permanent magnets (or constant field superconducting magnets) would allow very fast patient treatment within the required energy range (protons: 65-250 MeV; carbon: 400-225 MeV/u - or 225-128 MeV/u) as there is no need for changing the magnetic field. The constant field design allows for rapid longitudinal scanning, making this gantry deign the optimum solution for fast-cycling linacs, fast cycling synchrotrons, or cyclotron-based cancer therapy systems with rapid energy scan. The gantry makes significant simplification of the patient treatment as no magnet adjustments are needed.

The permanent magnet gantry also has reduced operating costs due its very low electric power consumption. The permanent magnet design is based on the superb results obtained in the recent CBETA commissioning [1]. The successful performance and agreement between the design and measured orbits in the CBETA Fixed Field Alternating Linear Gradient (FFA-LG) beam lines with momentum acceptance of -60%< $\Delta p/p$ <60% confirms that the proton gantry built on the same principle should be very feasible.

World-wide, cancer is the second cause of death after the cardiovascular diseases. There are many types of cancer treatments depending on the type of cancer. Most of the treatments are a combination of different methods: surgery, chemotherapy, immune therapy, targeted therapy and /or radiation therapy, etc. There are multiple methods in using the X-ray therapies like: Intensity Modulated Radiation Therapy (IMRT), 3D-CRT three-dimensional conformal radiotherapy, or the Image-Guided Radiation Therapy (IGRT) etc. The main difference between the hadron cancer radiation therapy and X-ray therapies is that the X-rays always completely propagate through the patient body while in the hadron (proton, light or heavier ions like carbon ions) most of the energy is deposited at the tumor where the "Bragg peak" is. There are unavoidable side effects of the X-ray treatments to the cardio-vascular and other internal organs affected by complete propagation of the X-rays through the body. This is especially critical in the case of children. The advantages of hadron therapies are recognized world-wide as the number of treatment facilities is growing exponentially (~70 operating facilities). A total number of the patients until the end of 2019 treated by the particle therapy is 260,000 [5]. Importance of the hadron therapy was recognized in USA by the National Institute of Health (NIH), National Cancer Institute, Department of Health and Human Services - USA and Department of Energy as they organized very important Workshop on Ion Beam Therapy [6]. In the conclusions of the workshop, it was emphasized that a cost reduction is a major problem for further hadron therapy expansion; further, for the delivery systems - gantries need to be "less massive and more compact beam delivery systems" and "Technology that can provide for rapid (seconds) scanning of the beam over a tumor volume in three dimensions is preferable". This presentation follows the previous patent [7].

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NEW PERMANENT MAGNETS

Details about new permanent magnet developments at Brookhaven are presented in the paper at this conference in the contributed talk by S. Brooks [8]. The combined function magnets can produce very strong magnetic fields: quadrupole gradients in 150 T/m and bending fields of the order of 1.8 T. The initial design of the gantry magnets is shown in the next sub section. The lattice design follows multiple successful Fixed Field Alternating (FFA) gradient applications and confirmations of the principle: in Electron Model for Multiple Applications 'EMMA' at Daresbury UK [9], ATF experiment at BNL [10] and CBETA commissioning [1].

Combined Function Permanent Magnet Design

The 'CBETA' combined function permanent magnet assembly and magnet, built by *'KYMA'* [11] and BNL are shown in Fig. 1.

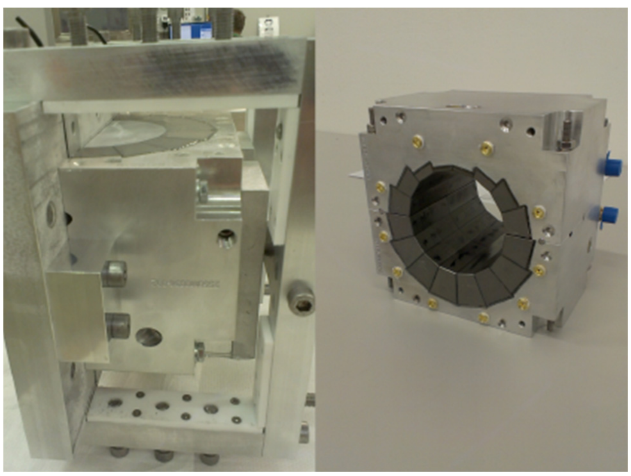

Figure 1: Assembly tools (left) built by 'KYMA' and the assembled combined function permanent magnet (right).

The magnetic field measurement system with the harmonic probe is shown in Fig. 2. A new approach to the gantry permanent magnet design is to switch from the circular Halbach type to the oval cross section as the different energy orbit oscillations are within the radial plane.

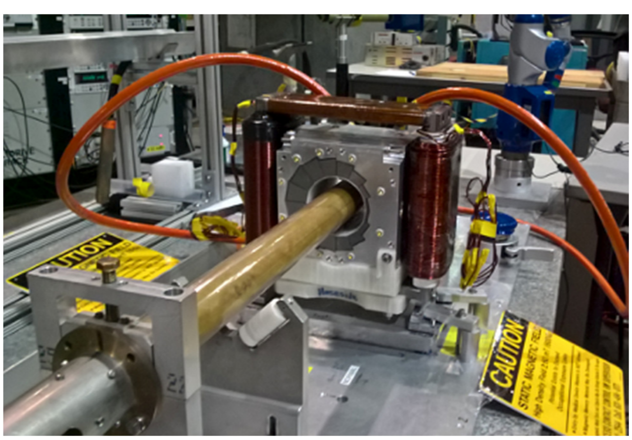

Figure 2: Magnet measurements of the 'CBETA' magnets.

The initial gantry magnet design of the focusing and defocusing combined function magnet are shown in Figs. 3 and 4, respectively. There have previously been suggestions that going from the circular cross section to the oval magnet cross section one can gain in the magnet strength in order of 30% [12, 13]. We present initial examples for the proton permanent magnet design with the cross sections similar to the oval one.

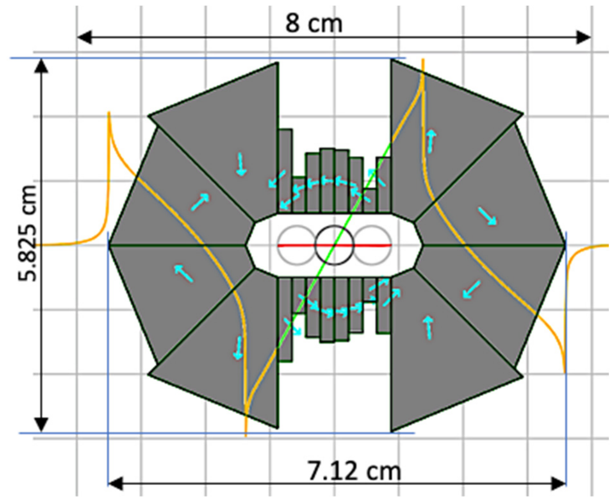

Figure 3: Initial permanent magnet gantry design with quadrupole gradient of 150 T/m.

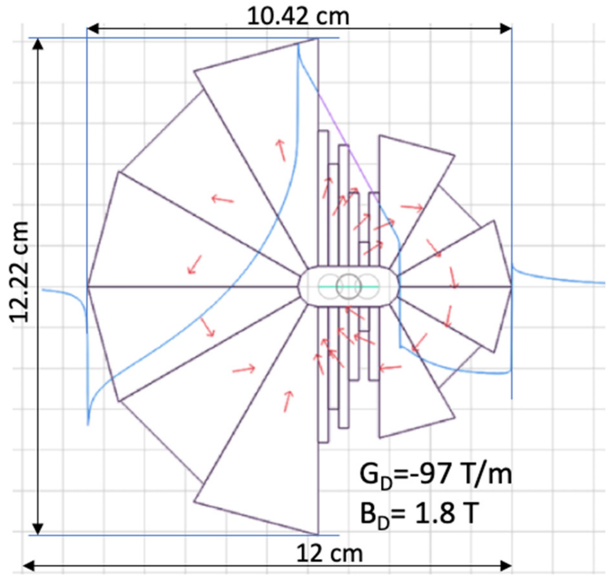

Figure 4: Initial design of the proton gantry defocusing combined function magnets with a gradient of G_D=97 T/m and bending field of B_D=1.8 T.

LATTICE FUNCTIONS DESIGN

The isocentric proton gantry has to be able to rotate around the patient allowing all possible angle of incidence. This is necessary especially in cases where sensitive organs need to be avoided: like the spine or the cardiovascular system. The entrance to the gantry assumes that protons, within the kinetic energy range required for the treatment are between 65 KeV< E_k < 250 KeV, enter with zero

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offsets. The proton beam needs to bend upward above the patient and to return perpendicular to the patient. The transverse scanning requires for the transverse distances in both x and y directions a minimum distance of ±10 cm.

The first module of the proton gantry accepts all proton energies is achromatic. All energy orbits reach the maximum offsets at the middle of the first module where proton beams have zero slopes of the betatron and dispersion functions as shown in Fig. 5.

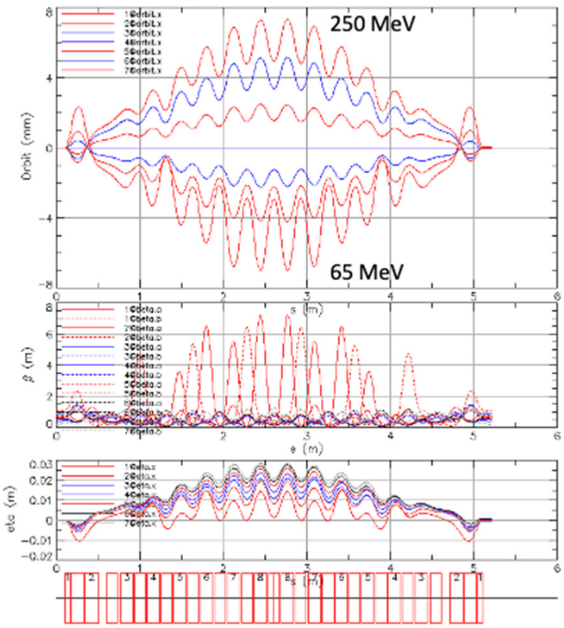

Figure 5: Lattice functions in the first achromatic gantry module with proton orbits between 65-250 MeV.

Geometrical presentation of the first achromatic module is shown in Fig. 6.

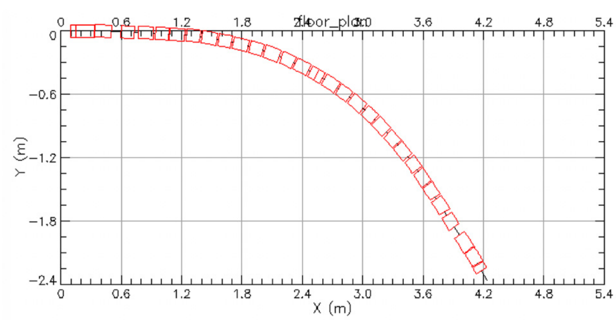

Figure 6: Layout of the first achromatic permanent magnet proton gantry module.

The next part in the optical gantry design is a matched FFA gradient arc. It bends the beam back into the perpendicular direction to the patient keeping the same structure and repeating the same FFA gradient cells. The last part of the gantry needs to merge again all the orbits to the patient into one, with horizontal and vertical betatron functions values as close as possible to 1 m. A distance of the last magnet to the patient is ~2 m. The transverse scanning system is made of two sets of magnets: the first following to the triplet magnets and the second above the patient, with a distance of ~1 m between their centers. The protons orbit oscillations within energy range of 65-250 MeV and their merging at the patient are shown in Fig. 7.

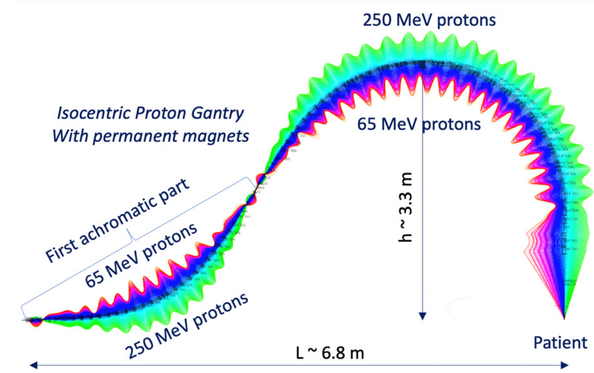

Figure 7: Orbits throughout the whole proton gantry up to the patient.

Major Components of the Gantry

The gantry has three basic modules: an achromatic beam line bending upward, an FFA-LG opposite bending arc bending directed to the patient and the third part where orbits of all energies are focused on the patient.

The scanning magnets are surrounding the permanent magnets. The value of the relative permeability of the permanent magnet material is very close to one and the superposition of the two magnetic fields one from the permanent magnets and the other from the surrounding iron magnets was clearly shown in the CBETA commissioning.

SUMMARY

There is a list of important advantages of the permanent magnet proton therapy gantry:

- Fixed magnetic field throughout the whole gantry. The only variable magnetic field comes from the scanning dipoles at the end of the gantry.
- The transverse scanning is significantly slower as the longitudinal energy scanning occurs for each radial position.
- Magnets are small and light made of permanent magnet material (NdFeBr).
- The large momentum acceptance: For the proton kinetic energy range between 65-250 MeV, corresponds proton propagation equal to 0.15 cm or 38 cm, respectively (depth after the Bragg peak position).
- Fast energy change without magnetic field variation.
- The patient treatment time is shorter as there is no need for a change of the gantry magnets.
- Significant reduction of the electric power bill as magnets are made of permanent magnet material.
- Overall cost is significantly reduced.
- The overall weight is significantly smaller.
- The rotating structure is significantly lighter, easier to construct with a cost reduction.
- Very easy operation – after commissioning no tuning necessary.

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