PERMANENT HALBACH MAGNET PROTON AND SUPERCONDUCTING CARBON CANCER THERAPY GANTRIES*

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Abstract

Hadron cancer therapy facilities are expanding exponentially as advantages with respect to other radiation treatments are localized energy deposition at the tumor and reduction of side effects. The main problem of expansion is the high cost and large size of the facility. The largest cost is the delivery systems, especially isocentric gantries. We present first, the permanent Halbach gantry with significant reduction in cost and simplified operation as all treatment energies are transported from an accelerator to the patient through the same Fixed Field Alternating Gradient (FFAG) structure. The superconducting FFAG gantry also transports at one setting all energies required for the cancer treatment of the patient with carbon ions.

Background

The Joint DOE-NCI Workshop on Ion Beam Therapy in Bethesda [1] January 9-13, 2013 made recommendations for the future delivery systems and gantries. In part the conclusions state: “When planning the design of a beam line for clinical use there are several parameters that need to be considered: Virtual-source-to-patient distance … A proper gantry design should be adaptable to a variety of accelerator system types and site constraints. The gantry design should include the design of the beam scanning system, which requires careful consideration of the tradeoffs between parameters described above. In particular, a gantry considerably smaller and less massive than the HIT version would be desirable. Several possible concepts for gantries exist. Typical design features include: Mobile and fixed isocenters; Large momentum acceptance (fixed-focusing alternating gradient magnets and achromatic designs); “Less massive and more compact beam delivery systems capable of delivering ion beams from protons up to carbon that are suitable for patient therapy; Technology that can provide for rapid (seconds) scanning of the beam over a tumor volume in three dimensions, that is both transversely and longitudinally; Beam diagnostic technologies for ion beam therapy, with emphasis on increased readout speed and accuracy of position and dose.”

The NS-FFAG optics use very strong focusing structures, with linear magnetic fields across the transverse aperture, in contrast to the non-linear radial field variation that is required in scaling FFAGs. All magnets are linear combined function magnets. Abandoning FFAG scaling allows the tunes and the chromaticities to vary with energy. The minimum horizontal beta function is found at the middle of the bending element in an NS-FFAG cell, just as it is in the light source lattices. This is the place where the orbit offsets are the smallest, being at the minimum of the dispersion function. The largest orbit offsets are in the focusing element, where both the horizontal betatron function and the dispersion function are at their maxima. We are reporting first on a new permanent Halbach magnet type technology already established at Brookhaven National Laboratory. Two types of the Halbach magnets have been produced and their magnetic properties measured and confirmed very high quality magnets as shown in Fig. 1.

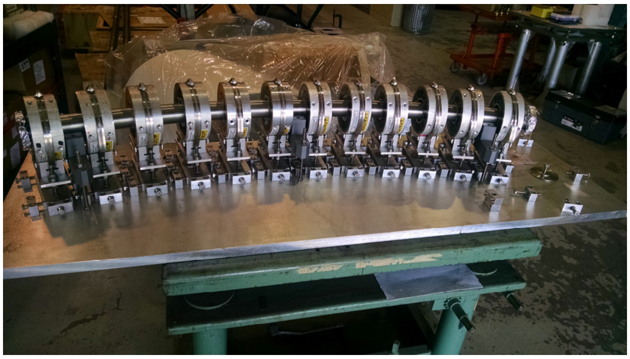

Figure 1: NS-FFAG with 12-magnet girder at BNL.

Permanent Magnet Proton Gantry Advantages

There are few significant advantages of the isocentric proton permanent magnet gantry with respect to other already available gantries:

- Significant cost reduction in construction and operation.
- Simplified operation with fixed magnetic field transport up to the scanning magnets from 65-250 MeV.
- Significant reduction in weight.
- Reduction in time of patient treatment as the magnetic field in the transport is fixed.
- Already established production technology

How are the 65-250 MeV Protons Transported?

The Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) structure [2,3] has ability to transport the beam of four times in momentum in a very small aperture. This is a very strong focusing structure based on a very small dispersion function $\Delta x = D_x \bullet \delta p/p$, where D_x is the horizontal dispersion function, Δx is the horizontal orbit offset, and $\delta p/p$ is the momentum range. Orbits in the proton permanent gantry are shown in Fig. 2. The gantry design for proton only is made of permanent magnet with a height similar to the state-of-the art PSI proton gantry [6], but with a dramatically reduced overall weight

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and volume, and with unprecedented energy acceptance of 30 to 250 MeV.

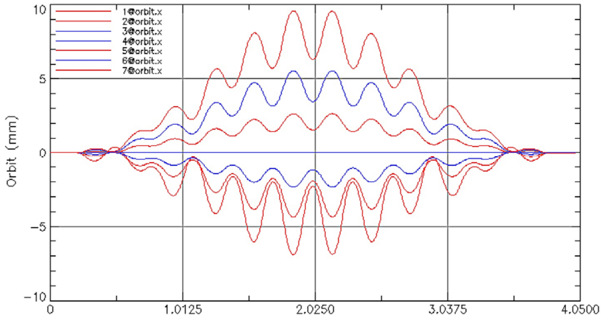

Figure 2: Orbit offsets in the first part of the gantry.

We will provide the complete gantry design as well as one gantry cell with of focusing and defocusing combined function magnets of the Halbach type.

Permanent Magnet Technology

S. Brooks [4] and N. Tsoupas [5] designed the Halbach type of the magnets. Two types of magnets were built, tested and assembled in the girder structure [4] during this year. The magnetic measurement results [4] are superb for the aperture required. The first type is the round structure shown in Fig. 3, while in the second type the same type of permanent magnet material blocks are held in the square aluminium holder. The NS-FFAG magnets are the combined function magnets. The kinetic energy range of the protons for the cancer therapy is between 65-250 MeV (or in the momentum range 355.25-729.1 MeV/c). The central proton energy is E_k=150 MeV or E=1.0883 GeV with -35.6%≤δp/p≤32.2% momentum range with the central momentum equal to p_o=551.3 MeV/c. The 12-magnet NS-FFAG girder, structure, with a momentum range of -66.7%≤δp/p≤44.5**%** is presently being tested as shown in Figs. 1 and 3.

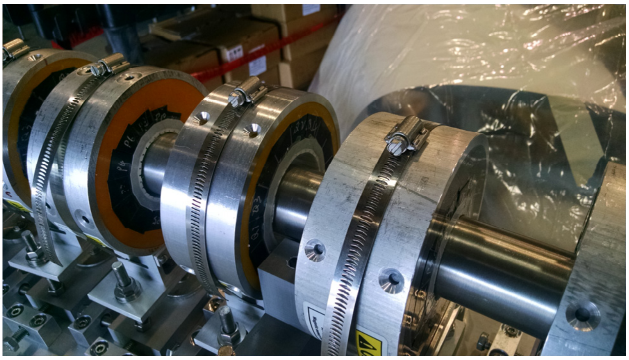

Figure 3: The focusing (in the middle) and the defocusing (left side of the figure) Halbach type magnets.

The regular NS-FFAG structure has a transition module where the orbits offsets of different energies are merged into one single orbit – the straight section in the two examples [6] the Energy Recovery Linac (ERL) at Cornell University-'CBETA' project and in the future proposed Electron Ion Collider in (EIC) in Relativistic Heavy Ion Collider (eRHIC) at Brookhaven National Laboratory.

A design permanent magnet proton cancer therapy gantry complete structure is shown in Fig. 4.

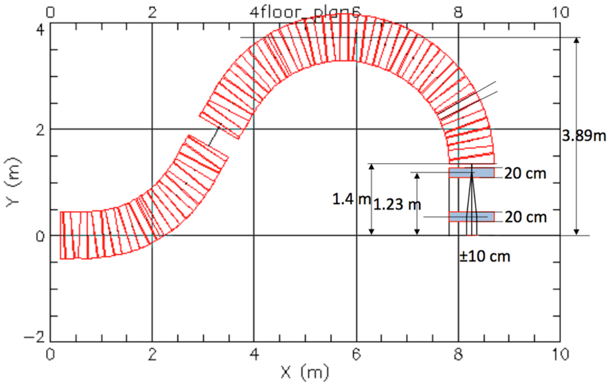

Figure 4: Permanent Magnet gantry with the scanning magnets. The height of the gantry is 3.89 m. The combined function magnet lengths are 14.9 cm and 13.2 cm for the focusing and defocusing magnet, respectively.

The defocusing magnet has a gradient of G_D=-137 T/m and the bending dipole field of B_Y=1.66 T. The focusing magnet has a gradient of G_F=152 T/m with a dipole field of 0.147 T. The inside radius of the focusing magnet is r_{IN}=13 mm, while the outside permanent magnetic block radius is r_{OUT}=5.8 cm, with a cross section area of 72.7 cm^2. The defocusing magnet inner radius is 9.1 mm, with the outside radius r_{OUT}=5.8 cm, with the cross section area of 70.8 cm^2.

Permanent magnet proton cancer therapy gantry represents dramatic simplification of the required therapy devices. The gantry is of the same size as the existing proton gantries but it is of significantly smaller weight, as the magnet sizes are much smaller. Magnets are fixed for all energies required for the treatment. It is the largest momentum acceptance gantry reported.

Superconducting Magnet Technology

We propose state-of-the art superconducting carbon/proton gantry (based on the principle of Fixed Field Alternating Gradient optics previously patented [2] will propagate ions with an unprecedented momentum range of -15% < Δp/p < 18% (with a kinetic energy range from 225 to 400 MeV/u or 128 to 225 MeV/u for carbon ions, or from 65 to 250 MeV for protons). This is the largest momentum acceptance reported for a carbon ion or proton gantry. The size of the carbon gantry will be dramatically reduced, with a maximum height of 3.8 m (compared to 5.7 m at the warm Heidelberg gantry [7], or 5.45 m in the Toshiba superconducting gantry [8]). The mass of the superconducting carbon gantry will also be dramatically reduced, thanks to much smaller magnet coils that are made of superconducting wire direct wind on the pipe. Superconducting magnets reduce the size and weight of the carbon/proton gantry. This proposal uses linear superconducting combined function magnets, based on the NS-FFAG concept, to simplify the procedure and treatment.

Only the scanning magnets vary quickly during therapy. The orbits in the main cell and dimensions of the magnets are shown in Fig. 5.

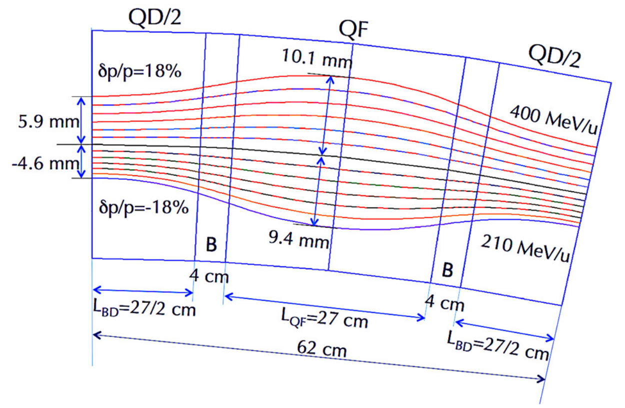

Figure 5: Orbit offsets for the Basic NS-FFAG cell for the carbon cancer therapy gantry.

Brett Parker design of the combined function superconducting gantry magnet cross section is shown in Fig. 6.

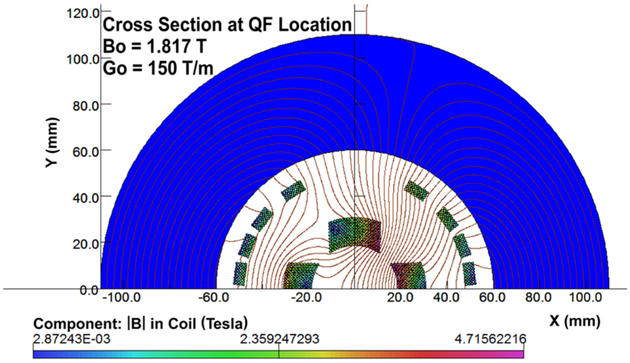

Figure 6: Brett Parker design of the superconducting gantry combined function magnet. The magnetic field shown is 1.82 T with the gradient of 150 T/m.

A method of winding the superconducting coils as well as the quadrupole coil for the combined function gantry magnet at Brookhaven National Laboratory – Superconducting Magnet Department is shown in Figure 7, while the dipole coil is shown in Fig. 8, and couple of first cells shown in Fig. 9.

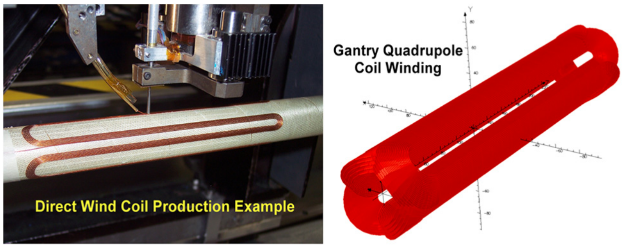

Figure 7: The winding of the superconducting coils at BNL together with the gantry quadrupole superconducting coil.

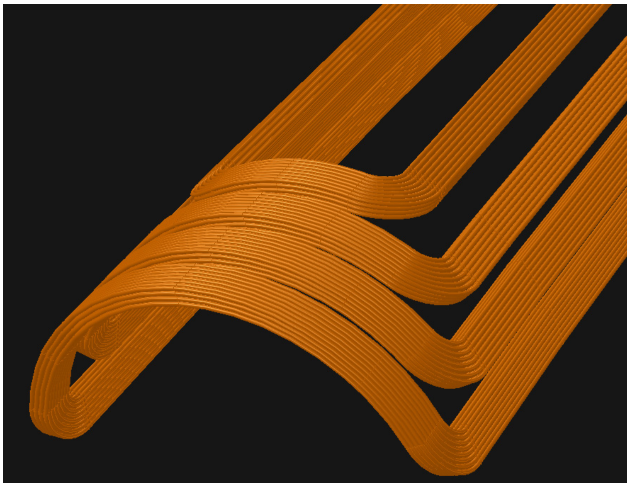

Figure 8: Dipole winding in the combined function-superconducting magnet.

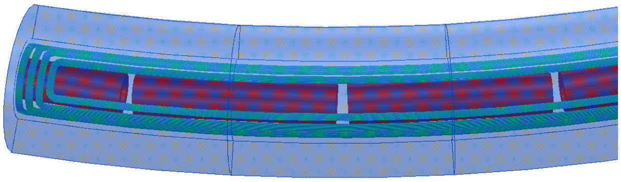

Figure 9: A part of achromatic superconducting carbon cancer therapy gantry.

SUMMARY

Two kinds of isocentric gantries are presented: the permanent magnet proton gantry with a kinetic proton energy range of 65-250 MeV and the superconducting carbon cancer therapy gantry with two operating ranges of the kinetic energy one with 194.5-400 MeV/u, and the second with 91.5-194.5 MeV/u. Major advantage of both gantries is the large momentum – energy range. The permanent magnet proton gantry is very close to reality as at BNL two kinds of Halbach type have already been built, measures and installed. We are showing very clear feasibility for building the whole permanent magnet gantry in a very near future. There is clearly a dramatic advantage of the permanent magnet gantry not to mention a dramatic reduction in cost.

REFERENCES

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