NON-SCALING FIXED FIELD ALTERNATING GRADIENT PERMANENT MAGNET CANCER THERAPY ACCELERATOR*

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Abstract

We present a design of the proton therapy accelerator from 31 MeV to 250 MeV by using racetrack lattice made of Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) arcs and two parallel straight sections. The magnets in the arcs are separated function Halbach type magnets. The dipole bending field is 2.3 T, while the Neodymium Iron Boron magnetic residual induction is B_r=1.3 T. The radial orbit offsets in the NS-FFAG arcs, for the kinetic energy range between 31 MeV < E_k < 250 MeV or momentum offset range -50% < δp/p < 50%, are -11.6 mm <x_{max}< 16.8 mm, correspondingly. The straight sections used for the cavities and single turn injection/extraction kickers and septa are with zero orbit offsets. The permanent magnets accelerator should reduce overall and operating cost. It could fit into 8 x 12 m space.

INTRODUCTION

Number of proton/carbon ion cancer therapy facilities is growing with an enormous rate. This is due to very clear advantage with respect to any other radiation therapies. Unfortunately, a price of the whole proton/carbon facility is still not affordable for many hospitals. For the delivery systems, the most expensive part of the ion therapy facility, we had already presented non-scaling Fixed Field Alternating Gradient (NS-FFAG) proton/carbon isocentric gantry designs with dramatic reduction in weight and reduction in cost. This time, we present a compact proton accelerator with the NS-FFAG racetrack lattice. The two arcs are made of Halbach type permanent separated function magnets, allowing proton acceleration from 30-250 MeV with small orbit offsets within the arcs through the whole energy range. Two matched straight sections are used for a single turn injection/extraction and acceleration purposes. Advantages of the accelerator with respect to the cyclotron are: variable energy without degraders (they introduce radiation and beam emittance blow-up), and the single turn extraction avoiding always present beam loss and residual radiation in cyclotrons. Fast acceleration rate represents advantage with respect to the synchrotrons making therapy treatments shorter allowing fast spot scanning technique.

NON-SCALING FFAG

The first results from the NS-FFAG have been shown at this conference during commissioning of EMMA (Electron Model for Many Applications) in Daresbury, UK [1]. The author had come to a concept [2] of NS-FFAG by using the relationship between the orbit offsets and dispersion function: $\Delta x=D\bullet\Delta p/p$, where $\Delta p/p$ is the difference in momentum. To reduce the orbit offsets to ±2 cm range, for momentum range of $\Delta p/p$~±50% the dispersion function D_x has to be of the order of D_x~4 cm, as 2/0.5= 4 cm. During the fifties a concept of scaling FFAG was developed theoretically as well as by building electron models of the proton accelerators. The fixed magnetic field has non-linear $B=B_o(r/r_o)^k$ transverse dependence. The transverse orbits in the magnets follow the momentum change as $p_o=eB_or_o$, $p=erB_r$, $p=p_o(r/r_o)^{k+1}$. There are many very advantageous properties of the scaling FFAG's: like zero chromaticity for all energies, orbits are parallel to each other for each energy, both tunes are fixed for all energies, very large available momentum with very large momentum acceptance, and orbits are isochronous (time of flight is the same for all energies). Unfortunately they require relatively large apertures. The author's first attempt to design a smaller aperture FFAG accelerator, with a large momentum acceptance, was by using the synchrotron light source lattices; by adjusting the magnet lengths in order to obtain a very small dispersion function $<H>$. Disadvantages of the NS-FFAG's are tunes, chromaticities, and path length variation with momentum. Advantages are very small aperture - small magnets. A comparison between the NS-FFAG and scaling FFAG is shown in Fig. 1.

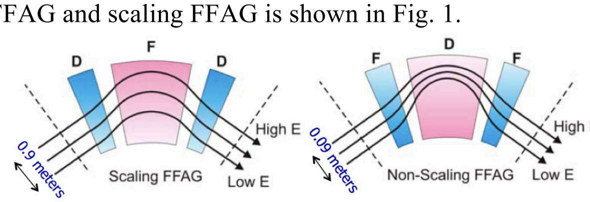

Figure 1. An illustration showing the major differences between the scaling FFAG and NS-FFAG's. The aperture in NS-FFAG is at least an order of magnitude smaller but orbits are not parallel to each other.

TRIPLET NS-FFAG

The NS-FFAG concept came as a consequence of a search for the cost effective solution of fast muon acceleration as they have very short lifetime. The NS-FFAG is proposed for muon acceleration. An example, with the combination of the triplet combined function magnets with drifts between them, large enough to allow placement of the RF cavities has been previously shown [7]. Most of the NS-FFAG designs have circular shape with accelerating cavities placed between either triplet or doublet magnets. There was a previous report by P.

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Meads on a straight section introduction in the scaling FFAG design [8].

Previous solution for the FFAG straight section

A problem of matching at different energies orbits, betatron functions to the zero dispersion straight using three combined function magnets. Additional details of the scaling FFAG solution shown in ref [8] are: bending angles of the 10^o -20^o $+10^o$ and the zero offsets in the horizontal plane are in the center of the straight section while the dispersion function is zero for all energies at the end of the triplets.

Design of the two arcs of the racetrack lattice

The lattice design for NS-FFAG cancer therapy proton accelerator is based on the properties of the permanent magnets and maximum achievable magnetic fields created by the Halbach structure. The recoil induction B_m [T] is the "magnetic induction that remains in a magnetic material after magnetizing and conditioning for the final use" [9].

The permanent magnet material considered in this application is Neodymium-Iron-Boron(Nd-Fe-B) sintered. A range of B_r nominal values offered sintered Nd-Fe-B varies between 1.06-1.5 T corresponding to listed names of materials as N2880-N5563, respectively. A material "N4561" was selected with a nominal value of B_r =1.35 T with a maximum operating temperature of 70^o C.

There is no upper limit for air gap flux density in Halbach dipole structure according to equation but in reality is limited by realistic size and demagnetization effects. The Halbach magnet made of 16 slices produced better quality magnetic field. A sketch of the magnet to use in the accelerator for proton cancer therapy is presented in Fig. 2.

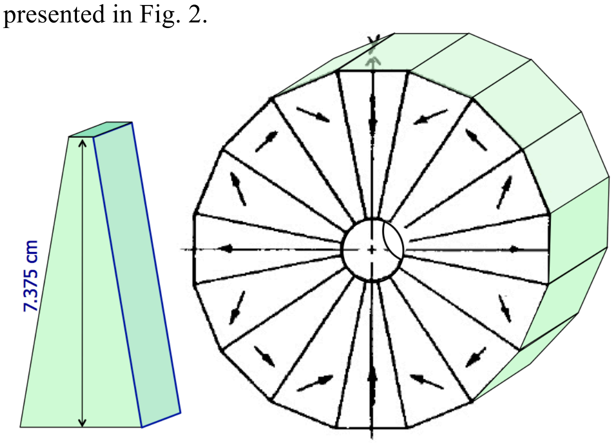

Figure 2. A sketch of the dipole magnet used in constructing the arc lattice for the proton accelerator.

For the inside radius of r_{ID}=3 cm and outside radius r_{OD}=7.375 cm, with B_r=1.35 T, the dipole bending magnetic field is estimated to be B_g=2.4 T.

ARC LATTICE

The combined function magnets in the NS-FFAG make always the most efficient way to make the very strong focusing structures creating the smallest dispersion function. This makes the largest momentum range with smallest orbit offset for the NS-FFAG's.

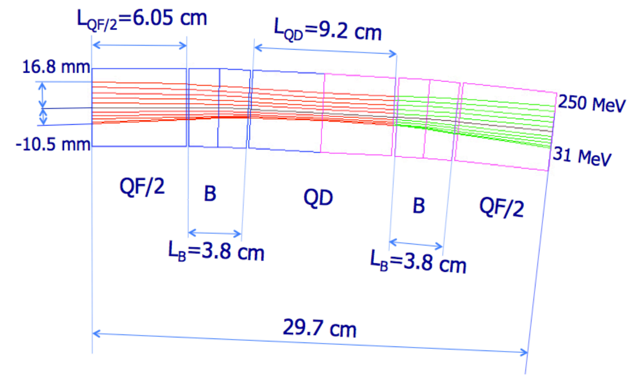

Figure 3. Basic cell of the NS-FFAG made of permanent magnets as presented in Fig. 2.

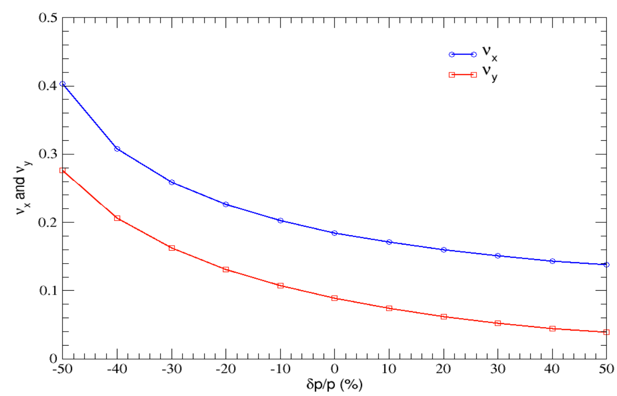

Figure 4. Tune variation with momentum

Due to difficulties in obtaining strong magnetic fields using the permanent magnets a separated function magnets are selected for the proton acceleration lattice.

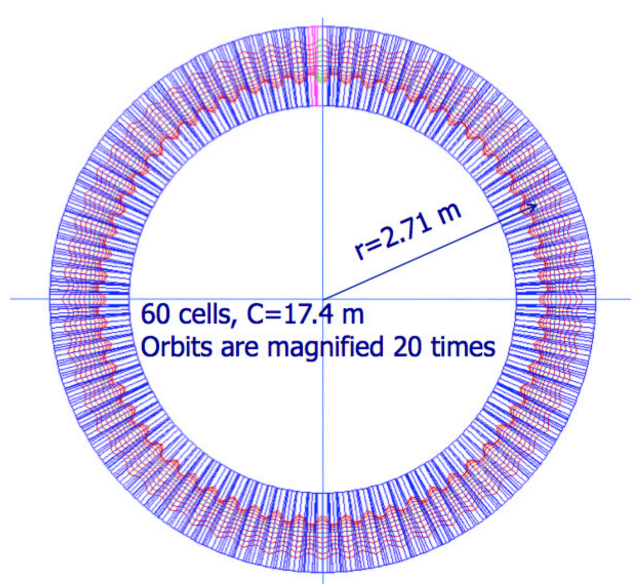

Figure 5. Ring made of 60 cells with permanent magnets. The orbits are magnified 20 times.

The basic cell with orbits, for the proton kinetic energy range 30-250 MeV, is shown in Fig. 3.

The time of flight in NS-FFAG used in non-relativistic applications is dominant by fast change of the relativistic factor 0.251<β<0.614 as the circumference changes due to parabolic dependence on momentum are much smaller. The tune variation with momentum is presented in Fig. 4.The betatron functions vary with momentum but their maximum values do not exceed 1.5 m, showing extreme focusing. Two arcs are made of the 30 cells. The ring is made of 60 cells. The closed orbits for energies in a range between 31 MeV to 250 MeV are magnified 20 times. The racetrack is made of two arcs with two straight sections one for injection/extraction and the other one for the RF cavities. The straight sections similar way as described in the [8]. A solution where combined function magnets were used at the ends of each arc is shown in Fig. 6.

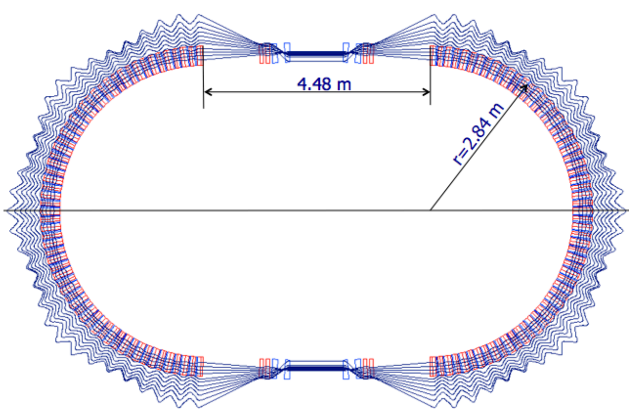

Figure 6. Closed orbits for 31-250 MeV in a racetrack.

ACCELERATION – PHASE JUMP

We apply the same solution for acceleration as previously reported [11]. Acceleration is performed by adjusting the RF phase each turn. The phase jump during acceleration with a fixed frequency has already been shown at CERN [12]. The RF frequency needs to be in a high range, ~370 MHz, because of the required large number of RF cycles between the passages of bunches, in order to achieve higher values of Q. The basic idea is to accelerate a train of bunches with a gap. During the gap the RF phase is adjusted so that when the bunch train next arrives the phase is correct for acceleration. The challenge is find a low level RF drive signal, which causes the cavity voltage to reach a certain target value during the gap. The solution is presented in Fig. 7. The bunch train fills half of the ring at the injection. We have modeled an RF cavity for proton acceleration to 250 MeV, the β value changes from injection 0.251 to 0.614 and the cavity impedance varies by a factor of three. At top energy R/Q = 30Ω throughout the cycle Q = 50 and f = 374 MHz, and the exponential decay time for the field is 43 ns. There is 80 ns time to change the cavity frequency when there is no beam.

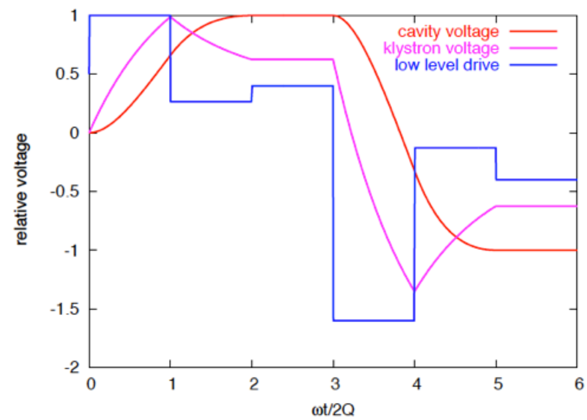

Figure 7. The full cycle with the cavity voltage (red) during the phase jump acceleration. The klystron voltage in shown in pink, while the low level RF drive is shown in blue color.

If the synchronous voltage is 22 kV, a number of turns required for acceleration of protons is N_{TURNS}=((250-31)*10^6)/(20 10^3/cav*N_{CAV})~800, for the N_{CAV}=12.

SUMMARY

Today most of the proton cancer therapy accelerators are cyclotrons or slow extraction synchrotrons. An example of racetrack NS-FFAG was described were fast acceleration is assumed with a total number of turns less then 1000 as the integer resonance crossing can be a problem. To simplify the application the permanent separated function magnets of the Halbach structure are proposed. The orbit offsets in the example presented are within a range 11 mm<Δx<17 mm. This allows use of an aperture of 30 mm. With the outside diameter of 7.375 cm from the available Nd-Fe-B (for temperatures less than 70 C) materials a bending dipole field of 2.4 T could be obtained. Advantage of the accelerator is very small magnets and simplified operation, as the magnets are permanent. Acceleration is assumed to be with a fast phase jump scheme where the voltage on the cavities is changed within one turn of the circulating bunch.

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