DESIGN OF A NON-SCALING FFAG ACCELERATOR FOR PROTON THERAPY*

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Abstract:

In recent years there has been a revival of interest in Fixed Field Alternating Gradient (FFAG) accelerators.[1] In Japan a number have been built, or are under construction. A new non-scaling approach to the FFAG reduces the required orbit offsets during acceleration and the size of the required aperture, while maintaining the advantage of the low cost magnets associated with fixed fields. An advantage of the non-scaling FFAG accelerator, with respect to synchrotrons, is the fixed field and hence the possibility of high current and high repetition rate for spot scanning. There are possible advantages of the non-scaling design with respect to fixed-field cyclotrons. The non-scaling FFAG allows strong focusing and hence smaller aperture requirements compared to scaling designs, thus leading to very low losses and better control over the beam. We present, here, a non-scaling FFAG designed to be used for proton therapy.

INTRODUCTION

Proton therapy facilities for treating cancer are becoming reality in many medical centers (Loma Linda University Hospital, in California, USA, Facility in Chiba-Japan, Tsukuba-Japan, Therapy Center at Massachusetts General Hospital in Boston-USA, Paul Scherrer Institute in Villligen-Switzerland, Heavy-Ion Research GSI in Germany, etc.). The newest 250 MeV scaling FFAG proton accelerator in Tsukuba, Japan has been commissioned. This report explores possibility for a proton therapy accelerator with a non-scaling FFAG. The small magnets due to smaller beam offsets during acceleration should be an advantage with respect to CYCLOTRONS or scaling FFAG's. Parameters for the proton therapy accelerator are described in Table 1.

TABLE 1. Proton Therapy Accelerator Requirements

	Injection	Top energy
E_k (MeV)	30	250
γ	1.0319736	1.26645
$\beta\gamma$	0.2548915	0.7771
p (MeV/c)	239.158	729.134

This report contains two types of non-scaling designs: a first one with fixed gradients in the elements, where betatron tunes vary within the basic cell between 0.4 < $\nu_{x,y}$< 0.1, and the second one with adjusted field profiles with dramatically smaller tune variations during acceleration. Details of the non-scaling FFAG developments are being described by an invited talk at this conference [2].

BASIC CELL PROPERTIES AT THE REFERENCE MOMENTUM

The basic cell properties of the two lattices are described at the lowest momentum and during acceleration. The reference momentum is set at injection, the lowest energy. The magnetic field has the smallest value. The basic cell consists of two types of combined function magnets. The defocusing magnet is a major bending element placed in the middle of the triplet as presented in Fig. 1. It is surrounded by two focusing opposite bend magnets. Detail properties of the magnets are presented in Table 2.

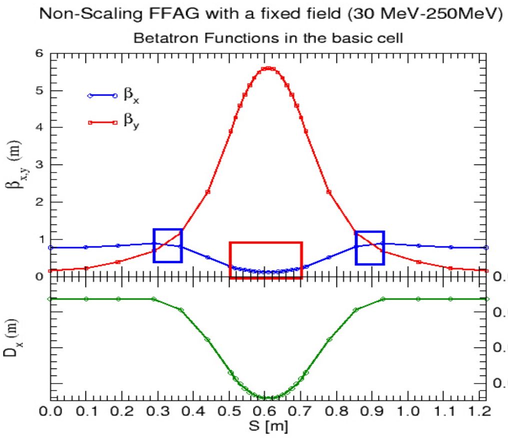


Figure 1. Betatron functions in the basic cell.

The betatron functions within the basic cell show that the dispersion function at the reference momentum has the maximum value of D_{max}=2.616 cm. The small aperture is a consequence of the small D_{max}.

TABLE 2.Magnet properties(fixed gradients lattice)

Combined magnet	F	D
Length (cm)	15	21
Bending angle	-0.0542	0.2931
Field (T)	-0.270	1.0628
Gradient (T/m)	19.265	-20.83

Layout of the ring

There are 34 cells and the ring is presented in Fig.2. The circumference is 42.2 meters, and one cell is 1.287 m long. A drift for the cavity is 0.58 meters long, while a distance between the magnets is 6.55 cm.

** Work performed under Contract Number DE-AC02-98CH10886 and DE-AC02-98CH10886 under auspices of the US Department of Energy*

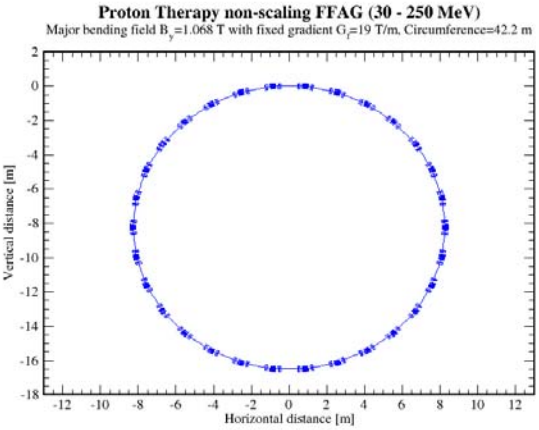


Figure 2. The whole ring of the fixed gradient lattice with 34 cells, C=42.2 m.

LATTICE FUNCTIONS DURING ACCELERATION

The optimization of orbit offsets and at the same time solutions with the stable tunes in the whole energy range is obtained by adjustments of the bending fields, gradients, and drift lengths. Orbits of the particle during acceleration are shown in Fig. 3. The orbits through the magnets are not parallel to each other as in the scaling FFAGs. It is important to note that especially within the major bending element orbits are not circular. The path of a particle with the reference momentum pass both sector combine magnets perpendicular to the entrance plane. As particle is accelerated, there is an edge effect from the planes of magnets.

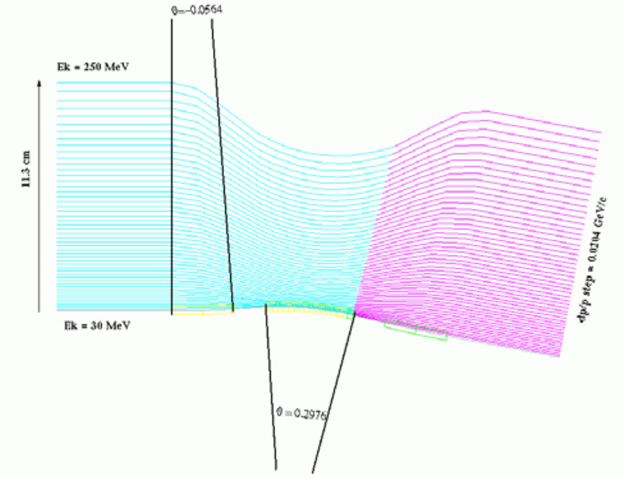


Figure 3. Orbits of particles during acceleration.

The initial momentum of p_o=194.76 MeV/c corresponds to the 30 MeV kinetic energy at the injection, as presented in Table 1. The horizontal betatron function depencence on momentum is presented in Fig.4. Stable solutions for the tunes in both horizontal and vertical planes calculated by the Polymorphic Tracking Code (PTC) are shown in Fig. 5.

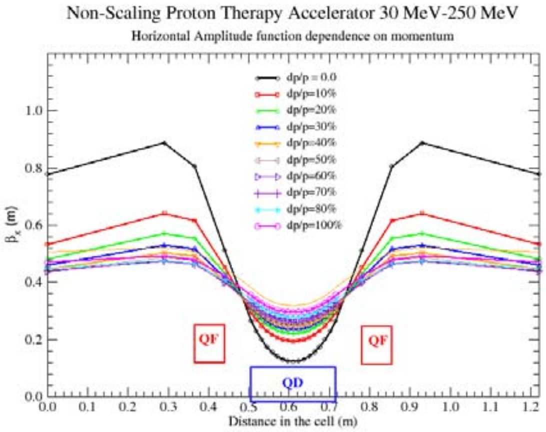


Figure 4. Horizontal amplitude β_x during acceleration.

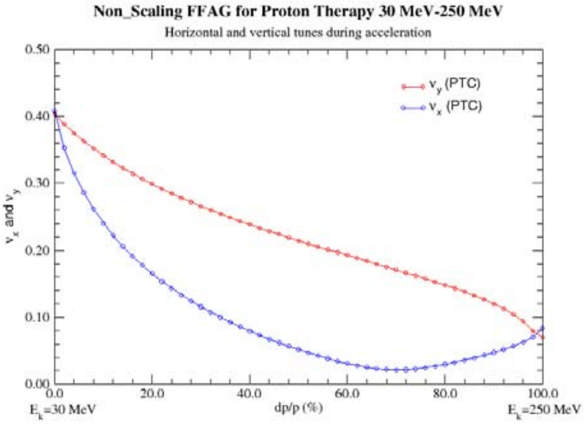


Figure 5. Horizontal and vertical betatron tune dependence on momentum.

LATTICE WITH ADJUSTED MAGNETIC FIELD PROFILES

An independent design of a lattice with similar properties was performed first with the fixed gradient and a special method was applied [3] to cancel the chromatic effect of the gradients of the two combined function magnets. The magnet properties are shown in Table 3. The reference momentum was again selected at the injection energy. The exact equations of motion had been shown before [3]. A correction the effect of the momentum deviation δ is provided by adjusting the magnetic index n – making the field profiles to cancel deviations.

TABLE 3: Magnets in “Adjusted field profile” lattice

	F	D
Length	0.175	0.350
Field (T)	-0.406078	0.950083
Gradient (T/m)	9.49977	-8.72587
Bending angle	-0.0977112	0.228611

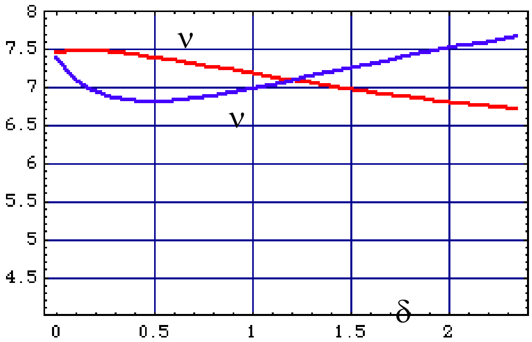
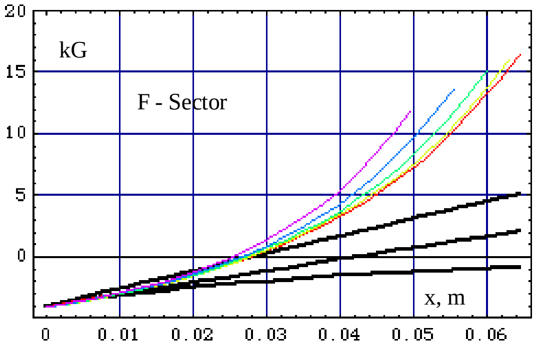


Figure 6. Horizontal and vertical tunes in the whole ring for the “Adjusted field profile“ lattice.

The field profile adjustments calculated by *Mathematica* is shown in Fig. 7



ACCELERATION:

Acceleration from 25 to 250 MeV is using the harmonic number *h*=8, with an energy gain with the peak RF voltage of 200 kV. A number of revolutions – turns is 2,250 with an acceleration period of 0.610 ms. The repetition rate is 1kHz. The RF frequency change during acceleration is shown in Figure 8.

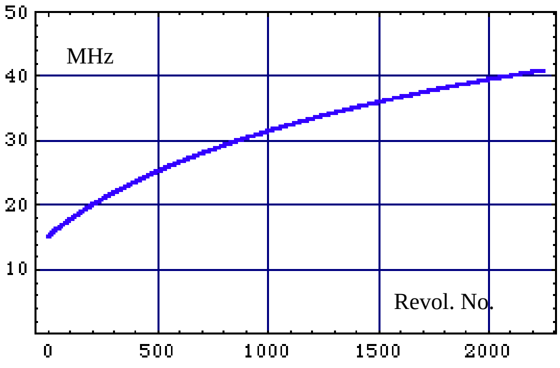


Figure 8. The frequency variation during acceleration.

The reference momentum is chosen at the injection energy with the magnetic fields set at lowest values. The magnet sizes are defined in the horizontal plane by the orbit offsets (the maximum offset is at the highest energy $x_{co\_max} < 8.6$ cm at the focusing combined function magnet and the drift for the RF cavity). In the vertical plane the beam size is defined by the size of the vertical amplitude function in the middle of the major bend. Because of the very low values of the magnetic field and modest gradients for the combined function magnets the use of permanent magnet looks attractive. These very small size magnets are to be compared to a cyclotron with a weight of a few hundred tons.

CONCLUSIONS

This report shows the feasibility of a non-scaling FFAG for a proton therapy accelerator with kinetic energy range from 30 MeV to 250 MeV. Two examples are presented: one with fixed gradients and the second with “adjusted field profiles”. The example with fixed gradient shows that the horizontal and vertical tunes vary within the cell between the half and full integer resonance. The overall tunes of the whole ring, in the lattice with “adjusted field profile”, have small changes: the tune in the horizontal plane between $6.5 < \nu_x < 7.5$, and in the vertical plane tune reached at the end of acceleration value $\nu_y \sim 7.7$. Crossing resonances is a vital aspect of these machines and the tolerances required for this purpose have not been examined in this paper. The maximum energy in the non-scaling FFAG could be easily adjusted by reducing the number of turns. The energy spread of the beam for the non-scaling FFAG is expected to be dE/E ~ 0.1%, which is at least one order of magnitude smaller than what is achievable in cyclotrons. The maximum energy in the non-scaling FFAG could easily be adjusted by reducing the number of turns. The non-scaling FFAGs can also be devised for other medical purposes. One possibility is a carbon therapy machine, similar to the proton therapy machine designed here. Another possibility is the production of radio-isotopes, which typically requires much lower energies than considered here. The Sloan medical facility in New York has been treating special cases of leukemia with α-emitters. These short-lived isotopes deposit large amount of energy to the cancerous cell and may become a therapy method in common use.

REFERENCES

[1] M. Craddock, CERN Courier 44 (#6), p.23 (2004).
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[3] A. G. Ruggiero, “Feasibility Study of a 1.5-GeV Proton FFAG in the AGS Tunnel,” BNL report CAP/148(2004).

100 keV/turn