SPIRAL FFAG FOR HADRONTHERAPY*

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Abstract

High repetition rate of the FFAG accelerator and compactness of the spiral type of the design makes it a good candidate as medical machine for hadrontherapy. The principle of the variable energy extraction, the lattice design and the beam dynamics simulations are presented. The spiral magnet design undertaken in the frame of the RACCAM project is briefly described.

INTRODUCTION

Rising tall of cancer cases in present day societies requires improvement of availability of the modern high technology based therapies, in particular of hadrontherapy. Recently the rebirth of FFAG (Fixed Field Alternating Gradient) accelerators resulted in several designs for medical facilities based on this principle [1,2]. The potentially high repetition rate (up to 100 Hz) of FFAG, which allows the use of the Bunch to Pixel treatment strategy together with the variable extraction energy enables to substantially simplify the operation of the medical accelerator comparing to conventional installations based on synchrotrons or cyclotrons. The design undertaken in the framework of the RACCAM French National Research Agency (ANR) project [3] focuses on proton machine as protontherapy has a big chance to become a radiotherapy of choice in the near future.

Here we give main properties of FFAG accelerators, which motivates an interest in using them as a medical machine:

- High repetition rate, which can translate into high dose delivery.
- Variable extraction energy.
- Simple and efficient extraction, which results in low machine activation.
- Compact size and low cost.
- Easy and stable operation due to constant magnetic field during acceleration

PRINCIPLE OF THE VARIABLE ENERGY OPERATION

The issue of variable energy operation for every medical accelerator complex is of primary importance, as the depth of the Bragg peak inside a human body, which should be located inside the irradiated tumor, depends on energy. The variable energy operation can be achieved in FFAG accelerators without the need for energy degradation, which limits the intensity and quality of the beam for the medical treatment.

We propose to achieve the variable energy operation of a medical facility based on the scaling FFAG in the following way:

- Injector delivers variable energy beam for injection into the FFAG ring. In particular this can be easily realised with the H^- stripping extraction in the injector cyclotron by varying position of the stripper [4, 5].
- The magnetic field is changed in the FFAG ring keeping the machine field index defined by $k=(dB/dR)/(B/R)$ unchanged. As machine optics in the scaling FFAG is dictated by the value of k and the machine geometry, the tunes will be conserved and the injection and extraction radii will be the same for all energies. This assumption is valid assuming very linear behaviour of the magnet, substantially far from saturation conditions. It is estimated that a fast slice to slice energy variability within about 1 s can be obtained with relatively modest ramping rate of 0.1 T/s.

In addition to the scheme described above the fast, even pulse by pulse energy variability can be achieved by installing addition extraction kicker. This method of the variable energy operation, being assumed as a baseline one in non-scaling FFAGs [6], is limited only to certain energy range in the case of scaling designs due to a larger orbit excursion in this machines.

SPIRAL FFAG RING DESIGN

Design constraints

The design of the medical machine for protontherapy within the RACCAM project is based on the following constraints:

- Spiral scaling type of FFAG accelerator was chosen due to compact size and zero chromaticity condition, which avoids resonance crossing during acceleration.
- Relatively small number of lattice cells was assumed (8, 10) in order to avoid fringe field dominated magnet design. On the other hand small number of lattice cells do not allow large field index values, which dictates rather large orbit excursion and increases the magnet weight. The cell number of 10

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is a compromise between the minimization of the magnet cost and the need for straight section length mainly for cavity placement and injection/extraction systems.

- Both injection and extraction are based on horizontal phase space because of relatively predictable behaviour of the horizontal focusing and dynamical aperture in contrast to the vertical plane. The need for multiturn injection in order to store beam intensity up to a few 10^9 protons dictates the horizontal fractional tune to be around 0.2 (0.8) in order to enable horizontal betatron stacking with typical 50 % efficiency in about 10 turns. Additional possibility of the combined horizontal-vertical stacking would result in similar constraint in the vertical plane.
- The choice of the packing factor was a compromise between the need for space in the straight section and small orbit excursion.
- Working point should be located well outside of the systematic resonances and characterized by good dynamic apertures in both transverse planes.
- Extraction energies between 70 – 180 MeV was chosen as a compromise between the medical needs and injection/extraction momentum ratio of 3.4. The corresponding injection energy range is 6-17 MeV.

Table 1:Parameters of spiral FFAG ring.

Number of cells	10
Injection energy range	6-17 MeV
Corresponding extraction energy range	70-180 MeV
Injection type	multiturn by betatron stacking
Extraction type	fast with kicker
k	5.15
Spiral angle	53.5º
(Q_H, Q_V)	(2.8, 1.6)
Packing factor	0.34
B_{max}	1.7 T
R_{max}	3.46 m
R_{min}	2.84 m
Harmonic number	1

The Fig. 1 shows betatron function and dispersion in one lattice cell and its several parameters are listed in Table 1.

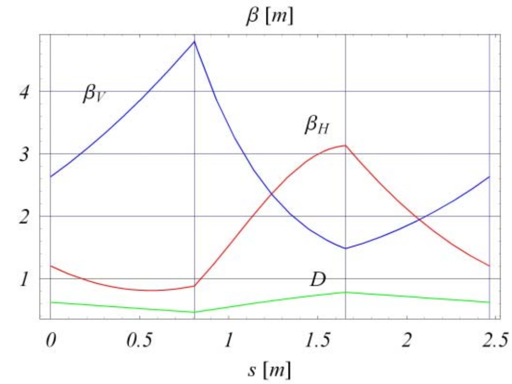

Figure 1: Horizontal and vertical betatron (β_H, β_V) functions and dispersion D in one cell of the spiral FFAG ring.

BEAM DYNAMICS SIMULATIONS

In order to simulate the beam dynamics in a complicated geometry of the spiral FFAG, substantial development was performed in the Zgoubi tracking code. It enables tracking in geometrical models of spiral FFAGs [7]. In particular an automatic procedure for scanning machine parameters like k and spiral angle was developed to study working points and their associated dynamical apertures [8]. Fig. 3 shows the typical result of such a scan. Out of this study several working points were chosen for modelling with the Opera 3D magnetic code. Then tracking in 3D field maps was performed for energies between injection and extraction.

Immediate output of this work was definition of the vertical tune problem, which shows up as a big vertical tune change during acceleration crossing several resonance lines. This tune excursion cannot be tolerated and the goal is to achieve a design of the spiral scaling FFAG with constant tunes.

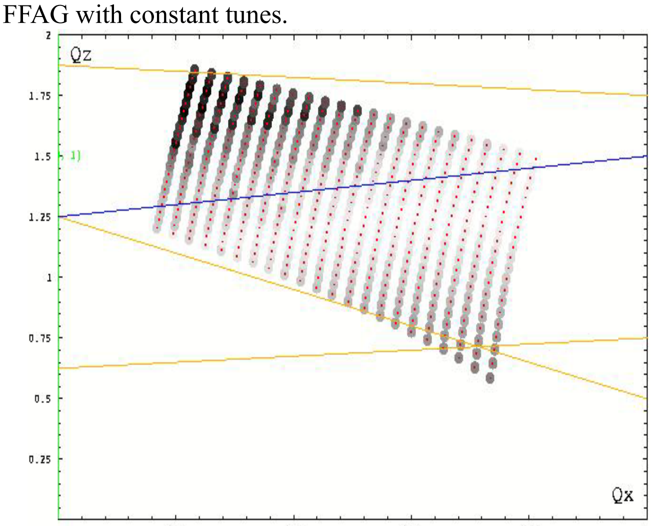

Figure 2: Horizontal dynamical aperture scan in the tune diagram. Points with large dynamical aperture are marked with dark points.

BASICS OF THE MAGNET DESIGN

Two types of magnet design were considered for the spiral FFAG ring: based on usual “gap shaping” technology performed at SigmaPhi [9] and “parallel gap – distributed conductors”, where the scaling field low is produced by independently powered series of conductors distributed on magnet poles [10]. In spite of smaller vertical tune shift due to parallel gap assumption design with distributed conductors showed large field under/overshoots. Below we focus on the “gap shaping design”, which was chosen for a prototype construction.

Gap shaping design

An iterative approach was developed in OPERA (version 11) to carry out the magnet design.

An automated 2-D iterative process determines the needed pole shape in the magnet mid-plane. Then a 3-D spiral magnet model, based on the previous gap shape law, is automatically constructed. After computation, vertical B field values in the magnet center at every radius are obtained. The difference with the theoretical radial field law is then used as input to another series of 2-D automated calculations, which leads to the determination of a new pole shape. A new 3-D model is generated, and so on. This iterative process converges after about 2 or 3 iterations to a relative field quality better than 1.10^{-4} in the good field region.

The magnetic spiral shape is also corrected using a 3-D iterative process. Vertical B field integral is calculated in 3-D models along reference trajectories (particle trajectory in smooth approximation) on each side of the magnet. The mechanical spiral is then bent to obtain the right effective length at each radius, and thus the right magnetic spiral shape. But this process is not assisted by rapid 2-D iterations and takes between 6 and 9 iterations to converge to a relative precision of 1.10^{-3} on effective length values.

In order to get a constant vertical tune, we need to adjust the fringe field extend, which should be proportional to the machine radius for perfect scaling.

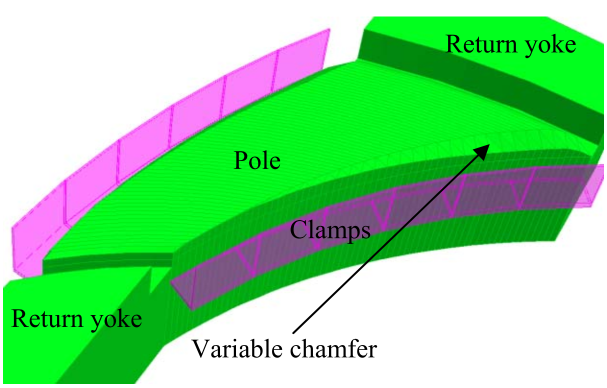

Figure 3 – OPERA 3-D Model of a spiral gap shaped magnet with variable chamfer and field clamps.

The decrease in fringe field extent due to the gap narrowing is compensated by an increase in chamfer height and by application of clamps.

Tracking with Zgoubi code has validated this solution (see *Figure 4*), vertical tune variation has been reduced by a factor 2.

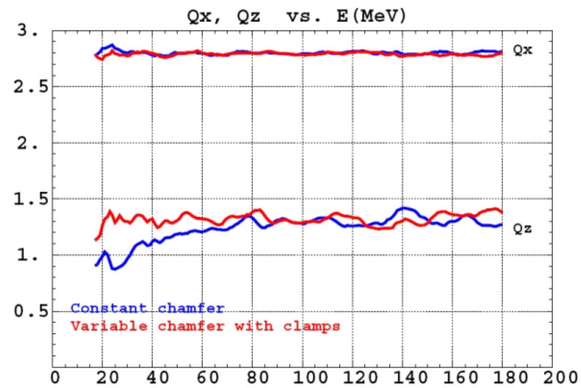

Figure 4 – Horizontal (Qx) and vertical (Qz) tune versus Energy (MeV) from tracking in 3-D field maps.

SUMMARY

Substantial progress have been achieved towards the design of a variable energy spiral scaling FFAG accelerator for hadrontherapy within the RACCAM ANR project. The ring parameters have been investigated and the method to design the spiral magnet fulfilling the scaling properties, in particular zero chromaticity condition have been established. Work will continue towards the magnet prototype construction and hopefully in farther future towards the demonstration machine.

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