A NOVEL SOLUTION FOR FFAG PROTON GANTRIES

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Abstract

In the recent years FFAG gantries have been studied for medical applications, but none has so far been realised. The FFAG solution would reduce the complexity of beam line set-up, its weight and therefore the cost of the rotating support, in particular for heavy ions. The Imperial College London is using the experience gained in the Pamela Project and in the design and commissioning of EMMA to work on a solution of a non-scaling FFAG gantry, which could potentially fulfil the full requirements for the spot scanning - parallel beam treatment technique, and provides an easy interface to the upstream accelerator. The preliminary results will be presented in this paper.

INTRODUCTION

The research on Fixed Field Alternating Gradient (FFAG) accelerators was restarted after long period of silence in recent years, which triggered the successful construction and operation of several scaling machines in Japan and the world's first linear Non-Scaling one - EMMA [1] in the UK. Following these vigorous progress it was proposed to apply the FFAG principle for next generation hadron therapy machines [2] aiming to reduce the cost of treatment by utilising the very strong focusing and high repetition rate offered by FFAGs to make the machine dimensions more compact and the treatment time shorter.

In modern hadron therapy applications it is preferred to use the gantry as the final beam transport system, which allows to precisely vary the beam angle at the patient in the large range simultaneously allowing to carefully control the beam spot size and position in the spot scanning. Although the existing gantry solutions (non-FFAG type) have been constructed and are in operation, they consist of room temperature iron magnet system with a very large weight and overall dimensions, which is a significant fraction of the total cost of the facility.

FFAG solutions for proton and carbon gantries have been proposed [2, 3], which allow to greatly reduce the size and weight of the gantry by using superconducting magnets. Stable particle orbits exist in such gantry for the broad momentum range eliminating a need for magnets' ramp or requiring to ramp only between small number of operational regimes, which offers an opportunity to reduce the treatment time. Thus FFAG gantries will contribute in decreasing the cost of modern hadron therapy facilities. It may be fed by any conventional medical accelerator including cyclotron or by a future medical FFAG.

FFAG gantries studied so far were based either on linear non-scaling magnets, scaling ones or such that break only partially the scaling law. This paper describes a novel gantry type using nonlinear non-scaling FFAG magnets, which explicitly violates the scaling law maintaining the zero-chromatic condition.

NONLINEAR NON-SCALING FFAG GANTRY DESIGN

Requirements and Assumptions

As the starting point of the study the classical shape of the gantry is assumed, in which the beam is firstly deflected outwards from the common incoming beam/patient axis, which also serves as gantry axis of rotation. Secondly the beam is deflected in opposite direction cancelling the initial negative angle and finally bending by the final 90° pointing at the patient. If this configuration is rotated using the incoming beam as the axis of rotation, it allows for the full flexibility in the choice of the treatment angle in a very broad angular range.

As the goal a gantry for proton therapy was chosen as it allows an easy comparison with other existing gantries and can be further extrapolated to a carbon case. It was also decided that the operation energy range of 100-200 MeV is potentially interesting especially for applications in paediatrics and is also quite ambitious at the start.

To simplify the orbit matching in the presence of rotation for different energies, zero dispersion condition is preferred at the input of the gantry. To avoid any correlations between the beam position and energy, zero dispersion at the patient is also required. The identity matrix is needed as the total betatron transfer map through the gantry, which will allow to set the particular condition required for treatment downstream the gantry in the non-rotating part and transparently reproduce it at the patient position simplifying the gantry operation.

Linear Optics Design

In order to minimize the orbit excursion in an FFAG many short cells are required with a very strong focusing. As the compromise between the orbit excursion, the maximum value of the magnetic field and space constraints in the magnet design, the design of the first bend consists of 8 identical FDF triplet cells, with the total deflection angle of -72°. As the preliminary studies showed that zero dispersion is preferred also at the end of the negative bend section as it minimises the orbit distortion downstream, the phase advance of $\pi/2$ rad per

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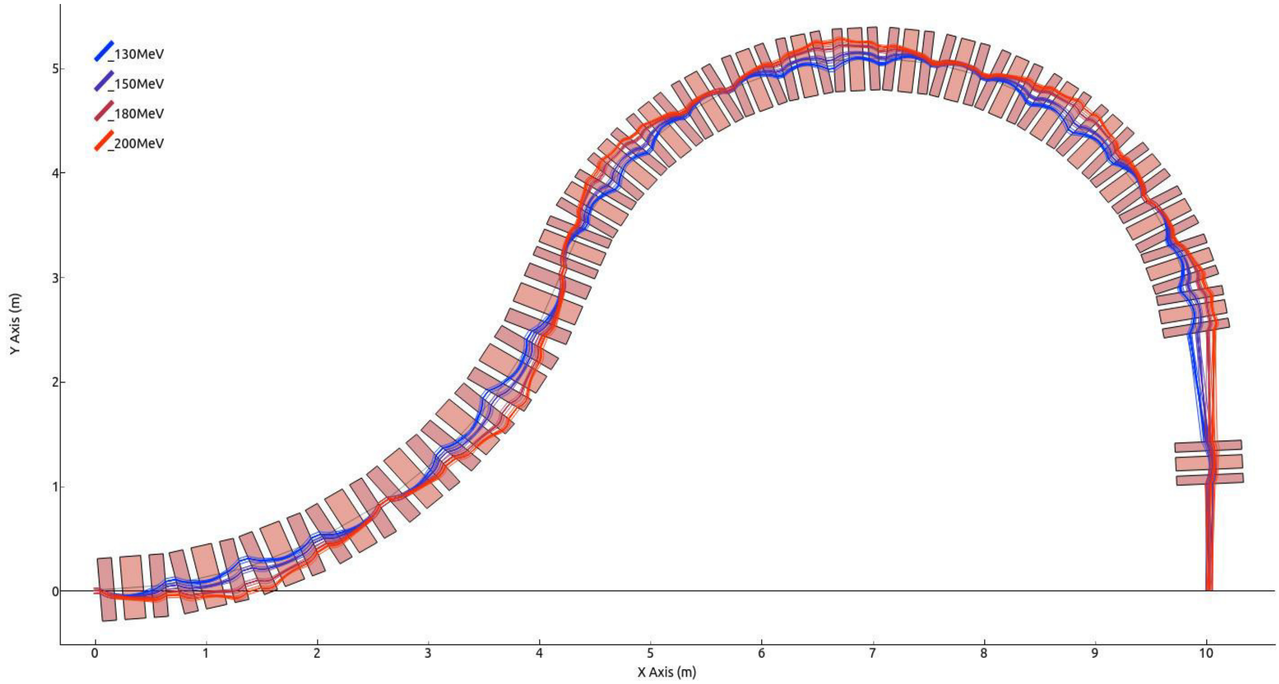

Figure 1: The layout of the novel FFAG gantry. The orbits for different energies and magnets have been 10 times enlarge for visibility. The zero dispersion condition can be clearly seen at the end of the first bending section and at the end.

cell was set in the bending plane to allow this condition; 3π/8 rad per cell was chosen in the non-bending one.

The next downstream bend section deflects the beam by 156.6° and consists of 17 identical FDF triplet cells. The value of deflection angle and the choice of the phase advances per cell (1.339 and 0.609 rad in bending and non-bending planes, respectively) have been adjusted to take into account the need to accommodate the final cell focusing the beam to the patient position, providing space to place scanning magnets and diagnostic tools, and allowing the magnetic field to practically decrease to zero at the patient position. The final cell is also of FDF triplet structure and it accommodates long straight sections of 1m in length. The additional constraints are such that the symmetric betatron functions and dispersion need to be the same as in the downstream section to assure the correct matching of the dispersion and the transparent character of the entire gantry. It sets the values of the phase advances in the final cell and together with the need for the total deflection of the gantry to be equal 90°, it fixes the value of the deflection in the final cell.

The layout of the gantry with all three cell types and long straight sections in the final cell are shown in Figure 1.

Nonlinear Optics Design

In order to avoid ramping the magnets optical conditions described in the previous section need to be preserved in a broad momentum range. In order to achieve it, the chromaticity correction is performed adjusting the phase advances in three points: at the central energy and two points close to the boundaries of the selected range (100-200 MeV) both in the bending and non-bending planes. In fact all 3 cell types are considered as periodic and the symmetry condition for the orbit is assumed. Multipole field components: dipole, quadrupole, sextupole and octupole ones are found numerically in the triplet magnets to fulfil the zero-chromatic condition in a broad momentum range. In addition the central orbit is controlled in two symmetric points to keep it centred in the vacuum chamber and to improve the stability of the numerical procedure. The resulting phase advances per cell are shown in Figure 2. The required total magnetic field obtained by summing all multipole components inside the transverse aperture, which was estimated to be about 6 cm is presented in Figure 3. The magnets assumed in the gantry would be of the superconducting type and rectangular in shape with the maximum field strength up to 4 T. Although the shortest magnet required would be only of 8.5 cm in length, it seems to be feasible. Table 1 shows the summary of the main parameters of the novel nonlinear non-scaling gantry.

Table 1: Main Gantry Parameters

Parameter	Value
Radius of the main arc [cm]	300
Proton energy range [MeV]	100-200
Max B field [T]	4
Betatron phase advance (H, V)	(12 π, 7 π)
Total number of magnets	78
Min magnet length [cm]	8.7
Magnet radius [cm]	~3

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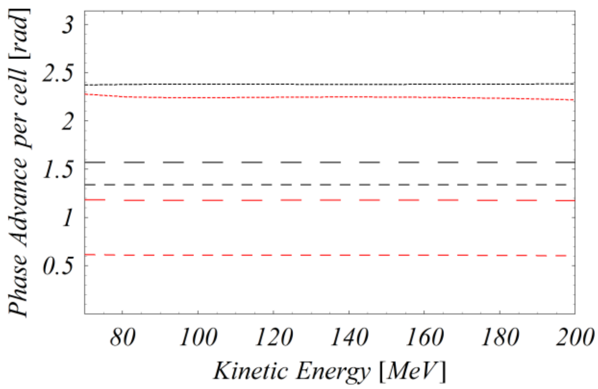

Figure 2: Phase advances per cell after correction for the first, middle and the final lattice cell types as a function of proton energy are shown using lines with decreasing order of dashing. The black and red lines correspond to bending and non-bending planes.

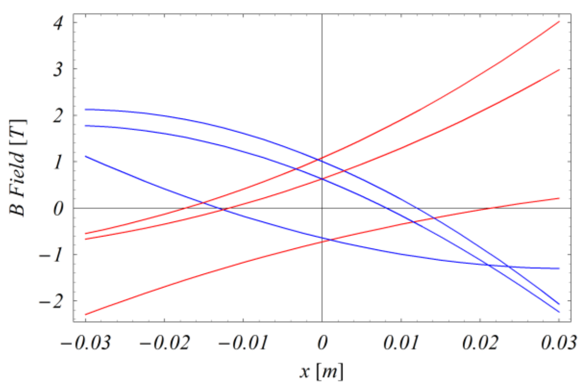

Figure 3: Total magnetic fields in all 3 lattice cell types (all 6 magnet types) within estimated aperture. Red and blue lines correspond to F and D magnets, respectively. The strongest field is required in the middle section, a bit weaker in the final cell. The different sign of deflection angle can also be seen in the magnets with the lowest fields. All magnets violate the scaling FFAG law.

TRACKING STUDIES

Tracking studies were performed in the designed gantry using Zgoubi [4, 5] and Elegant [6] codes. Results obtained with Zgoubi are presented in Figure 1, showing the orbits for different energy, while Figure 4 and 5 are showing the final phase spaces. The gaussian particle distribution with rms normalized emittance of 5π.mm.mrad was assumed. Some nonlinear distortions have been observed especially in the vertical plane, which are present only after beam passes the final cell, which may be due to a specific choice of the phase advance in that cell.

The results obtained using Elegant agreed on the middle momentum, however certain discrepancies have been observed for the off-momentum motion. It was identified for instance, that the current version of the code does not support octupole components in the combined function elements, while Zgoubi has this capability.

CONCLUSIONS

These results show that a nonlinear non-scaling FFAG gantry could be suitable for use in proton therapy. The principles of the design: the transparent beta propagation, zero dispersion and good beam transmission have been obtained. Further optimization to decrease the size and improve the final cell configuration will be performed. The gantry shown here would require superconducting magnets, which design needs still to be addressed.

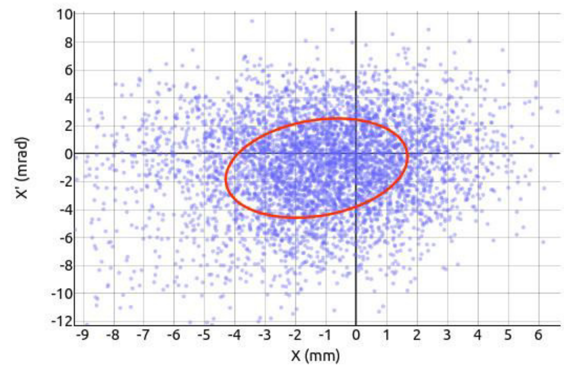

Figure 4: X-X' phase space at the end of the gantry obtained using Zgoubi at 150 MeV. Red ellipse corresponds to the rms geometrical emittance.

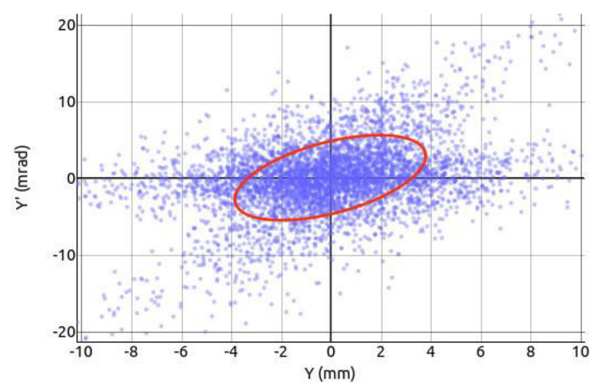

Figure 5: Y-Y' phase space at the end of the gantry obtained using Zgoubi at 150 MeV. Red ellipse corresponds to the rms geometrical emittance.

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