A NON-SCALING FFAG GANTRY DESIGN FOR THE PAMELA PROJECT

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Abstract

A gantry is required for the PAMELA project using non-scaling Fixed Field Alternating Gradient (NS-FFAG) magnets. The NS-FFAG principle offers the possibility of a gantry much, lighter and cheaper than conventional designs, with the added ability to accept a wide range of fast changing energies. This paper will build on previous work to investigate a design which could be used for the PAMELA project.

INTRODUCTION

The PAMELA (Particle Accelerator for MEdicaL Applications) project [1] aims to design a Charged Particle Therapy machine that will be compact and affordable enough to be used in hospitals to treat some forms of cancer.

Like the main PAMELA accelerator, the gantry must accept a large range of energies and cope with very fast switching between them. The optics of FFAG type magnets offer this possibility, so this paper will build on existing work on FFAGs [1] and seek to design a gantry for the PAMELA project.

REQUIREMENTS

The very basic requirement of the gantry is to deliver a beam from 360° around the isocenter without distorting the beam. To help achieve this, there can be no dispersion at the entrance (point A in fig.1). This is a problem because, as this is part of the PAMELA project, another requirement is that rectangular FFAG type magnets must be used in which the horizontal position depends on momentum. The field profile of these magnets is given by the scaling law[2]:

$$\frac{Bz}{Bz_0}=\left(\frac{y}{y_0}\right)^k \tag{3}$$

Where y_0 is the radius of curvature of the magnet, y is the horizontal distance from it, Bz_0 is the vertical field at y_0 and Bz is the vertical field at y. k is the field index which controls how quickly Bz rises with y.

The spread in horizontal position also has to be reduced at the end of the gantry, but anything up to 5cm is acceptable there. The overall height of the gantry should be kept to a minimum because in a treatment centre, height is more expensive than length or width. However, 1.5m is required between the end of the bending magnets and the iso-centre for the scanning magnets and the patient. The momentum range required is 0.369 to 0.729 GeV and this paper only considers protons.

BASIC DESIGN

To create the elevation and 90° bend required in a gantry, the initial design strategy was to take three quarters of a ring and flip round the bottom quarter [3]. An example layout is shown in Fig.1 where 75cm long triplets with bends of 22.5° and long drifts of 50cm are used. Points A, B and C mark where dispersion suppression is required. A and C were discussed above, but dispersion suppression at B is required because the change in the sign of curvature means that the particles have to swap to the other side of the magnet.

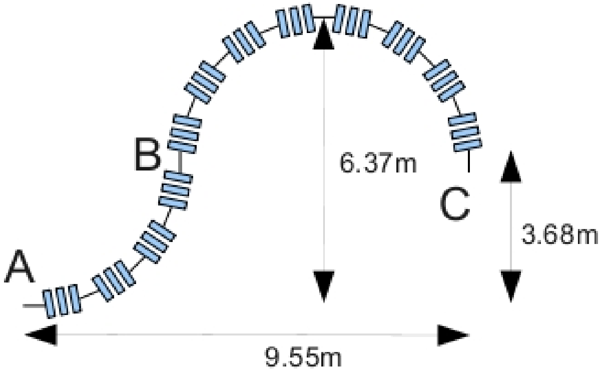

Figure 1: Basic layout of an FFAG gantry.

Dispersion suppression in an FFAG is achieved by making use of the betatron oscillation of a particle around its equilibrium orbit. A particle with a horizontal position y_1 and y' = 0 can be bought to a position y_2 with y' = 0 by going through a π phase advance with the equilibrium orbit set half way between y_1 and y_2. In an FFAG, the horizontal positions of the equilibrium orbits with respect to y_0 (eq.3) can be halved for all energies by doubling the field index 'k' and so dispersion suppression can be achieved [4][5].

For this reason, the basic gantry was designed to have a 2π phase advance in the 'double k' cells between points A and B, then a π phase advance in the next two cells, followed by four 'normal k' cells and two more 'double k' cells to suppress the beam at the end.

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CHALLENGES

Although this gantry can deliver equilibrium orbit particles there are a few problems with this design that need addressing. Firstly, it is too tall needing around 13m to be rotated through 360°. Secondly, because the dispersion suppression makes use of fields with high 'k' and wide amplitude betatron oscillations, the peak field can become too high. Also, because the effective gradient varies along the paths of the oscillating particles, the beta functions become inconsistent over the momentum range and reach very large values by the end of the gantry.

The height could be reduced by taking out cells either side of point B. In fact, only the final bend needs to be 90°, which means the height is constrained by the 1.5m clearance plus the height of the final bend. This also helps reduce the field in the dispersion suppressors of the first section as well as the bending, which could have a beneficial effect on the beta functions.

DESIGN STRATEGY

The design of this gantry has to begin with the final 90° bend. How it is achieved determines the overall height of the gantry and constrains the characteristics of all other sections. So the starting point has to be an FFAG cell with the largest bend possible in the smallest space. After that is set, the cell that makes up what is left of the 90° bend should also act as a dispersion suppressor for point C. Thankfully, this doesn't have to be as good as at points A and B and can be done in a single cell.

Next, a scheme has to be worked out to go from zero dispersion at point B to the closed orbit positions in the large bending magnet. Then, the entrance section can be designed with the opposite total bend, a height to make sure the clearance at C is 1.5m and dispersion suppressors at either end.

Table 1: Gantry specifications by section

	Section 1	**Section 2**	**Section 3**	**Section 4**
No. Cells	3	4	1	1
Bend Angle	10	7.5	60	30
Phase advance	2π/3	π/2	na	π
Field index 'k'	2.23	3.69/7.38	3.69	5.72
Magnet Length (cm)	66.66	37.5	45	45
Maximum Aperture (cm)	29.3	20.75	32.59	22.08
Field at Maximum Aperture (kG)	9.28	-21.49	38.78	31.57

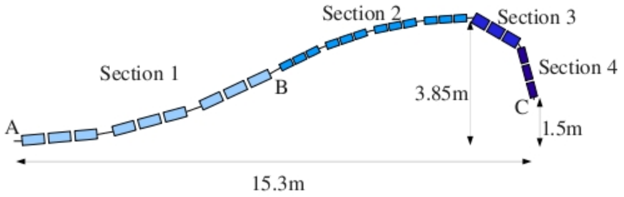

Figure 2: Schematic of new gantry design.

NEW DESIGN

A schematic of the new design is shown in fig.2 It is split into four sections with four different cell designs summarised in Table 1.

The final 90° bend is split 60 / 30 between two triplet cells with a 'k' in section 3 as high as possible to reduce the aperture. The 'k' in the final section is increased until the horizontal spread is about 3cm, the phase advance is as close to π as possible but Bz is too high.

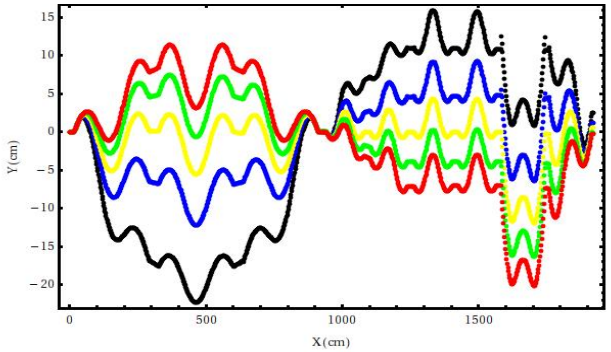

Figure 3: Tracks through new gantry design. The colours represent momenta from 0.369 GeV/c to 0.729 GeV/c.

So that the equilibrium positions match into the 60° bend, the normal 'k' in section 2 equals that in section 3. Because 'k' is then set, the phase advance achievable in section 2 is limited. A π/2 phase advance per 'double k' cell was settled on giving 30° bending across 4 cells.

The bending in section 1 had to be the opposite of section 2, but because k was not constrained, I decided to use as few magnets as possible and create a 2π phase advance over three cells. The lengths of the cells and drifts were used to make the section the correct height.

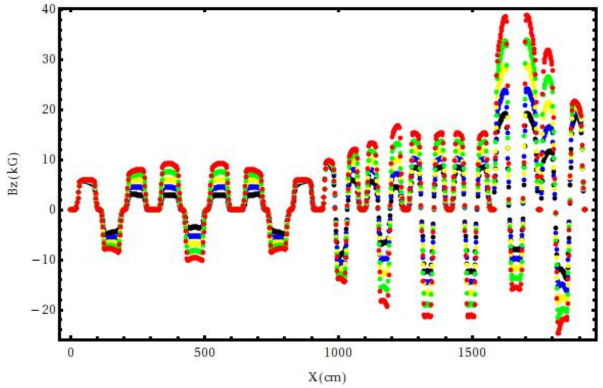

Figure 4: Vertical field through new gantry design.

The tracks through the gantry can be seen in fig.3, the fields in fig.4 and the beta functions in fig.5. The latter were found by assuming that the beam is rotationally symmetrical at the entrance (i.e. horizontal β = vertical β and both α = 0).

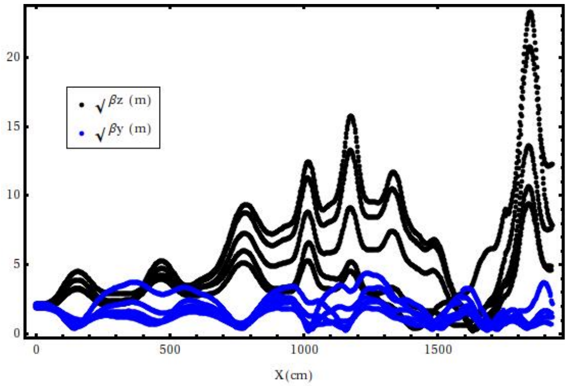

Figure 5: Beta functions.

CONCLUSIONS

This design is approaching a workable solution, and is certainly an improvement on the basic design. However there are some issues for further investigation:

The magnet in section 3 is probably still unrealistic. This could be resolved by decreasing the bending slightly, or increasing the length of the magnets. Decreasing the bend would be preferable, because this would bring down the height of the gantry, however, care must be taken not to increase the field in the final section too much.

The beta functions are too large at the end of the lattice. A lower phase advance per cell in section 1 would help, or a series of non-linear magnets could be designed to control the vertical growth in beta at point B, where dispersion is zero. The latter option may prove overly complicated, and both options add to the height of the gantry.

Despite these issues, this paper has set out a design strategy which will find the smallest FFAG gantry possible for this momentum range.

REFERENCES

[1] K. Peach et. al., "PAMELA Overview: Design Goals and Principles", This conference, TH4GAC03.

[2] K. Symon, D. Kerst, W. Jones, L. Laslett, K. Terwilliger, "Fixed-Field Alternating-Gradient Particle Accelerators" Phys Rev. Vol. 103, No 6, (1956) p.1837

[3] D.Trbojevic, E. Keil, B. Parker, and A. M. Sessler,Phys. Rev. Spec. Topics-Accel. and Beams 10,053503 (2007) p. 1-6.

[4] S. Machida, "Beam transport line with scaling fixed field alternating gradient type magnets", submitted to Phys. Rev. ST Accel. Beams.

[5] R. Fenning, "Non-Scaling FFAG Dispersion Suppressor" Proc. FFAG'09 Fermilab, Illinois, (2009)