AN FFAG TRANSPORT LINE FOR THE PAMELA PROJECT

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Abstract

The PAMELA project to design an accelerator for hadron therapy using non-scaling Fixed Field Alternating Gradient (NS-FFAG) magnets requires a transport line and gantry to take the beam to the patient. The NS-FFAG principle offers the possibility of a gantry much smaller, 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 transport line which could be used for the PAMELA project. The design is presented along with a study and optimisation of its acceptance.

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.

In order to treat patients, the beam must be transported to the treatment room without distortion. Figure 1 shows a possible lay-out of such a transport line. Using double 45° bends rather than a single bend into the treatment room helps to remove dispersion caused by bending the beam.

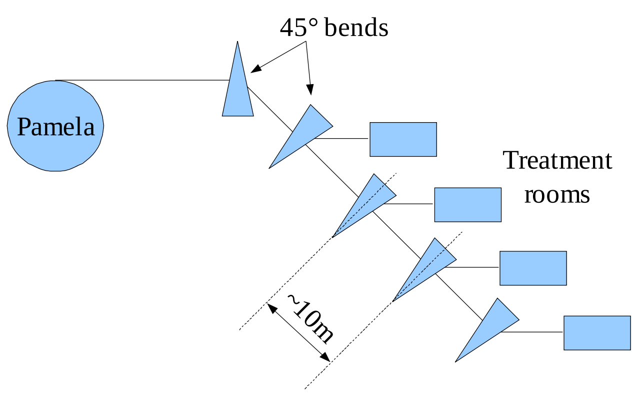

Figure1: Proposed layout of the transport line.

Like the main PAMELA accelerator, the transport line 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 FFAG transport lines [2] and look into the possibility of using one for the PAMELA project.

FFAG magnets can have highly non-linear fields, so the acceptance must be tested very carefully to make sure beam blow-up is kept in check. This paper will describe a test of the acceptance of a simple transport line, then optimise its acceptance by altering the field index 'k' Eq. (3) and the ratio of the focusing magnet strength to the defocusing magnet strength (FD ratio).

ACCEPTANCE DEFINITION

The definition of acceptance that has been chosen makes use of the 'smear'. This is defined as:

$$smear = \frac{\sqrt{\langle(\varepsilon_i - \varepsilon_{av})^2\rangle}}{\varepsilon_{av}} \quad (1)$$

Where: $$\varepsilon_i = \beta Y'^2_i + 2\alpha Y_i Y'_i + \gamma Y_i^2 \quad (2)$$

Y and Y' are the horizontal phase space coordinates and are measured from the closed orbit in this equation. Vertical phase space (Z, Z') smear is calculated in the same way.

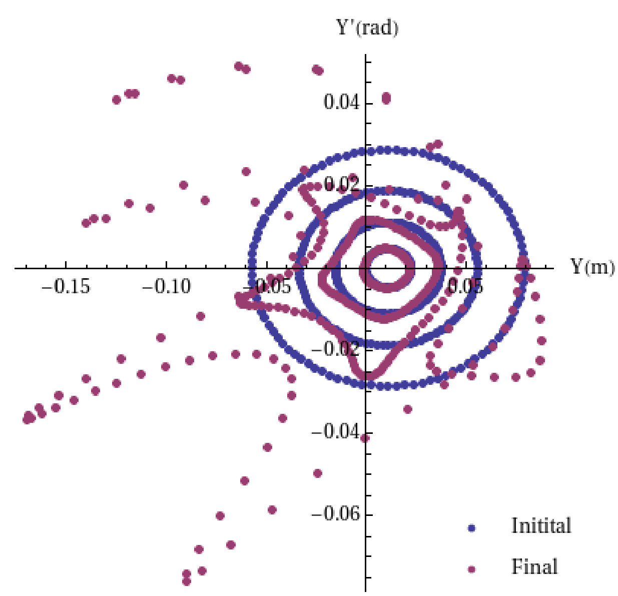

Figure 2: Phase space ellipses with smears of (from centre) 0.1, 0.25, 0.5 and 1.

The acceptance is defined as the initial emittance given to particles which results in a smear of 0.1 after passing

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through the lattice being studied. So the average deviation from the average particle emittance is 10% when the particles reach the end. The initial emittance is equal in both planes and the acceptance is found when the smear reaches the limit in either plane.

Figures 2 and 3 give an illustration of why a smear limit of 0.1 was chosen. In figure 2 phase space ellipses with smears of 0.25 upwards show noticeable distortion, so a significant change to the properties to the beam over the full range of the transport line is likely to occur; whereas the ellipse with a 0.1 smear is much less effected. The 10 π (mm mrad) emittance shown in figure 3 appears only slightly affected through a lattice with an acceptance of 54 π(mm mrad) and has a smear of just 0.004.

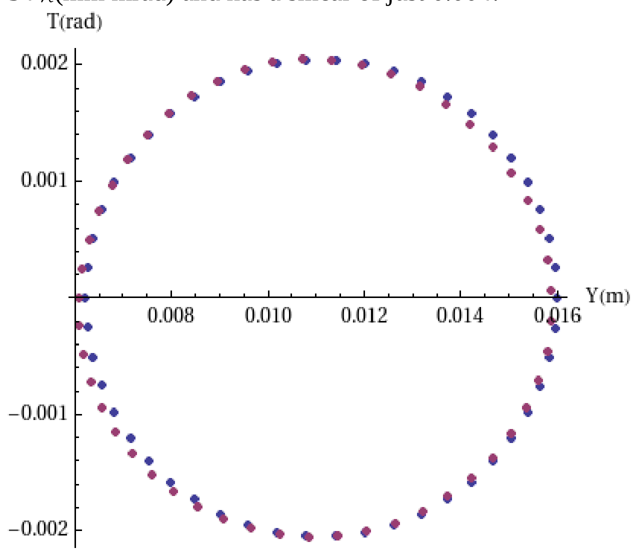

Figure 3: A 10 π(mm mrad) emittance in a lattice with a 54 π(mm mrad) acceptance defined using a smear of 0.1.

LATTICE DESCRIPTION

The FFAGs used in this study is described in [2]. They obey the scaling law:

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

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.

To transport the beam in a straight line, y_0 was set very large (1km) compared to the cell length (1.6m). However to create similar behaviour as a beam with a y_0 of 1m, the field index, k, is increased by the same proportion, so a k of 5 becomes k = 5000. For convenience this paper will refer to k/y_0 simply as k.

Each cell consists of equal length focusing and defocusing magnets in an FDDF configuration with the Bz_0 of F = 2.0T and D = -3.0T. k= 5.

ACCEPTANCE CALCULATION

It was decided to test a transport line with a length of 9.6m because this is close to the proposed length of the straight sections (figure 1) and exactly the length of 6 cells. The transport considered will be straight as this is the simplest case.

The energy range of this study is taken from the planned extraction energy of PAMELA: protons from 60MeV to 240MeV and carbon from 110MeV/u to 450MeV/u [1]. This study will consider protons with momentum ranging from 0.25GeV/c to 0.75GeV/c. Later studies will consider carbon.

Closed orbits were found for the highest, lowest and an intermediate momentum by finding the centre of the phase space ellipse drawn by a single particle moving through a single cell multiple times.

The Twiss functions required for Eq. (2) were found by calculating the transfer matrices at the required points using a modified version of the Zgoubi [3] tracking code.

Groups of particles were then tracked through the lattice with larger and larger initial emittances until the smear exceeded the 0.1 limit. The acceptance was found by approaching the limit in smaller and smaller emittance steps until the smear = 0.1 to an adequate precision.

There was little variation of acceptance with momentum, but a large variation with tune, so a range of k and FD ratios with a fixed momentum of 0.5GeV/c was chosen. An initial working point study indicated that k should range from 5 to 10 and FD ratio from 1.3 to 1.8. The FD ratio was changed by holding the F strength and altering the D.

RESULTS

As is shown in figures 4 and 5, the optimal k seems to be 4.75 and the FD ratio 1.4. This is close to the initial working point, however the acceptance is increased by an order of magnitude.

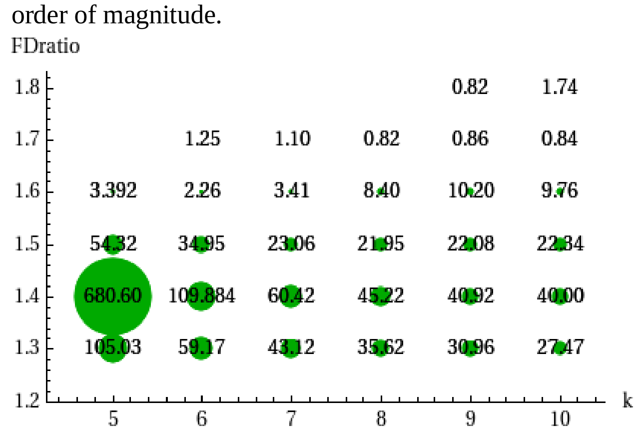

Figure 4: Acceptance/ π(mm mrad) in numbers and dots proportional to the square root.

This dramatic variation in acceptance could be due to the resonance structure of the cell, however, the points from figure 5 were mapped onto the tune diagram (figure

6) and it is not obvious that this is the case. Further studies will test the resonance structure more fully in this and longer transport lines.

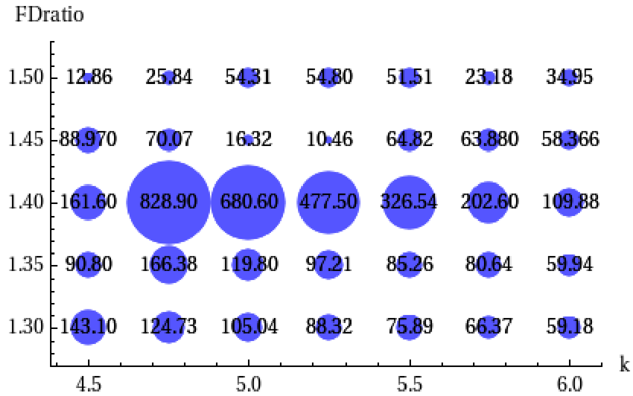

Figure 5: Acceptance/π(mm mrad) zoomed in around likely working point.

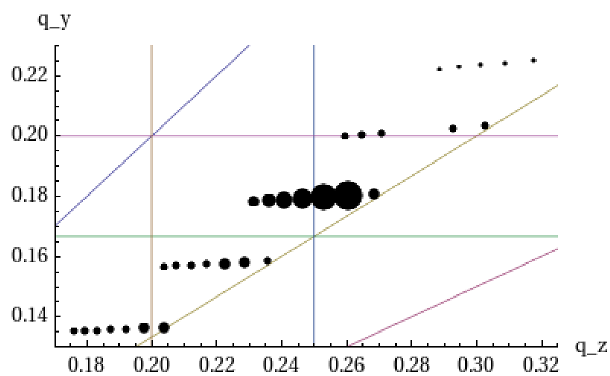

Figure 6: Tune diagram showing the square root of the acceptance in dot size. The diagonal resonance lines are: (from left) q_y-q_z=0, $3q_y$-$2q_z$=0 and $2q_y$-q_z=0.

Optimal Configuration

The closed orbits and β functions were found for the optimal configuration (figures 7, 8) and a 10 π(mm mrad) ellipse was tracked at each momentum to check the distortion (figure 9).

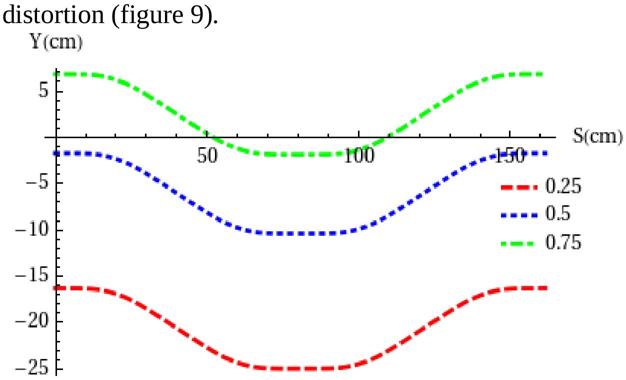

Figure 7: Closed orbits for the three different momenta (GeV/c) in one cell of the optimised lattice.

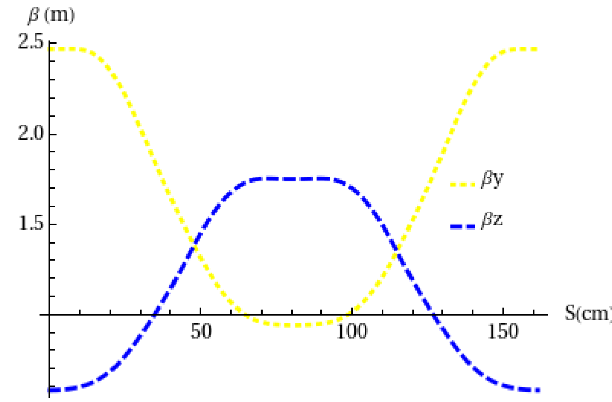

Figure 8: βfunctions for the optimised lattice.

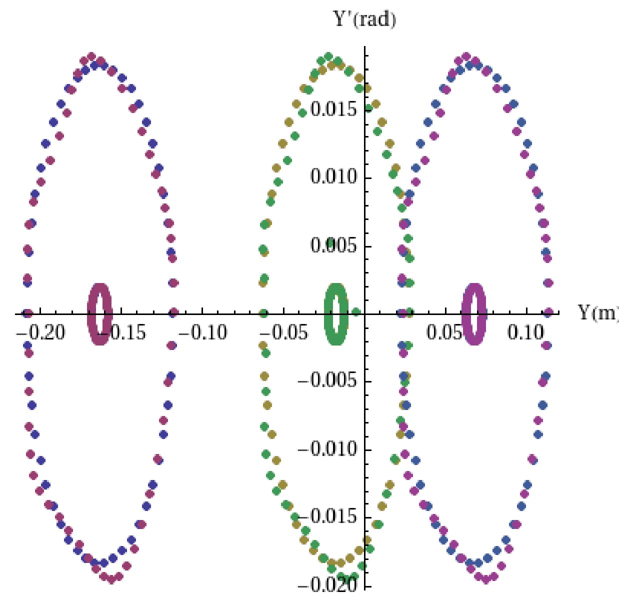

Figure 9: The initial and final states of 10 π(mm mrad) ellipses in the centre of ellipses corresponding to the 828π (mm mrad) acceptance.

CONCLUSIONS

A transport line with an acceptance far in excess of the expected PAMELA beam has been designed and there are many other working points with an adequate acceptance. Further studies will track through a much longer transport line, look at the resonance structure and investigate how to introduce 45° bends without creating additional dispersion. The field profile Eq. (3) will also be relaxed to make a transport line with NS-FFAG magnets similar to those used in the PAMELA ring.

REFERENCES

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

[3] F. Meot, Nucl. Instr. Meth. A, 427, p. 353 (1999).