PAMELA: LATTICE SOLUTION FOR A MEDICAL C6+ THERAPY FACILITY*

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Abstract

PAMELA (Particle Accelerator for MEdicaL Applications) employs novel non-scaling Fixed Field Alternating Gradient (ns-FFAG) technology in the development of a proton and C6+ particle therapy facility. One of the challenges of this design is the acceleration of high energy C6+ in a lattice which enables high flexibility and reliability for treatments, yet remains minimal in size and complexity. Discussed here is the carbon 6+ lattice solution in terms of both design and performance.

INTRODUCTION

The aim of the PAMELA project is to design a Charged Particle Therapy (CPT) facility using the features of ns-FFAG technology to improve performance over existing facilities [1, 2]. A unique feature of the ns-FFAG is the ability to provide variable energy beams at repetition rates of around 1 kHz. In a treatment scenario, the fast beam scanning can be optimised depending on the target volume not only in the usual transverse plane, but also longitudinally. It is this added flexibility which can only be realised with an FFAG accelerator.

Clinical considerations require that a proton/carbon CPT facility provides protons from 70 to 250 MeV and Carbon (C^{6+}) from 68 to 400 MeV/u. To achieve this, two accelerating rings are required. The first will accelerate protons to 250 MeV and carbon ions to 68 MeV/u and the second will accelerate carbon to 400 MeV/u. The design of the second ring is particularly challenging due to the high rigidity of the ions - a factor of more than 2.5 higher than that of full treatment-energy protons, as seen in Table 1. The design of the second ring is discussed in this paper.

In addition to providing variable energy beams with a high repetition rate, the lattice design for PAMELA is required to minimise the overall footprint of the accelerator while ensuring that sufficient drift space is available for RF cavities, injection and extraction systems, corrector magnets and diagnostics [3]. Another important requirement is for the total betatron tune variation throughout acceleration to be minimised to within half an integer. This avoids deterioration due to resonance crossing, which has been shown to be a problem for proton/ion non-scaling FFAGs [4, 5, 6].

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LATTICE DESIGN

Design Strategy

The design strategies for both PAMELA rings start with a scaling FFAG with a FDF triplet focusing structure, with the field index k resulting in a horizontal phase advance of greater than 180° per cell, which is possible in the second stable region of Hills equation. A number of changes and simplifications are then made to the lattice. The magnetic field which starts out following Eqn. 1 is approximated by a polynomial fit, the order of which corresponds to magnetic multipoles up to the order of octupole, decapole or dodecapole. The effect of the differing order of polynomial fit is discussed in the optimisation section. The magnets are made rectangular rather than sector or wedge shaped and aligned parallel to one another along a straight line. This makes magnet construction simpler and will improve the alignment accuracy in practise. Each of these simplifications violate the original scaling law, making this accelerator a non-scaling FFAG. Details of each simplification and its effect on lattice dynamics for the smaller proton ring can be found in Ref. [7].

$$B_z = B_0 \left(\frac{r}{r_0}\right)^k \tag{1}$$

Selection of Baseline Lattice

A number of parameters can be adjusted to achieve a realistic lattice design, including the ring radius, field index k, lattice packing factor - defined as the ratio of triplet cell length over the circumference - and number of cells. It is important to understand the effect that changing each of these parameters has on the peak magnetic field, orbit excursion - and therefore magnet bore size - and the length of long straight sections.

A scan of these parameters and their effects was undertaken making the following assumptions:

- The field described by the polynomial fit in the lattice magnets is close to the scaling law and the particles follow an approximately circular trajectory when inside the magnets.
- Given that the magnets are in an FDF configuration where the D provides reverse bending, if the F and D strengths are approximately equal it can be assumed that each F magnet needs to provide the total bending of, for example, 30° in a 12-cell lattice. This results in a total bend of 30° from the combination of the three

Table 1: Particle Kinetic Energies and Magnetic Rigidities for 2 Ring Complex

Particle	H+		
Ring	1 inj	1 ref	1 extr
Kin. En./u [MeV]	30.95	118.38	250
Bρ [Tm]	0.811	1.621	2.432

Particle	C6+				
Ring	1 inj	1 ref	1 extr/2 inj	2 ref	2 extr
Kin. En./u [MeV]	7.84	31.0	68.36	208.75	400
Bρ [Tm]	0.811	1.621	2.432	4.401	6.370

magnets in the FDF triplet. This gives an indication of the peak field required.

Making these assumptions allows the use of basic geometric equations to describe the changing of parameters in this type of lattice. The number of lattice cells does not greatly affect the required maximum bending field strength, however factors such as the ring radius and lattice packing factor have a much greater impact, as expected. The main contribution to the total magnetic bore size requirement is determined by the field index, k. As a result of this, it is possible to solve for feasible configurations of the lattice design. The possible configurations are shown in Fig. 1 for varying machine radius and lattice packing factor, assuming straight sections $>$ 1.2 m with a peak magnetic field $<$ 4.0 T and a magnetic bore less than 0.35m. The parameters of the chosen baseline lattice are given in Table 2.

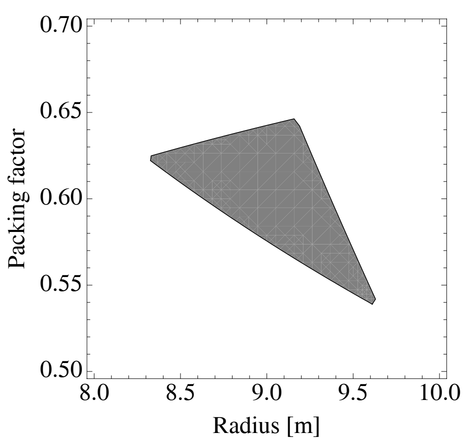

Figure 1: Possible configurations of carbon lattice obtained by varying radius and packing factor.

Optimisation

The optimisation procedure begins by calculating the positions of particle orbits throughout acceleration in a perfectly scaling version of the FFAG. The non-scaling version then takes the middle point of the orbit excursion within each magnet as the central point of the polynomial fit, in order to achieve the best possible fit of the multipole coefficients to Eqn. 1 in the region of magnetic field that the beam experiences. Outside the region that the beam traverses, the magnetic field is allowed to be different to Eqn. 1. In cartesian co-ordinates the expansion of the field takes the form of Eqn. 2, where x_0 is used instead of r_0 of Eqn. 1, the distance from the centre of the machine to the centre of the magnet.

Table 2: Lattice Parameters of the Baseline Lattice (all lengths are quoted in metres)

Parameter	Value
Radius	9.3
Lattice packing factor	0.65
Circumference	58.4
Approx. k value	42
Long straight	1.1979
Short straight	0.1266
Magnet length	1.1395
Orbit shift	0.217
Bore size	≈0.35

$$\frac{B_z}{B_{z,0}} = 1 + \sum_{n=1} \frac{1}{n!} \frac{k(k-1)\cdots(k-n+1)}{x_0^n} x^n \quad (2)$$

PERFORMANCE

Orbit Excursion

The total orbit excursion throughout acceleration is shown in Fig. 2. The total change in orbit position between the lowest and highest energy orbits is 0.217 m for the energy range required. A larger energy range is achievable with the same lattice design, for example an energy range of 50 to 430 MeV/u is possible with a total orbit excursion of 0.237 m. The final choice of energy range will depend on magnet and RF designs, as the aperture of these components will determine the allowed orbit excursion.

Tune Variation

The variation of the betatron cell tunes throughout acceleration are shown in Fig. 3 for varying orders of polynomial fit to Eqn. 1, corresponding to different orders of multipole. The total machine tune variation for each case

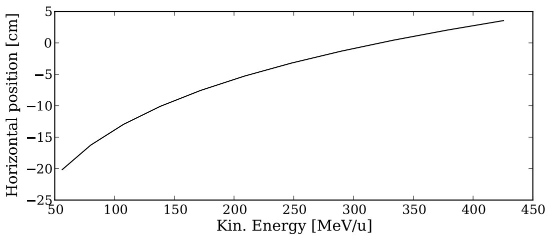

Figure 2: Variation of orbit position in the horizontal direction during acceleration.

is given in Table 3. In each case, including the simplest case of multipoles only up to the octupole, the tune variation is less than half an integer, the upper limit imposed by the lattice requirements to avoid resonance crossing. The operating point can be shifted to completely avoid the half-integer resonance currently crossed at high momentum in the octupole case.

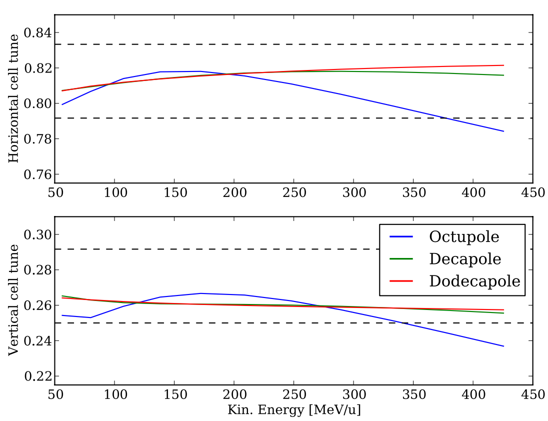

Figure 3: Variation of horizontal cell tune (upper) and vertical cell tune (lower) for different orders of multipoles. Dotted lines correspond to integer and half integer resonances of the total machine tune.

Table 3: Total machine tune variation for different orders of polynomial fit to the scaling law.

	ΔQ_x	ΔQ_y
Octupole	0.4056	0.3574
Decapole	0.1297	0.1165
Dodecapole	0.1727	0.0805

Dynamic Aperture

The dynamic aperture is determined at the injection energy (68.36 MeV/u) for a range of horizontal and vertical tunes, determined by changing the k value and ratio between the F and D strengths. The lattice does not have any alignment errors, and the case of polynomial fit up to decapole is used. Single particles are tracked over 1000 turns, starting with the same normalised amplitude in both horizontal and vertical planes. The amplitude is then increased until the particle is lost, and the dynamic aperture plotted next to each point in Fig. 4 is the highest amplitude surviving particle in units of π mm mrad.

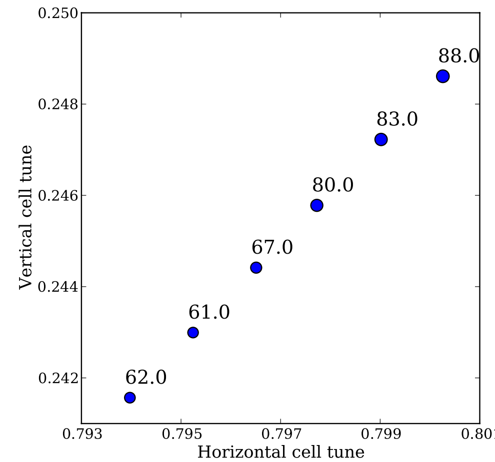

Figure 4: Calculated dynamic aperture at injection energy for varying horizontal and vertical tunes, dynamic apertures are listed next to each point in π mm mrad (normalised).

CONCLUSIONS

A non-scaling FFAG lattice has been designed which meets the requirements for accelerating carbon 6+ ions for particle therapy, with variable energy extraction at a repetition rate of up to 1 kHz. The achievable repetition rate may be limited by the RF and extraction kicker requirements, but it is expected that a repetition rate of at least 200 Hz is achievable, which is far in excess of any present system. The betatron tunes are very well constrained to within half an integer in order to avoid the crossing of resonances. The design has sufficient dynamic aperture for this application.

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