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NORMA - A NORMAL-CONDUCTING, SCALING RACETRACK FFAG*

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Abstract

We present a design for a 30 - 350 MeV scaling racetrack FFAG accelerator for medical application - NORMA (NOrmal-conducting Racetrack Medical Accelerator) - which utilises normal-conducting magnets. NORMA consists of 12 FDF triplet cells with a maximum drift length of ~2 m; an additional drift space inserted into two places forms a racetrack lattice with enough space for injection/extraction. Optimisation routines in PyZgoubi are used to find optimum cell parameters and working point.

INTRODUCTION

Fixed-field alternating-gradient (FFAG) accelerators have been proposed to accelerate protons for radiotherapy in the range 30 - 250 MeV [1,2]. Increasing the energy range from 30 - 350 MeV may provide useful diagnostic techniques to be utilised such as proton computed tomography (PCT) [3]. FFAGs may be advantageous compared to cyclotrons and synchrotrons in that they may deliver variable-energy protons with a sufficient repetition rate to enable fast tumour repainting. To be used in a hospital setting, such machines are required to be as cost-effective as possible; this includes minimising the footprint and minimising the complexity of magnets and operation. Previously, development of scaling-type FFAGs utilised the second stability region of Hill's equation to minimise the orbit excursion during acceleration [4] and thus keep the magnet apertures as small as possible. PAMELA ('Proton Accelerator for MEdicaL Applications') [2] proposed superconducting, non-scaling magnets which simultaneously allowed the average bend field to be high whilst minimising the orbit excursion; however, the resulting magnets are relatively complex and potentially expensive [5]. In this work, we propose a normal-conducting, scaling FFAG for medical applications - NORMA (NOrmal-conducting Racetrack Medical Accelerator) - with an energy range of 30 - 350 MeV, where the average bend radius (and hence circumference) is increased, but in which the magnets are significantly simplified. We use PyZgoubi to optimise the magnetic parameters of this lattice whilst minimising the circumference in order to make a machine with as small a footprint as possible. We also include an additional pair of long straights (needed for injection and extraction) by modifying the lattice into a racetrack structure. The major advantage of such lattices is the use of normal-conducting magnets, which are simpler and cheaper to construct, but where the circumference is reduced by optimising the drift space and added flexibility is present in the use of racetrack drift spaces. We show the optimisation procedure followed to design NORMA and discuss the relevant parameters.

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THE PAMELA ACCELERATOR

We considered the PAMELA lattice [2] before starting out design. PAMELA consists of 12 FDF triplet cells; each magnet is a superconducting multipole including dedicated coils for octopole and decapole components, which are adjusted to approximately obtain the scaling FFAG relation [6]. The focusing gradient is high such that the stable working point is in the second stable region of Hill's equation; this allows the orbit excursion to be small [4] (see parameters in Table 1). Due to the likely expense and complexity of the proposed PAMELA magnets [5] we have proposed to use magnets with a maximum field of $\lesssim$ 1.8 T. A simple scaling-up of of PAMELA - in which the lattice dimensions are in the same ratio and where the tune is preserved - results in a circumference of around 110 m and the longest drift is ~4.5 m; clearly this is impractically large. We therefore examined alternative lattices; we extend the energy range from 250 to 350 MeV, use a simpler scaling FFAG-type magnetic field which is $\lesssim$ 1.8 T.

Table 1: PAMELA Parameters

Parameter	Value
Energy range [MeV]	31 - 250
Circumference [m]	39.3
Max. drift [m]	1.7
Max. field (F/D) [T]	3.48/-2.62
Orbit shift [m]	0.176
Ring tune (H/V)	8.76/3.48
Field index K	36.7

THE NORMA DESIGN PROCESS

We used PyZgoubi [7] to optimise a normal-conducting, 12 cell scaling FFAG lattice to obtain a smaller circumference. Figure 1 shows the parameters of the FDF cell which were optimised: the magnet length is L_M, the two drift lengths are L_{LD} and L_{SD} and the packing factor in this case is defined as the fraction of the cell occupied by he FDF triplet, $\alpha = L_{trip}/L_{cell}$. A dedicated routine in PyZgoubi was used which calculated the required L_M for the given 30 - 350 MeV energy range and minimised the drift lengths L_{LD} and L_{SD} to produce a lattice with a small circumference. The transverse tunes were kept constant by optimising the strengths of the F and D magnetic fields ($B_{0,F}$ and $B_{0,D}$)

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along with their field index K; unstable solutions were disregarded. The magnetic field index K was kept as high as possible to minimise the orbit excursion and keep the magnet aperture as small as possible.

PAMELA required long drifts of ≈ 1.7 m to accommodate conventional injection and extraction (at 250 MeV) and to incorporate the required RF. We have initially assumed around 2 m is needed for injection and extraction (at 350 MeV), and have minimised the lengths of the other straights.

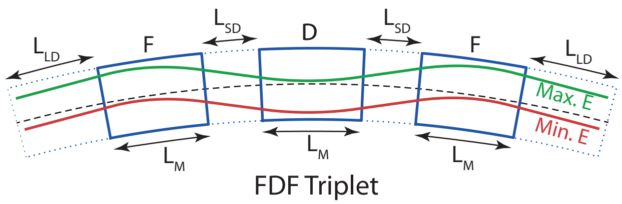

Figure 1: Geometry of the FFAG cell optimised in NORMA. Variable parameters were the cell length L_{cell}=2L_{LD}+3L_M+2L_{SD}, the triplet length L_{trip}=3L_M+2L_{SD}, and the packing factor α=L_{trip} / L_{cell}.

PyZgoubi was used to calculate the maximum insertable drift space at two locations in the ring whilst both keeping the tunes constant and maintaining focusing stability over the energy range. Three stable working points were first explored by varying the packing factor α (see Fig.1). The stable lattices found by PyZgoubi are shown in Fig.2 where the black points represent ring-type lattices and the coloured points represent racetrack-type deviations from a ring, with a variable amount of additional insertable drift length L_{RTD}; the maximum available drift length in each case is L_{max} = L_{RTD} + 2L_{LD}.

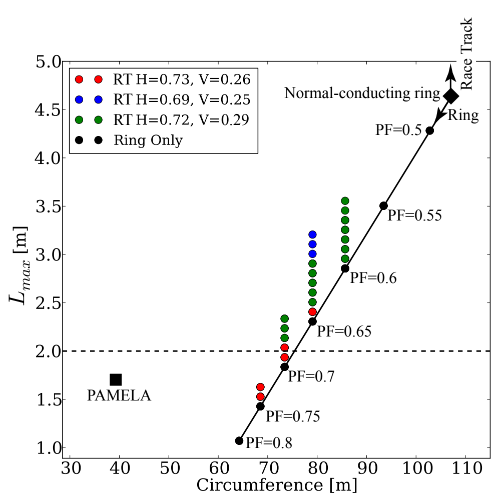

Figure 2: Parameter-space study using PyZgoubi showing the circumference variation with packing factor (PF), for ring-type lattices (black) and their racetrack equivalents (coloured). PAMELA and a scaled, normal-conducting 110 m lattice are also shown. The coloured points represent different initial tune point investigations.

A packing factor α =0.65 was selected from the parameter space shown in Fig.2 for 2nd stage optimisation due to the fact that all the lattices with L_{max} >2 m were stable and the circumference was reduced with respect to the 110 m normal-conducting ring shown at the top right of the figure. The 2nd stage of optimisation was to reduce the length L_{SD} in order to minimise the circumference whilst retaining L_{max} >2 m. A scan of possible configurations with a target α =0.65 is shown in Fig.3. As the circumference is fixed when a racetrack drift is inserted (to minimise the footprint), α is naturally reduced, such that α =0.62 for the optimised lattice rather than the target value 0.65.

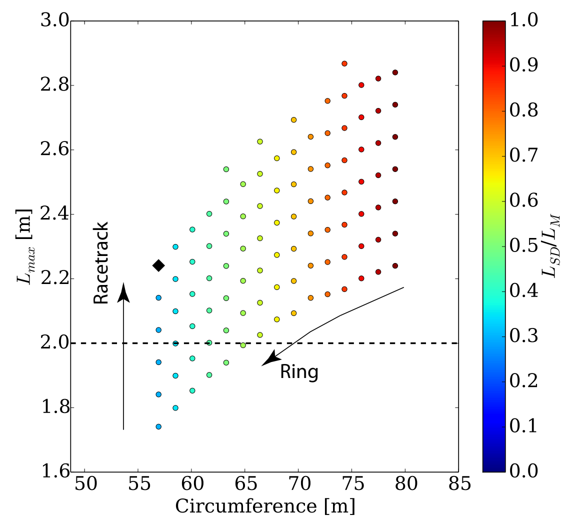

Figure 3: Parameter-space scan using PyZgoubi showing the reduction in circumference when the ratio L_{SD}/L_M is varied; L_M is a constant so this shortens L_{SD}. The black point shows the eventual selected lattice.

A ring and racetrack version of NORMA with the final selected circumference of 56.9 m (see Fig.3) were explored, and the ratio L_{SD}/L_M = 0.3. The tunes were kept constant in the same way as previously discussed, and the radius of the arcs in the racetrack was reduced to keep the circumference constant. The parameters for the selected lattices are shown in Table 2 where it can be seen that the circumference is greater by ≈50% with respect to that of PAMELA, but the maximum magnetic field is more than halved. The increase in L_{max} between the racetrack and ring version should be noted; it may be possible to increase L_{max} later by inserting matching sections into these straight sections. Drift space of ∼1.5 m exists between cells in the arcs which may be used for diagnostics and RF structures, but the extra drift space in the racetrack shows the potential to create longer drifts for injection/extraction and more RF structures if required.

The tune variation with energy is shown in Fig. 4 for the ring and racetrack; it can be seen that the difference between the two is very small showing that it is possible to optimise accurately to a given working point using PyZgoubi. It can also be seen by comparing tables 1 and 2 that the tune agreement is good between PAMELA and NORMA which

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Table 2: Comparison of parameters for a NORMA ring with small straights between magnet and a racetrack (RT) NORMA with 2.14 m straights at two positions to meet injection/extraction requirements.

Parameter	NORMA-Ring	NORMA-RT
Energy range [MeV]	30 - 350	30 - 350
Circumference [m]	56.9	56.9
Max. drift [m]	1.74	2.14
Max. field (F/D) [T]	1.68/-1.28	1.69/-1.29
Orbit shift [m]	0.304	0.301
Ring tune (H/V)	8.66/3.24	8.66/3.24
Field index K	37.6	37.0

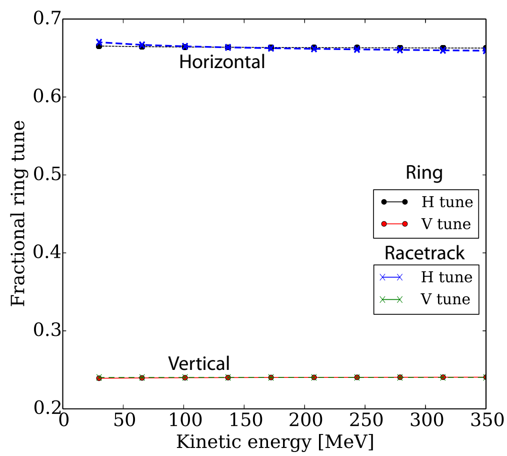

Figure 4: The fractional part of the ring tune as a function of kinetic energy for the ring and racetrack lattices.

also shows the ability to optimise a lattice to a given working point in PyZgoubi.

It is possible to optimise the lattice to obtain a desired dynamic aperture (DA) in PyZgoubi. This is important as the DA changes significantly within the optimised parameter space. For example, Fig. 5 shows how the DA changes when the packing factor is varied for the NORMA ring lattice in Table 2. Figure 6 shows the DA when the ratio L_{SD}/L_M is varied. In Figs. 5 and 6 the DA is calculated for 1000 turns by assuming the same action in the horizontal and vertical phase space and by taking the minimum DA calculated from 16 single-particle trajectories which arise from all the combinations of single particle amplitudes in both transverse phase spaces [7]. This allows us to be confident about the minimum DA assuming a round injected beam rather than simply investigating the pure horizontal and pure vertical DA. With further optimisation in PyZgoubi it is possible to realise a DA in NORMA above ~35 mm.mrad as shown in Fig. 5.

CONCLUSIONS

We have proposed a normal-conducting, scaling FFAG for medical applications - NORMA - with simplified magnets, an optimised circumference and an energy range of 30 - 350 MeV. An optimisation procedure in PyZgoubi was used to reduced the circumference by minimising the drift lengths, while keeping the tune constant by varying the magnetic field parameters. It was shown that a small normal-conducting ring lattice with circumference 56.9 m could be obtained with a maximum magnetic field of 1.69 T. A racetrack version of NORMA allows for larger straight sections to be inserted for easier injection/extraction without compromising the lattice parameters; this will be explored further in the future and incorporate matching sections to potentially make the racetrack straights longer. It was possible to keep the tune constant between the ring and racetrack versions of the lattice as well as the circumference, by using the optimisation in PyZgoubi. Further optimisation will be carried out, including reducing the size of the magnets and optimising the lattice in order to obtain the largest DA; DA will ultimately be studied with reasonable lattice errors.

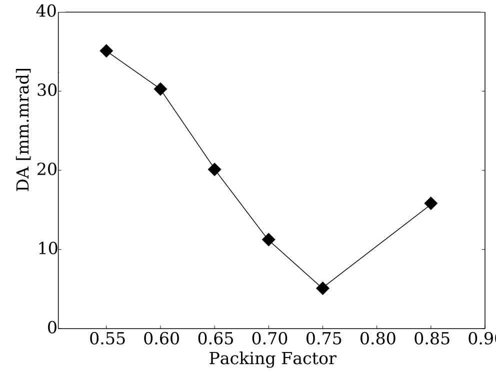

Figure 5: The variation of dynamic aperture in the NORMA ring when the packing factor α is changed.

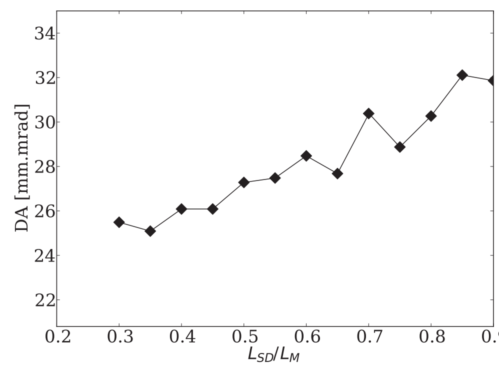

Figure 6: The variation of dynamic aperture in the NORMA ring when the ratio L_{SD}/L_M is changed and α=0.62.

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