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PROGRESS ON A 30 - 350 MeV NORMAL-CONDUCTING SCALING FFAG FOR PROTON THERAPY*

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Abstract

We present our progress on a new design for a 30 - 350 MeV scaling FFAG for proton therapy and tomography - NORMA (NOrmal-conducting Racetrack Medical Accelerator) which allows the realisation of proton computed tomography (pCT) and utilises normal conducting magnets in both a circular and racetrack configuration which are designed using advanced optimisation algorithms developed in PyZgoubi. The ring and racetrack configurations have average circumferences of around 60 and 70 m respectively, peak magnetic fields of < 1.8 T, average orbit excursions < 50 cm and dynamic aperture calculations of > 50 mm.mrad using a novel technique. The racetrack design has a total magnet-free straight length of 4.9 m at two opposing points, designed to ease injection and extraction systems.

INTRODUCTION

The treatment of cancer using proton therapy is widely regarded as having many advantages over conventional therapies due to the more localised dose deposition in the tumour, realisable as a characteristic Bragg peak at a depth determined by the incident proton energy; around 70 - 250 MeV for human tissue treatment [1–3]. Fast, effective treatment of a tumour volume requires precise and rapid energy variation and transverse beam scanning for effective use of treatment time and localisation of dose so as to limit surrounding healthy tissue damage. Furthermore, the technique of proton computed tomography (pCT) is highly desirable clinically due to the ability to obtain real-time diagnostics on the treatment of the tumour; however pCT requires a proton energy of around 350 MeV, not currently attainable from current proton therapy centres or designs.

An FFAG (Fixed-Field Alternating-Gradient) accelerator [4] is a good choice of machine which meets these requirements as protons may be accelerated up to 350 MeV with pulse-to-pulse energy variation up to 1 kHz and variable energy extraction. The 70 - 250 MeV proton (and carbon ion), non-scaling FFAG PAMELA (Particle Accelerator for MEdicaL Applications) [5] is capable of the desired treatment regime but not pCT in the proton ring, and has potentially complicated and expensive superconducting magnets [6]. Previous studies [7] showed the possibility of inserting magnet-free straights into a ring while maintaining a suitable DA and optics. We are designing a 30 - 350 MeV scaling, proton FFAG with normal conducting magnets which has a conventional ring and a racetrack configuration to ease injection and extraction. Although our second design has only magnet-free drifts inserted, we still refer to it as a racetrack to distinguish it form the circular design. The ring design has a circumference of around 60 m and a dynamic aperture (DA) of > 60 mm.mrad, the racetrack has a circumference of around 70 m, with two 4.9 m magnet-free straight sections and a DA of > 50 mm.mrad. Both designs will have orbit shifts over the energy range of < 50 cm with peak magnetic fields <1.8 T, but relatively large sized magnets; 0.5 m aperture, 1.0 m length. However, scaling FFAGs with similar sized magnets have been constructed and successfully operated [8–10].

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NORMA RING

An FDF (focusing - defocusing - focusing) triplet is being used and optimised in the NORMA design with scaling, sector-type magnets where the field in each magnet in the radial direction is defined by

$$B(r) = B_0 \left(\frac{r}{r_0}\right)^k , \qquad (1)$$

where B_0 is the magnetic field at the reference radius r_0 and k is the field index. A schematic diagram of the cell is shown in Fig. 1 where the geometric parameters are indicated. The

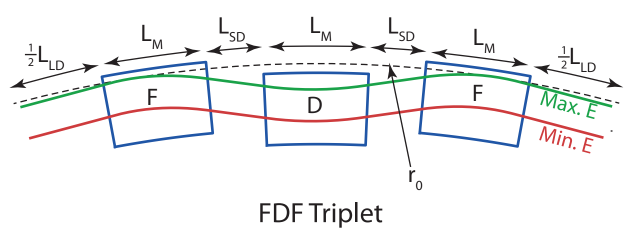

Figure 1: Geometry of the FDF triplet cell used in NORMA showing the sector-type magnets in blue, the minimum and maximum energy orbits (30 and 350 MeV) in red and green respectively and the reference radius r_0 as a dashed black line. For optimising the geometry, the free parameters were selected as 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}.

number of cells, geometry within each cell, magnetic field strengths of the F and D magnets and the field index were optimised using specific algorithms which we developed using PyZgoubi for the optimisation of NORMA [11, 12]; some initial analytical analysis was also used in this process.

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The second stability region of Hill's equation [13] is being used in order to reduce the orbit excursion and the DA is being optimised over a large tune-space by using computationally intensive methods which yield a high level of precision and allow us to make a highly precise parameter selection. We are using the University of Manchester's High Throughput Computing (HTC) cluster Condor [14] in order to perform tens of thousands of parallel calculations, each of which individually takes approximately 10 hours to complete; this allows years worth of single-machine calculations to be carried out in as little as 24 hours.

Figure 2 shows the DA in a region of the NORMA tune space used in the optimisation, where the highest DA region is indicated. The DA was calculated using a novel method [11] which involves taking the minimum of several single particle invariant amplitudes assuming a realistic, linearly matched elliptical bunch at injection. Table 1 gives an example of the optimised parameters for a particular solution with a high DA in the tune space, showing that we are able to design a lattice which can accelerate protons in the range 30 - 350 with magnetic fields in the normal conducting range with an orbit shift of around 40 cm and a DA > 60 mm.mrad. Figure 3 shows a schematic representation of such a NORMA ring lattice.

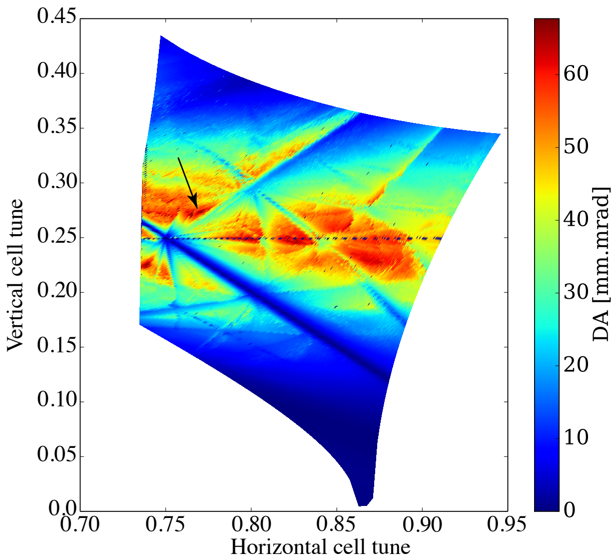

Figure 2: The DA is shown in the tune space for an error free NORMA ring lattice. The DA is represented by a colour spectrum with higher DA appearing in red and lower DA towards blue. The darkest blue points represent dynamically unstable lattices, for example those along the systematic resonance at vertical tune of 0.25. The black arrow indicates the region containing the highest DA. Due to the strong sextupole resonance at horizontal cell tune 0.66, the DA is only calculable from around 0.73 onwards. Over 1×10^4 individual calculations are shown, allowing high resolution analysis.

Table 1: The Approximate Parameters of an Example NORMA Ring Lattice

Parameter [unit]	Value
Average radius [m]	9.6
Average circumference [m]	60.0
Average orbit excursion [m]	0.4
Ring tune (Q_h, Q_y)	7.7, 2.7
k	27.5
Max. field seen by beam in F magnet [T]	1.5
Max. field seen by beam in D magnet [T]	-1.2
DA [mm.mrad]	60.0
Magnet-free drift L_{LD} [m]	2.4

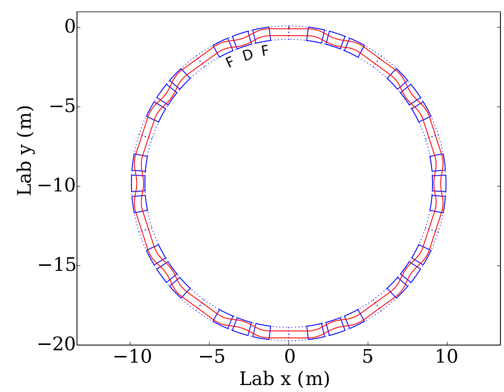

Figure 3: A schematic diagram of a NORMA ring lattice showing the lowest (inner) and highest (outer) energy orbits in red. Magnets are outlined by solid blue lines and the cell boundary as dashed blue lines. The approximate positions of the F and D magnets are indicated for one cell. Note that the solid blue outlines indicate only the approximate radial positions and horizontal aperture of the magnets.

NORMA RACETRACK

The circular design can be modified by inserting additional magnet-free drift space L_{RT} at two opposing points in the ring; in our design procedure the rest of the cell geometry is identical to the ring. Matching cells either side of the drift space are defined and along with the arc cells, are optimised in terms of their magnetic parameters for stability, working point, β-function matching and control etc; the five magnet families and their layout are shown in Fig. 4.

We investigated the effect on the DA of increasing the amount of drift length L_{RT}. The quantity L_{RT} was increased from 0.0 to 20.0 m and the lattice serially re-optimised to a fixed tune point with each iteration in L_{RT}. Figure 5 shows the reduction in the DA with L_{RT}; a more detailed study of this relationship will be carried out in future work. As L_{RT} is increased, the magnetic field in the F_{M1} magnet (see Fig. 4) increases to compensate the focusing. When L_{RT} >1.2 m, the field in the F_{M1} magnet increases above 1.8 T. We may perform a scaling of the ring geometry and fields which allowed us to moderately increase the lattice size and bring down the magnetic field strength for an example racetrack

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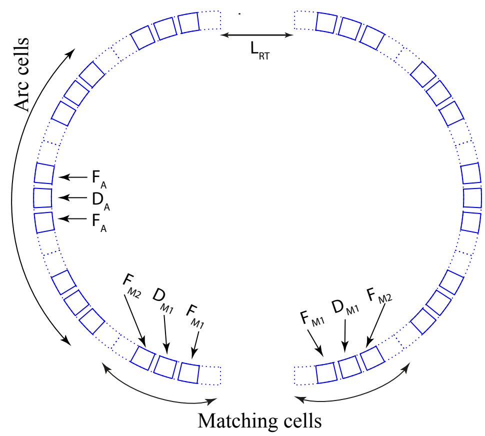

Figure 4: Schematic of the racetrack cells showing the long magnet-free straights L_{RT} and the two types of cell: arc and matching. Five families of magnets are shown, all have the same field index k and together they make up the six free parameters used in the optimisation.

lattice with $L_{RT} \approx 2.2$ m, resulting in a total magnet free straight of ≈ 4.9 m. The parameters for such an example are shown in Table 2.

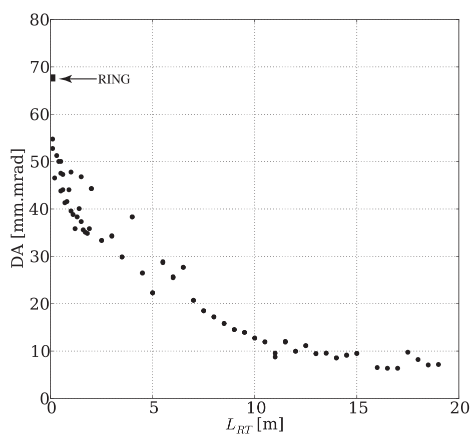

Figure 5: The DA for racetracks as a function of L_{RT} is shown. The DA for the NORMA ring lattice can be seen at $L_{RT} = 0$.

CONCLUSIONS

We have presented our preliminary designs and design method for a 30 - 350 MeV normal conducting scaling FFAG for proton therapy where 350 MeV facilitates pCT to be realised; this allows precise scanning of a tumour in order to irradiate a hard-edged profile and insure no healthy tissue is damaged. Using an FFAG enables rapid acceleration to take place over the energy range, allowing rapid voxel scanning, re-painting and depth control which are also highly desired clinically.

We developed new optimisation routines in PyZgoubi, and utilised HTC computing to facilitate our designs. Both

Table 2: The Approximate Parameters of an Example NORMA Racetrack Lattice

Parameter [unit]	**Value**
Average radius r_0 [m]	10.5
Average circumference [m]	70.0
Average orbit excursion [m]	0.48
Ring tune (Q_h, Q_v)	7.7, 2.7
k	26.0
Max. field seen by beam in F_{M1} magnet [T]	1.7
DA [mm.mrad]	55.0
Magnet-free drift [m]	4.9

our ring and magnet-free-insertion racetrack are optimised for a good working point, magnetic field in the normal conducting range and an adequate DA of > 50 mm.mrad over the proposed 1000 turn acceleration cycle. The orbit shift over the momentum range should be kept < 0.5 m for an acceptable magnet size, but may provide some challenges in RF design.

On-going work by the authors concerning the current NORMA designs includes lattice optimisation and parameter selection, a full 3D magnet design and field-map tracking, lattice error studies and multi-particle dynamics. We are also collaborating on an enhanced racetrack design in which we intend to independently adjust the reference radius and field index between the arc and matching cells and attempt to make the arcs more compact.

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