ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPM053

A NOVEL LARGE ENERGY ACCEPTANCE BEAMLINE FOR HADRON THERAPY

A. F. Steinberg*[1,2], R. B. Appleby[2], University of Manchester, Manchester, UK
J. S.L. Yap, S. L. Sheehy [3], University of Melbourne, Melbourne, Australia
[1]also at University of Melbourne, Melbourne, Australia
[2]also at Cockcroft Institute, Warrington, UK
[3]also at Australian Nuclear Science and Technology Organisation (ANSTO), Australia

Abstract

A design study is currently underway at the University of Melbourne for a large energy acceptance beamline to enable future hadron therapy modalities. As part of the TURBO project, a beam delivery system demonstrator is being developed for a DC Pelletron accelerator, which will provide 3 MeV H+ beams. Fixed Field Accelerator optics will be used to maximise momentum acceptance, with dispersion minimised at both ends of the transport line. This project aims to be the first 'closed dispersion arc' with fixed fields ever constructed. As part of the design process, the input beam phase space from the Pelletron has been characterised. Our results show that the Pelletron beam can be injected into the novel transport line successfully, and Zgoubi simulations show that near-zero dispersion at each end will be achievable. This is supplemented by error studies and magnet investigations, demonstrating that beam transport can be achieved under realistic circumstances. This initial study establishes the feasibility of this beamline design and work is continuing toward further optimisation for implementation.

INTRODUCTION

Fixed Field Accelerators (FFAs) have been proposed for many applications where a large energy acceptance and rapid acceleration can be advantageous, such as muon colliders [1] and medical facilities [2–4]. A key characteristic that distinguishes FFAs from standard synchrotrons is that the accelerator parameters are a function of rigidity: this not only leads to variation in the Courant-Snyder functions, but also different closed orbits for every energy, as in a cyclotron. This variation makes it difficult to integrate FFA-style optics with other accelerator systems, as there is inevitably a mismatch in beam parameters leading to significant closed-orbit distortion. The TURBO project [5] at the University of Melbourne seeks to explore some of these difficulties, with the ultimate goal of producing a beamline design to enable rapid energy switching for charged particle therapy [6]. The beam transfer line must constitute a 'closed-dispersion arc', with energy-independent beam position at either end.

There have been several large energy acceptance beam delivery system designs using fixed fields. Where a large bending angle is required to reduce beamline size, usually strong focusing is achieved over the full range of rigidities with sextupolar and higher order multipoles [7, 8]. In these cases, the momentum acceptance is limited to less than ±15 %, as the dispersion in the arc would otherwise be too large to fit within the feasible magnet aperture. Conversely, in designs where the bending strength is reduced, combined-function dipole/quadrupole magnets with fine-tuned length, strength, and edge angles can transport all energies [9–11]. By combining multipolar fields with low-dispersion beamlines, it may be possible to increase the energy acceptance while limiting the footprint [12].

The TURBO project will produce a technology demonstrator beamline, suitable for the 0.5–3.0 MeV proton beam from the 5U Pelletron. We choose 1.49 MeV as the reference energy which gives a momentum acceptance of ±42 % for our energy range. This beamline will also include a fast variable energy degrader, a collimator, and scanning system [13]. Beam steering and focusing will be achieved with Halbach arrays made from commercially available permanent magnet blocks in 3D printed holders, allowing for rapid prototyping and low costs. An initial design study for the closed-dispersion arc has been completed using Zgoubi [14], including error studies to ensure feasibility under realistic conditions.

BEAMLINE DESIGN

Initial Considerations

The design of achromatic insertions for synchrotrons is well understood, with standard schemes such as 'missing bend' and 'Chasman-Green' lattices [15] commonly employed for light sources. The first-order achromat theorem, requiring that the phase advance between the start and centre of the arc must be an odd multiple of π, is straightforward to achieve in a synchrotron, where the energy spread is low. In FFAs, the phase advance is in general a function of rigidity, unless the magnetic field B follows the scaling law

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

with B_0 and r_0 as a reference field and radius respectively, k is the field index, and $\mathcal{F}(\vartheta)$ describes variation in magnetic (fringe and body) fields along the azimuthal axis. Although this scaling law can be used to get a desired phase advance, it does not allow for independent control of focusing strength and dispersion. Moreover, it only applies in cases where the entire accelerator follows a scaling law: if it is broken at any point, the closed orbit trajectories no

* adam.steinberg@manchester.ac.uk

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longer follow the correct paths, and the phase advance becomes energy-dependent. It has previously been shown [16] that a dispersion-suppressing insertion with scaling fields is possible, but can be significantly improved by breaking the scaling law to reduce dispersion.

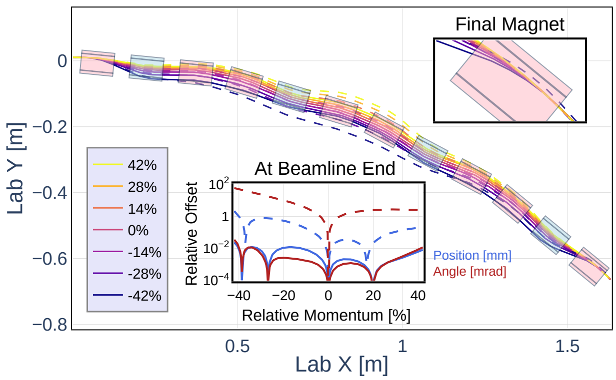

Figure 1: Trajectories through the arc, with magnet positions. Optimisation of the initial lattice (dashed) achieves a reduced dispersion (solid trace), with the solution listed in Table 1. **Lower Inset**: offset of trajectories by the end of the arc. **Upper Right**: zoom in on the final magnet.

There are several boundary conditions for our beamline design. To ensure that it would fit in the limited basement space at the University of Melbourne, the closed dispersion arc must have a footprint of less than 1.5 m^2, with a 45° overall bend to demonstrate nontrivial beam transport. In addition, the maximum magnetic field experienced by the beam must not exceed 0.8 T for reasons of safety and feasibility, and the maximum beam excursion must be less than 5 cm, otherwise the required amount of permanent magnet material would be excessive. The magnets will be rectangular to allow for fabrication. To demonstrate feasibility for medical applications, we aim to produce a beam spot in the transverse plane that is circular and energy-independent. The spot centre must not vary by more than one tenth of the beam size, as this would complicate quality assurance and potentially negate advantages of the large energy acceptance.

Our beamline design begins with a lattice that follows the scaling law up to decapole order, with a horizontal phase advance of π from the start of the arc to the midpoint. The arc comprises four identical FDF triplets, with 10 cm magnets and 5 cm drifts. We approximate the scaling law of Equation 1, with $r_0 = 0.4$ m, $k = 7.1$, and reference fields $B_{0F} = 0.346$ T, $B_{0D} = -0.537$ T. The periodic Courant-Snyder parameters for this cell fit the requirements for a dispersion suppressor. However the closed-orbit trajectories do not constitute a closed-dispersion arc and if we launch all particles from the closed orbit of our reference energy, we see in Fig. 1 that the final dispersion is significant, and the dispersion in the centre is larger than the feasible magnet bore. This lattice also has insufficient vertical focusing, leading to beam blowup at some energies. Despite these issues, this optics provides a suitable starting point for further optimisation.

Table 1: Lattice parameters after optimisation. Magnets are labelled by the order in which the beam goes through, with A first. Multipoles of order n have units of $\mathrm{Tm}^{n/2-1}$

Order	A	B	C	D	E	F
2	0.35	-0.54	0.35	0.35	-0.54	0.35
4	7.96	-3.54	5.84	10.6	-14.2	7.71
6	101	-26.8	7.43	170	-154	108
8	80.9	-657	366	735	-422	347
10	146	-139	205	474	-210	69.4

Detailed Optimisation

One key requirement fulfilled by the initial lattice in Fig. 1 is the reverse bending in the first section of the arc: this introduces the dispersion that is focused downstream, analogous to a traditional dispersion bump. To ensure that this bump is present in all solutions, the dipole component from each magnet is not varied. This has the added benefit of keeping the closed orbit of the reference energy approximately the same throughout the optimisation, although slight variation is introduced as rectangular magnets are used here.

To optimise the closed-dispersion arc, only the first two triplets (i.e. six magnets) must be considered: if the second half of the beamline is identical to the first but in reverse order, then symmetry requires that the initial and final beams be identical in the ideal case. For each of the six magnets, multipoles from quadrupole to decapole order are allowed to vary independently: this gives 24 degrees of freedom.

The goals of the optimisation are to minimise the final dispersion and the maximum dispersion, while ensuring beam stability for all energies. Even though minimising the required magnetic fields is not an explicit goal of the optimiser, it occurs as a byproduct of reducing the dispersion. The initial solution is set as the approximately scaling lattice from the previous section. It should be noted that the beam dynamics in FFAs can be highly sensitive to fringe fields, which have been neglected here: once a first magnet design has been completed, it will be possible to estimate these effects, and modify the beamline accordingly.

After optimisation, dispersion is significantly reduced at both the midpoint and the end: trajectories are shown in Fig. 1, and magnet parameters are in Table 1. In Fig. 2, we see that the beam size varies with momentum, however the distribution remains approximately circular: this is encouraging, suggesting that nonlinearities do not cause distortion in this single pass system. Further work may give a symmetric beam spot, which would be better for clinical use.

Error Study

In synchrotrons, where the beam circulates many times, the main contributions to beam distortion and loss are magnet misalignments and multipole errors. Here, such magnet errors contribute to deviations in the output beam characteristics, however the dominant effect is expected to be caused by variation in the injected beam, due to collimator issues

14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
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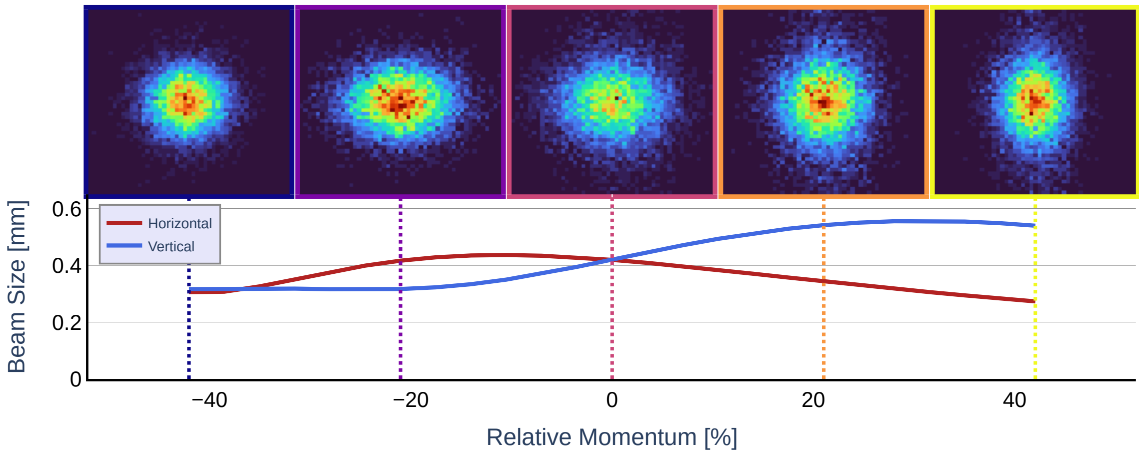


Figure 2: Beam spot size at the end of the closed dispersion arc as a function of momentum with the transverse position distribution for five energies. The same initial distribution, matched to the reference energy, is used in all cases. Horizontal and vertical emittances are set to approximate the beam produced by the University of Melbourne Pelletron.

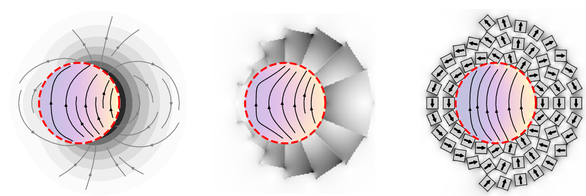
or Pelletron fluctuations. As such, we are investigating how susceptible the output beam profile is to variance in the input, ensuring that a small change to the incoming beam does not become a large error after the nonlinear beamline.

It is expected that the injection parameters will be defined by an energy degrader and beam collimator [13], significantly limiting the degree of variation of the raw Pelletron output. Here, we assume that the injected beam is matched to the reference momentum, as is the case in Fig. 2. Despite concerns that the strong nonlinear fields would exacerbate input errors, we have found that the output beam distribution is robust, even for input errors >1 %. This is likely due to the linear phase advance being far from resonances and the short length of the beamline not allowing time for errors to accumulate, and will be the focus of a future study.

MAGNET PROGRESS

Permanent magnet Halbach arrays [17] constructed using 3D printed mounts will produce the required magnetic fields. To reduce costs and allow for rapid testing, commercially available NdFeB magnet blocks will be used: each magnet array is expected to cost AU$2000, less than a tenth of the cost per magnet for CBETA [18], which required custom magnet blocks. This reduction in price also comes with a reduced maximum field strength and less accurate multipoles, but our required fields can still be readily achieved.

Magnet design to first order can be done with a reciprocity theorem: the magnetisation required to produce a B-field is the dual of the magnetic field produced by a magnetisation oriented with that B-field [19]. This is seen in Fig. 3a, where it is not possible to determine whether the inside is a magnet and the outside a B-field, or vice-versa. To demonstrate that this scheme will produce feasible magnets, the approximate required magnetisation has been calculated for the first magnet in the arc (magnet A in Table 1), with the solution from reciprocity, a trapezoidal segmentation similar



(a) Ideal magnetisation and fields (b) Trapezoidal segmentation (c) Square segmentation

Figure 3: Demonstration of magnet array creation, with the solution from magnetic reciprocity, trapezoids similar to CBETA, and segmentation with commercial magnet blocks. The inner bore radius is 4.5 cm.

to CBETA, and a first-order estimate of a segmentation with uniformly magnetised blocks given by the reciprocal solution. As shown in Fig. 3, approximately ideal magnetisation can be readily achieved. The next step will be to optimise the segmentation with uniform blocks, and iterate the design at the same time as beamline optimisation.

CONCLUSION

The TURBO project at the University of Melbourne will produce a proof-of-concept large energy acceptance beam delivery system, a world-first demonstration and a step towards improving charged particle therapy. Initial design and optimisation studies achieve suitable optics with a momentum acceptance of ±42 %, breaking the FFA ‘scaling law’ to reduce dispersion. Acceptable beam distributions are attainable over the full energy range, and are shown to be robust against errors. Investigations are ongoing for the permanent magnet arrays that will be used for beam steering and focusing. Future work will build on the current design, integrating realistic magnets and reoptimising this novel beamline.

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