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PRELIMINARY STUDY OF A LARGE ENERGY ACCEPTANCE FFA BEAM DELIVERY SYSTEM FOR PARTICLE THERAPY

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Abstract

The availability and use of ion beams for radiotherapy has grown significantly, led by technological developments to exploit the dosimetric advantages offered by charged particles. The benefits of particle therapy (PT) are well identified however its utilisation is still limited by high facility costs and technological challenges. A possibility to address both of these can be considered by improvements to the beam delivery system (BDS). Existing beamlines and gantries transport beams with a momentum range of ±1% and consequently, adjustments in depth or beam energy require all the magnetic fields to be changed. The speed to switch energies is a limiting constraint of the BDS and a determinant of the overall treatment time. A novel concept using fixed field alternating gradient (FFA) optics enables a large energy acceptance (LEA) as beams of varying energies can traverse the beamline at multiple physical positions given the same magnetic field. This presents the potential to provide faster, higher quality treatments at lower costs, with the capability to deliver advanced PT techniques such as multi-ion therapy. We explore the applicability and benefits of a LEA BDS.

INTRODUCTION

Particle therapy is an advanced modality of radiation therapy which utilises the advantageous physical characteristics of hadrons to deliver a precise amount of dose to treat cancers. Presently, over 220,000 patients have been treated with protons, 34,000 with carbon, 2000 with helium and 400 with other ion beams. There are over 100 operating facilities worldwide, the majority of these provide proton beam therapy and ~11 of these offer carbon ion therapy however many more are in planning stages or under construction [1].

Recent progress in accelerators and related technologies have allowed greater capabilities with current state-of-the-art systems, also supporting the development of advanced delivery techniques. This includes the shift to much higher dose rates (‘FLASH’ ≥40 Gy/s [2]), utilising beams with multiple ion species [3, 4] and possibilities of online imaging [5]. Nonetheless, the affordability, complexity and limitations with current technology restrict the availability of PT and a significant aspect of this relates to the dose delivery process and the treatment time. Although the beam delivery is a determinant of the overall treatment time, this is not solely dependent on the capabilities of the BDS; multiple factors are involved. However, improvements to the BDS can enable faster treatments: one such development is to increase the energy acceptance range of the BDS using an FFA optical configuration. This preliminary study presents an overview of the potential benefits for such a design and its applicability for multi-ion therapy and other possibilities.

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BEAM DELIVERY

The BDS determines how the beam is shaped, transported and ultimately delivered to the patient for treatment. This includes the beamline and gantry which rotates to transport the beam at multiple angles, in order to deliver the prescribed dose to the patient with the required beam parameters (spot size, position and intensity etc.). The BDS must be able to deliver the beam with high accuracy (sub mm precision), at different energies and with modern capabilities such as pencil beam scanning (PBS) as per the needs of the treatment. Consequently, these requirements amount to large associated costs with their weight, size, construction and operation.

In PBS, the beam is magnetically deflected across the tumour in the transverse plane across one layer or an iso-energy slice (IES) and then the beam is adjusted longitudinally to a shorter depth (Fig. 1).

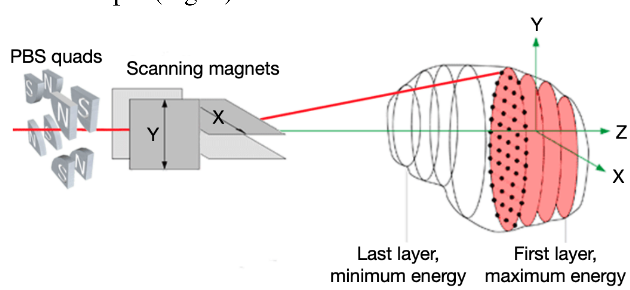

Figure 1: PBS delivery. Scanning magnets deflect the beam which traces across a target volume, superimposed in multiple layers to deliver a conformal 3D dose distribution. Adapted from [6].

Different scanning techniques (spot, raster and line/continuous) and optimisation methods may be used to irradiate each layer however this general process is repeated until sufficient coverage is achieved. The dose is painted such that the accumulation of the distribution in both planes results in the dose prescribed by the treatment plan. The number of spots and layers needed, depend on the tumour size and complexity of the treatment which dictates the treatment time. However, this consists of different time contributions from various components of the BDS: if we consider only the beam delivery process, this can be approximated to include the transverse scanning, energy adjustment and system dead times.

ENERGY VARIATION

As the energy variation has a significant impact on treatment time, we examine whether this can be improved with

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the BDS. For horizontal scanning and dead times (diagnostics, control system etc.), these are generally of the order of 1–100 ms [7–9] but comparatively, the time to switch energy ranges from the order of 100 ms to typically, seconds. Fast energy changes of 80 ms have been achieved with PBT gantry 2 at PSI [10] by using an energy selection system (ESS) where components are mechanically inserted within the beamline to actively degrade the beam. The additional interactions in the beam path however impact the resulting beam characteristics, introducing a range of other considerations (beam transmission, quality, energy spread etc.). The method of energy modulation is mostly dependent on the type of accelerator: different beam energies can be extracted from a synchrotron whereas for a cyclotron the energy is fixed and therefore an ESS is necessary. Varying the energy with beam modifying devices is faster than directly with the accelerator, as this then depends on the cycle time, it can take a few seconds to adjust the magnets for re-acceleration and extraction [11]. Further reductions in dead times are also possible as new accelerator control and extraction schemes are being tested and implemented (multi-energy extraction and extended flattops [12, 13]).

Nevertheless, all cases still require the beamline optics to be changed and each magnet must be ramped to accommodate for the change in energy. This time requirement is the main limitation when switching between energies to irradiate multiple layers at different depths and the common issue among existing facilities. Typical beamline and gantries have a $\pm 1\%$ momentum acceptance range (approximately $\pm 2\%$ energy acceptance) equating to changes of 5 mm in water equivalent depth which is the general spacing between each adjacent IES [14]. The accumulation of delays for each IES results in extended delivery times: irradiation duration times within the 3-5 s range has implications for treatment as this corresponds with the respiration cycle [15]. The deviation of motion between the beam and patient (interplay effects) results in dose inhomogeneity, reduced conformity and use of PT for certain tumour sites. To compensate, facilities apply a variety of motion mitigation strategies [16]. A common approach is by rescanning as repetitive irradiation statistically averages out dose errors. Improvements can be achieved depending on the efficiency, method and number of rescans and essentially, with a faster BDS [17]. Further benefits with volumetric rescanning and many other capabilities are possible with fast energy variations [10, 18].

FFA OPTICS

Given the momentum acceptance range of typical gantries, several different designs for proton therapy have been proposed which offer an increased acceptance range to ± 3–15% [8, 14, 19], using a combination of superconducting magnets with achromatic optics for the bending sections. FFA designs have reported a LEA of up to ± 25–30% for both proton and carbon ion therapy [20–22]. The non-scaling FFA concept utilises combined function dipole and quadrupole magnets arranged in repeated cells of alternating gradients. This results in strong focusing in both planes with small dispersion and is stable for wide range of energies, enabling transportation through the same fixed magnetic fields. The magnets can be constructed with smaller apertures, corresponding to reductions in the size and cost of the magnet. However, the beam rigidity increases with energy and heavier particles require larger gradients for the same bending radius. Superconducting magnets may be necessary as the maximum field for conventional normal conducting (NC) magnets should not exceed 1.8 T. The overall design relies heavily on the parameters and capabilities of the magnets.

Initial beamline design

As a first proof-of-concept study to explore the LEA capabilities of a BDS for PT using FFA optics, a beamline with a 45° horizontal bend was designed as a scaled-down prototype. An optical lattice was simulated and optimised given the constraints of the facility at the University of Melbourne (UniMelb), Australia. The laboratory operates a Pelletron accelerator which can generate low energy beams of various ions and as relevant for this design, 0.5–4 MeV protons.

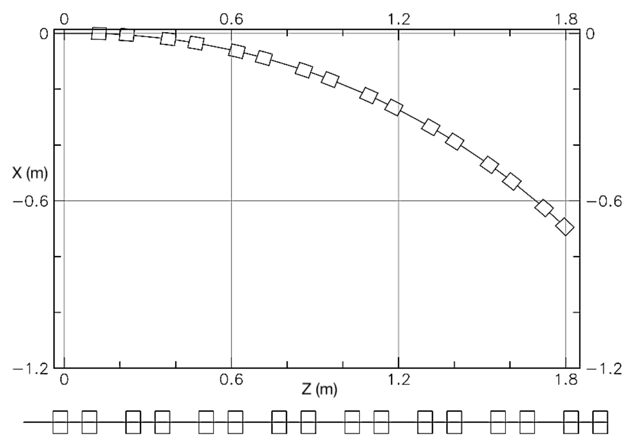

Figure 2: Optical lattice layout of FFA beamline with 45° bend comprising 8 cells of combined function doublets, the focusing and defocusing magnets are separated by 5 cm. Each cell is separated by 10 cm of drift space.

The optical lattice consists of pairs (doublets) of focusing and defocusing combined function magnets arranged into 8 cells (Fig. 2). The beamline was designed to be constrained within the 2 m of physical space available and to accept the output beam properties of the Pelletron. NC magnets were defined as 5 cm in length and drift spaces were chosen taking into account the cell configuration, reference energy and normalised quadrupole strength (k). The parameters exhibited an interdependence and a process of optimisation was necessary for the goal of generating a stable configuration whilst minimising the magnet aperture. The orbit excursion (distance between furthest offset orbits) changes according to the applied k value and the chosen reference energy, corresponding to the beam rigidity. Given these considerations, the multiple parameters were optimised for the full 0.5–4 MeV energy range. For a reference energy of

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1.5 MeV, this equates to a momentum range of -42.5% to +63.3%. The offset orbits of 12 different beam energies (displayed as their momentum deviation in %) passing through the NC quadrupole magnets are shown in Fig. 3.

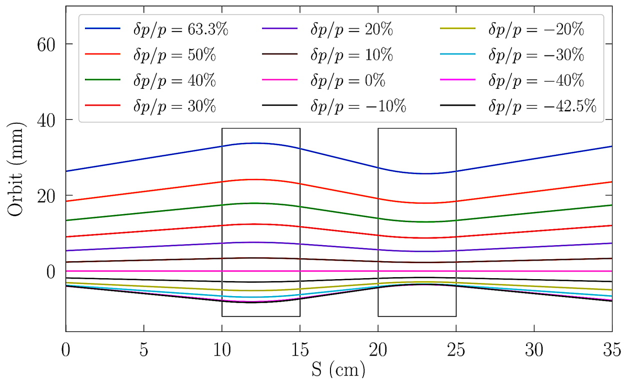

Figure 3: Varying beam energies as transported through a single doublet cell of the FFA bend.

Developments from this work will look at characterising the pelletron beam as well as further modelling for matching into this beamline. Future construction and first measurements are anticipated to follow.

Considerations for multi-ion delivery

Protons are most commonly used for PT as they are the lightest charged particle, therefore the simplest to accelerate and deliver. The benefits of heavier ions for treatment are well established, we briefly mention features such as: reduced range straggling and scattering, larger linear energy transfer and radiobiological effects [23], in-vivo imaging [24, 25]. As such, a variety of different ion species have been proposed for treatment including helium, lithium, carbon, oxygen, neon and argon.

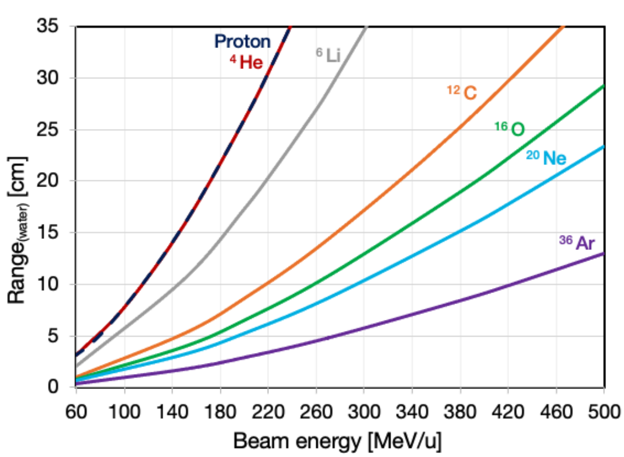

Figure 4: Approximated range of proton and helium, lithium, carbon, oxygen, neon and argon ions in water as dependent on beam energy.

Different ions can also be combined to capitalise on useful characteristics of the individual particle types; an enhanced dose distribution [26] can be achieved among several other potential benefits [27]. In practice however, to transport and deliver these beams involves many different considerations. As a first step, we examine some significant beam properties: energy, range in water and beam rigidity for relevant ions. To overview the energies required over the therapeutic depths (3–30 cm), the corresponding range values were approximated by applying a factor of A/Z^2 to the proton range as it scales for the same energy/nucleon [23] and also checked against [28, 29] (Fig. 4). As the range is a function of the kinetic beam energy, the beam rigidity was calculated for each ion species given their charge to mass ratio (Q/A) (Fig. 5).

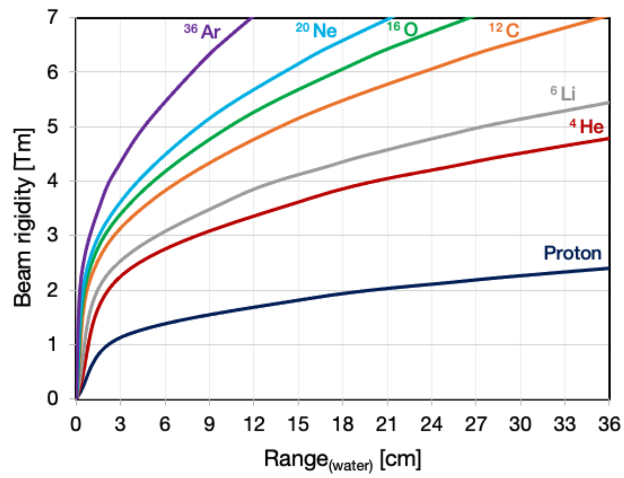

Figure 5: Beam rigidity of different ion beams across therapeutic depths.

Helium has the same Q/A ratio as protons and follows the same energy to range relation yet has almost double the rigidity. For heavier ions, the beam rigidity increases significantly across the therapeutic range, shown for values approaching the maximum treatment depth for carbon. This already warrants massive structures: for 30 cm range with a 430 MeV/u carbon ion beam, the NIRS superconducting gantry weighs ~300 tonnes [8]. Therefore further study is needed to define the optical parameters, assess what might be the necessary momentum acceptance, and to determine boundary conditions to design a BDS for multi-ion delivery.

CONCLUSION AND OUTLOOK

Existing BDS have a limited momentum acceptance range and are slow to switch energies. The time burden of energy variations can be minimised if the magnetic fields could remain fixed for the entire delivery yet still transport the beam with the required parameters. This is a potential solution offered by a LEA BDS. A scaled-down beamline design was optimised for low energy protons at UniMelb, providing a baseline to explore the feasibility of a BDS based on FFA optics. The benefits of a LEA and first considerations for transporting multiple beams of different ions were overviewed. The capabilities of a LEA BDS facilitate the delivery of advanced techniques for the future needs of PT.

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