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CONCEPTUAL LATTICE DESIGN FOR VERTICAL FIXED FIELD MEDICAL ACCELERATORS

M. Vanwelde *, C. Hernalsteens[1], E. Gnacadja, E. Ramoisiaux, R. Tesse, N. Pauly
Service de Métrologie Nucléaire, Université libre de Bruxelles, Brussels, Belgium
[1]CERN, European Organization for Nuclear Research, Geneva, Switzerland

Abstract

Hadron therapy is established as a method of choice for a number of cancerous diseases, and its advantages are well-established for specific malignancies. Modern medical particle accelerators still struggle to fulfil critical features required by advanced treatment modalities, such as variable energy beams, high repetition rate, and pulse-by-pulse intensity modulation. Fixed Field Accelerators (FFAs) are suited to tackle these challenges as they can accelerate particles over a wide energy range with fixed magnetic fields. Vertical orbit excursion FFAs feature constant tunes and a small horizontal footprint, making them excellent candidates for medical applications. We propose a conceptual design of a medical vFFA. Its linear and nonlinear beam dynamics is presented in-depth. This study demonstrates the vFFA potential to provide a new direction for the study and design of medical FFAs suitable for next-generation particle therapy systems.

INTRODUCTION

Hadron therapy is increasingly becoming the preferred method for several clinical indications [1], such as deep-seated malignant tumors, and the number of proton therapy centers worldwide is growing. The particle accelerators in use today for hadron therapy (cyclotrons or synchrotrons) are a limiting factor in the growth of charged particle therapy. These accelerators struggle in fulfilling simultaneously key features required by advanced treatment methods, such as arc therapy and flash therapy: variable energy beams with extremely fast energy changes, a high repetition rate of the order of 1 kHz or more, and pulse-by-pulse intensity variation with strict control on the charge per pulse. On the one hand, cyclotrons offer high repetition rates at the price of fixed-beam energy, requiring an energy degradation system and important shielding structures. On the other hand, synchrotrons offer variable beam energy but at the cost of a much lower repetition rate leading to longer treatment times.

Fixed Field Accelerators (FFAs) are well-suited to address these challenges because they can accelerate particles over a wide energy range with a high repetition rate allowed by the fixed-field nature of the magnetic fields. Due to these unique properties, they have been contemplated for medical applications [2]. Scaling FFAs [3–5] maintain constant tunes during acceleration by imposing a strong condition on the magnetic field, but exhibit significant orbit excursions resulting in large footprints with complex magnet geometries. To overcome these limitations, non-scaling FFAs relax the condition on the magnetic field to have easier-to-build magnets and to reduce the orbit shift at the expense of a non-zero tune variation during the acceleration cycle. This is a major limitation as it exposes the dynamics to resonant mechanisms that drastically limit the machine's performance. The resonance crossing mechanisms are substantial limitations for medical applications as the acceleration is not fast enough to avoid beam losses. One approach to stabilizing the tunes consists in starting from a scaling lattice with the working point in the second stability zone [6], then transforming into a non-scaling lattice by expanding the scaling FFA non-linear field in terms of multipoles and truncating this series at the lowest orders [7]. This approach was used in the PAMELA project [8], which studies a superconducting proton and carbon complex with two non-scaling FFA rings. Recently, vertical excursion Fixed Field Alternating Gradient Accelerators (vFFAs) have regained interest [9]. This variant of scaling FFAs features a magnetic field that increases exponentially in the vertical direction so that the orbits are stacked vertically with the particles' momenta. The scaling condition is met without increasing the horizontal size of the accelerator. The magnets are smaller with simpler configurations, such as rectangular superconducting coil-dominated magnets [9], which simplifies their construction and alignment. vFFAs thus feature constant tunes, a small horizontal footprint, and easy-to-build magnets, making them excellent candidates for medical applications.

This paper proposes a preliminary design for a medical vFFA ring suitable for the needs of the next generation of proton therapy systems. The available working points are studied in detail by considering the medical requirements, such as the energy range of 70-250 MeV, and technological constraints, such as the maximum field values for superconducting magnets. The linear and non-linear beam dynamics are investigated, accounting for the strongly coupled optics of vFFAs. This first characterization of a medical vFFA demonstrates that such accelerators can meet the clinical requirements and potentially provide a new direction for the study and design of medical FFAs.

DESIGN OF THE PROTON RING

In this work, we propose a proton accelerator that aims to accelerate protons from 31 MeV[1] to 250 MeV, hence covering the medical energy interval of 70-250MeV corresponding to the beam clinical range of 4.1 cm-37.96 cm in water needed to treat cancers including deep-seated tumors. The accelerator is based on vFFA elements, whose magnetic field satisfies the scaling condition $B = B_0 \exp[k(z - z_0)]$, where $k = (1/B)(\partial B/\partial z)$ is the normalized field gradient, z_0 is a vertical reference position and B_0 is the bending field at that reference position. To design and study this vFFA medical machine in detail, we used the ray-tracing code

* marion.vanwelde@ulb.be

[1] The injection system is assumed to be the same as in the PAMELA lattice: a commercial 31 MeV cyclotron.

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Zgoubi [10–12] as it allows step-by-step particle tracking in complex vFFA magnetic fields without assuming a specific closed orbit. Moreover, its Python interface Zgoubidoo [13] offers advanced tools including the Zgoubi input preparation, result collection and efficient storing, and the in-depth analysis of tracking data with advanced methods to explore the beam dynamics [14]. Specifically, it includes linear coupled optics computation at each integration step [15]. We have used the Zgoubi vFFA keyword that models the 3D magnetic field of scaling vFFAs[2] [16], with a fringe field function corresponding to an arctangent function to realistically describe the magnet field fall-off [17].

We started with the vFFA proton driver prototype presented in Ref. [18] studied under the ISIS-II project [19–21], and adapted the lattice to accelerate protons in the required energy range. We adjusted the length of the magnets and straight sections, as well as the offset between the magnets, to obtain available working points with maximum field values along the particle trajectory less than 4 T, ensuring the superconducting magnets are designable[3][8]. The length of the long straight section between consecutive cells is imposed to be greater than 1 m to facilitate injection and extraction and accommodate measurement systems for beam control.

Table 1 shows the main parameters of the lattice we have designed. It consists of an 8-cell ring with superconducting magnets, whose cells compose the side of a polygon. Each cell consists of an FDF triplet with the three vFFA magnets aligned on a straight line. The rectangular shape of the magnet eases their alignment in each cell and their alignment with other accelerator systems. The entire ring has a circumference of 40.16 m, which corresponds to an average radius of 6.4 m. The machine footprint is thus comparable to existing medical machine layouts (the PAMELA proton ring has a reference radius of 6.251 m) while remaining a scaling FFA.

Table 1: Main parameters of the preliminary vFFA medical lattice. It consists of an FDF triplet focusing lattice with the vFFA magnets aligned on a straight line for each cell.

Parameter	Value
Energy	31 to 250 MeV
Number of cells	8
Cell length	5.02 m
Bd magnet length	1.4 m
Bf magnet length	1.15 m
Straight length	1.24 m
Space between Bd and Bf	0.04 m
Fringe field extent	0.45 m
Bd/Bf ratio	0.98
Normalised field gradient (k)	0.74 m^{-1}

To ensure the selection of a working point that results in stable orbits, we computed the stability diagram, as illustrated in Fig. 1, containing the points with stable optics across the cell for different values of normalized field gradient k and ratios of the focusing and defocusing magnet fields B_D/B_F. For each stable working point, we computed the maximum field value along the periodic closed orbit for a particle at 250 MeV to ensure selecting a working point with maximum field values no greater than 4 T. Only a few points in the stable region meet the required criteria on the magnetic field. We carefully selected the normalized field gradient $k = 0.74\ m^{-1}$ and the D/F field ratio $R = 0.98$, as it gives reasonnable normalized linear invariants in the linearly decoupled planes. This working point presents stable optics with the eigentunes $\nu_1 = 0.153$, $\nu_2 = 0.592$, and a maximum field value encountered by the reference particle of 3.9 T.

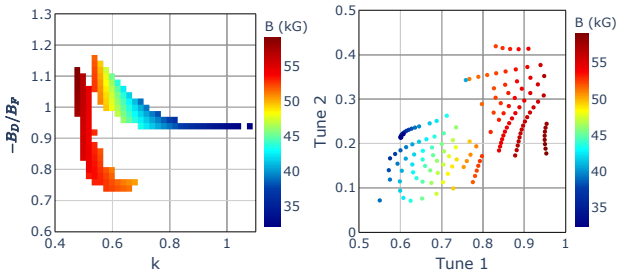

Figure 1: (a) Stability diagram indicating the available working points for the preliminary medical vFFA design, as a function of the normalized field gradient k and the ratio of the reference field in the focusing and defocusing magnet $\frac{B_D}{B_F}$. (b) Available working points in the eigentunes space, with the point colored with the maximum field value on the closed orbit of the reference particle at 250 MeV.

Figure 2 shows the vertical closed orbit solutions across a cell for several energies ranging from 70 MeV to 250 MeV, and the magnetic field components along these trajectories. The orbits are vertically stacked, resulting in a vertical orbit excursion of 92 cm. The accelerator presents a finite vertical dispersion, a zero horizontal dispersion, and constant cell eigentunes across the entire energy range, as expected in vFFAs. The magnetic field scales with energy, and the strongest magnetic field component is the longitudinal component, leading to a significant total magnetic field, while not contributing to bending the particle trajectories [22]. Obtaining lower total field values is thus challenging due to the intrinsic longitudinal component of vFFAs, which is one of the primary disadvantages of this type of accelerator.

BEAM DYNAMICS STUDY

vFFAs feature strongly coupled optics due to their skew quadrupolar and longitudinal field components [23]. The study of their linear beam dynamics thus requires using an adequate parametrization for coupled betatron motion [15]. As the lattice is strongly coupled, choosing the correct mode identification is essential to compute the lattice functions because some mode flip conditions[4] may occur at some places of the lattice. We computed the one-cell β-functions from the Edwards and Teng parametrization and the Lebedev

[2] The Zgoubi vFFA keyword implements vFFA analytical field expressions, with the magnetic field components expressed as a polynomial expansion in the horizontal coordinate which is truncated at the 10th order.

[3] In the PAMELA superconducting rings, the requirement is that the maximum magnetic field be lesser than 4.5 T [8]. We slightly lower the field limit to ensure the magnets can be constructed.

[4] See Refs. [15, 24] for more details.

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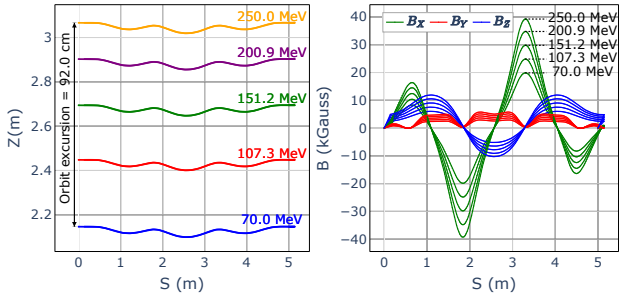

Figure 2: (a) Periodic vertical closed orbits across a cell for different energies ranging from 70 to 250 MeV, and (b) Magnetic field components along these trajectories. The vertical orbit excursion corresponds to 92 cm.

and Bogacz parametrization with Zgoubidoo, as shown in Fig. 3. The maximum β values are not larger than 8 m, which is deemed acceptable.

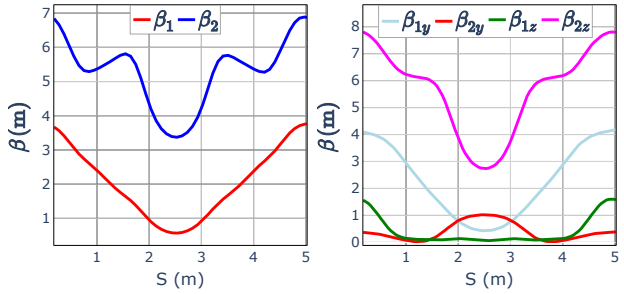

Figure 3: β-functions from the Edwards and Teng (left) and Lebedev and Bogacz (right) parametrizations across a cell.

We also briefly investigated the non-linear beam dynamics by examining the linearly decoupled phase spaces (u, p_u) and (v, p_v), as illustrated in Fig. 4. We computed the normalized linear invariants with single particle tracking in each linearly decoupled plane by searching for the maximum amplitudes in the u and v directions (with $p_u = p_v = 0$) for which the particle survives 1000 turns. To that end, we tracked over 1000 turns particles with initial coordinates $(u, p_u, v, p_v) = (iu_0, 0, 0, 0)$ and $(u, p_u, v, p_v) = (0, 0, jv_0, 0)$, where (i, j) are integers and the initial normalized amplitude corresponds to $u_0 = v_0 = 6.6$ mm. We gradually increased i and j until the particle was lost. Then, smaller steps (0.7mm increments) are chosen to scan between the maximum amplitude surviving particle and the first lost particle to obtain higher precision on the linear invariants. We obtained normalized linear invariants $e_u = 788.41\ \pi$ mm mrad, $e_v = 358.61\ \pi$ mm mrad for a particle at 250 MeV. As vFFAs are scaling machines, the phase spaces are invariant across all energies, so the dynamic aperture scales perfectly with the particle's momenta. It is thus straightforward to obtain the normalized linear invariants at the injection energy (31 MeV) $e_u = 262.94\ \pi$ mm mrad, $e_v = 119.60\ \pi$ mm mrad. These linear invariants in both decoupled planes are sufficient for charged particle therapy [8].

The design presented in this work is preliminary, and further studies are required, particularly to investigate the

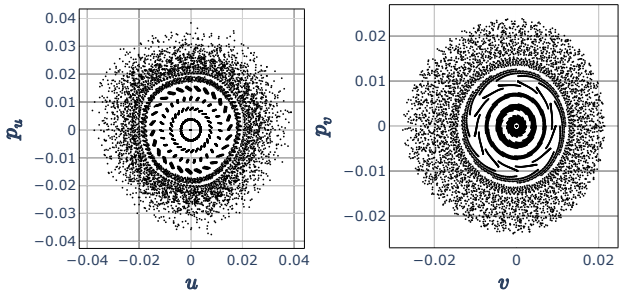

Figure 4: Linearly decoupled phase spaces obtained by tracking particles with several initial amplitudes in $[0, u_{max}]$ with $p_u = 0$ (a) and in $[0, v_{max}]$ with $p_v = 0$ (b).

extraction systems at different energies. Nevertheless, this preliminary design shows interesting characteristics, such as a similar footprint, maximum field values, stable optics, and acceptable linear invariants comparable with the values of the PAMELA proton ring while maintaining the advantages of a scaling FFA.

CONCLUSION

We proposed a conceptual design of a medical scaling vFFA. The design concerns the main ring that aims to accelerate protons from 31 MeV to 250 MeV. We have obtained a preliminary design with an average radius of 6.4 m and consisting of rectangular superconducting magnets that can be more easily constructed and aligned than conventional scaling FFA magnets. The maximum field values encountered by the particle are no more than 4T and are mainly due to the longitudinal field component, which does not contribute to bending the beam. The orbit excursion for the energy range 70-250 MeV is 92 cm. This orbit excursion should be reducible by adapting the design and utilizing higher normalized field gradient values. Nevertheless, it is the main drawback of the current lattice as it involves designing an extraction system that could handle variable energy extraction at different vertical coordinates. Further designs could explore setting an angle to the magnet faces [9] to reduce the cell length while keeping acceptable magnetic field values. The linear and non-linear beam dynamics have been investigated and present reasonable β-functions and linear invariants in the linearly decoupled planes. In-depth characterization of the dynamic aperture in this highly non-linear and coupled machine must still be explored, including a measure of the 4D stability domain and metrics to evaluate the phase space complexity. Further studies are also needed to investigate the other parts of a medical center, such as the injection and extraction systems, the transfer lines, and the gantries. This initial study of a medical vFFA machine shows promising results and suggests opportunities for further research and development of vFFAs for use in next-generation particle therapy systems.

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