A FIXED FIELD ALTERNATING GRADIENT ACCELERATOR FOR HELIUM THERAPY*

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Abstract

A non-scaling fixed field alternating gradient (nsFFAG) accelerator is being designed for helium ion therapy. This facility will consist of 2 nested rings, treating with helium ions (He^{2+}) and image with hydrogen ions (H_2^+). Compared to protons, ions deliver a more conformal dose with a significant reduction in range straggling and beam broadening. Carbon ions are currently used and there are no current facilities providing helium therapy. We are investigating the feasibility of an FFAG approach for helium therapy, which has never been previously considered. We investigate emittance and demonstrate that the machine meets isochronicity requirements for fixed frequency RF.

INTRODUCTION

There is an increased interest in the use of ions heavier than protons and lighter than carbon for treating cancer; helium, lithium, berylium and boron (these will be referred to as light ions). It is well established ions hold advantages over protons when irradiating cancerous tumours; the absorbed dose in the tumour increases relative to the entrance dose with reduced range straggling and beam broadening. This effect is improved as the mass of the ion species increases, but consequently fragmentation becomes more prevalent [1–4]. Fragmentation produces secondary particles from inelastic nuclear interactions between the ion and the tissue, causing more damage. Fragmentation occurs more in the Bragg peak because of the increased number of collisions, causing a dose tail beyond the target [5]. Currently only carbon ions are used to treat cancer, and the use of a lighter ion will result in less fragmentation and reduce the amount of dose in the tail, as shown in Fig. 1 [1–4].

The difficulty in accelerating carbon can be expressed via beam rigidity, as depicted by Fig. 2. Figure 2 shows the bending radius against energy for all ions up to carbon, and the requirements to accelerate each ion to the necessary energy for 30cm depth in water is highlighted. The beam rigidity data was calculated using SRIM/TRIM, a monte carlo code [6]. The reduced beam rigidity of lighter ions allow for a smaller accelerator, and hence a reduced cost. For a Bragg peak at 30cm depth carbon ions need an energy of 450 MeV/u, for which the beam rigidity is extremely high. To counter the high rigidity current carbon accelerators are
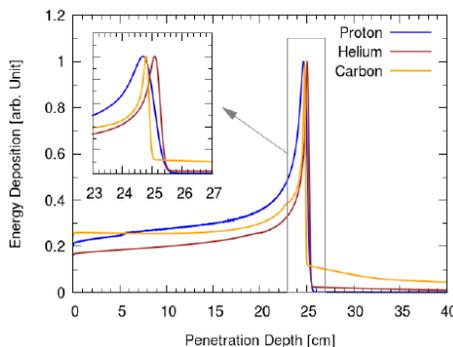

Figure 1: [3] A comparison of the Bragg peak for a specific penetration depth for protons, helium ions and carbon ions. The Energy deposition is relative to the maximum deposition for the ion species. A larger fragmentation dose occurs from carbon ions, in comparison to helium ions and protons.

large, HIT at Heidelberg for example, uses a 65m circumference ring to reach desired energies [7]. Helium would be the easiest lighter ion to accelerate, and in terms of rigidity is a half way compromise between carbon and protons, yet still obtaining advantages of ion therapy.
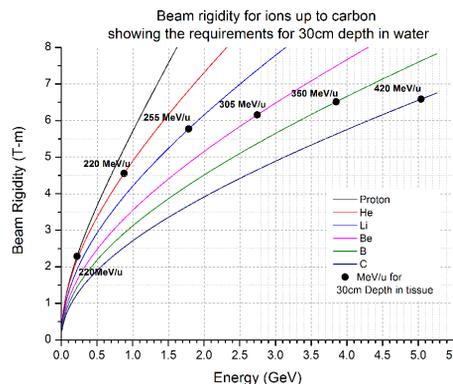

Figure 2: The beam rigidity required to bend the beam for varying kinetic energy for fully stripped ions up to carbon. The beam rigidity required to reach 30cm water depth is highlighted for each ion, and labeled with the energy required per nucleon.

There are no light ion therapy centres worldwide. Current carbon ion therapy facilities are capable of accelerating light ions, and light ion research is beginning to start [8]. It is clearly costly and challenging to implement proton therapy into an established clinical environment, and even more so for carbon therapy. A 65m circumference synchrotron

is not feasible in a general clinical environment and no current cyclotron is capable of accelerating carbon ions to the necessary energy. A compromise between the cyclotron and a synchrotron is a FFAG accelerator. The FFAG takes the benfits of an isochronous cyclotron by having a varying azimuthal magnetic field, and an alternating gradient from the synchrotron, producing a rapid variable energy machine. This makes FFAG accelerators ideal for ion acceleration [9]. The nsFFAG does not follow the scaling law, so as the beam accelerates the optics will change. The changing optics can cause issues, but if designed correctly, can deliver a smaller footprint compared to a scaling FFAG.The nsFFAG is conceptually more difficult, but has been demonstrated to work with EMMA at Daresbury [10].

The feasibility in accelerating helium ions using a nsFFAG accelerator is being investigated, hoping to evaluate if a nsFFAG is a technically feasible option for therapy with helium and how their performance and cost compare with other possible options. Ultimately size is cost, and using a nsFFAG accelerator will potentially allow for smaller magnets, a reduced footprint and hence a reduced cost.
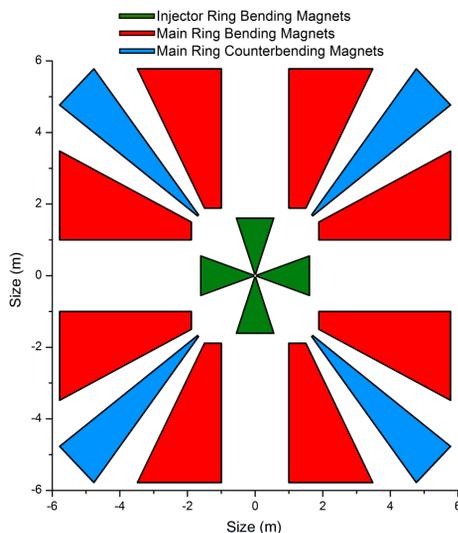

Figure 3: A representation of the magnet layout for the helium nsFFAG. The injector ring is highlighted in green and the main ring in red and blue. The blue magnets are counter bend magnets. All other magnets are bending magnets

SIMULATIONS

The accelerator design consists of 2 superconducting nested rings; an injection ring and a main acceleration ring. We aim to accelerate isochronously from 0.5 MeV through to 900 MeV over the two rings. The injection ring will accelerate He^{2+} ions from 0.5 MeV up to 250 MeV, using 4 multipole bending magnets. The main ring will then accelerate ions from 250 MeV through to 900 MeV, with 8 bending multipole magnets and 4 multipole counter bending magnets. A depiction of the layout can be seen in Fig. 3. The FFAG

is being designed to be capable of accelerating ions with a charge to mass ratio (Q/m) = ½. This feature is deliberate, so the it can image with (H_2^+) ions and treat with He^{2+}. This increases treatment accuracy and reduces treatment time.

The focus so far has been on the injection ring. FACT, a user interface for the COSY infinity particle tracking code [11] has been used to make changes to the initial field map design provided by C. Johnstone (PAC). The focus of the changes in COSY are to correct the tune and time of flight (ToF). The use of a nsFFAG does not follow the scaling law, instead the magnetic field profile is calculated by Eq. (1).

$$B = B_0 + B_1r + B_2r^2 + ...B_nr^n \qquad (1)$$

Where B is the total magnetic field in Tesla, B_n is the nth order magnetic field component and r is the radius in meters. This allows for the field component of each order to be optimised individually. COSY assesses the optics and allows one to find stable orbits for the input magnetic field configuration at a given energy. Once complete the field map was then input in OPAL, a charged particle tracking code capable of full 3D space charge calculations [12]. The tunes and ToF were extracted from OPAL and compared to the data produced from COSY.

RESULTS

The isochronicity of the machine was optimised in COSY. The tunes and path lengths are provided by COSY, and the ToF was manually calculated from the path length for each orbit. The geometry of the magnets were changed alongside the different orders of the magnet field to deliver isochronous acceleration. After optimisation the injection ring was found to be isochronous to within 0.11% excluding the first point where the variation is 0.75%. The tunes were found to be stable, however there is an integer resonance crossing between 1 to 5 MeV. This crossing is fast and should not be destructive to the beam. The ToF and tunes extracted from OPAL strongly agree with COSY and are displayed in Fig. 4 and Fig. 5 respectively.
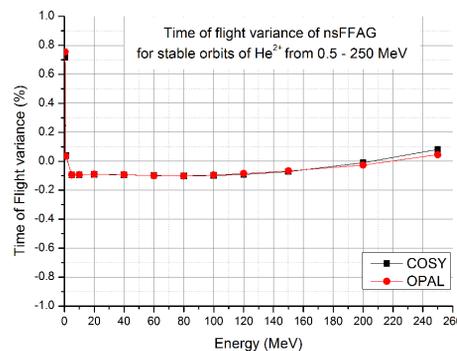

Figure 4: A graph showing the time of flight (ToF) variance compared to the mean against kinetic energy for helium in the injector ring. Results are shown from two different codes, COSY and OPAL.
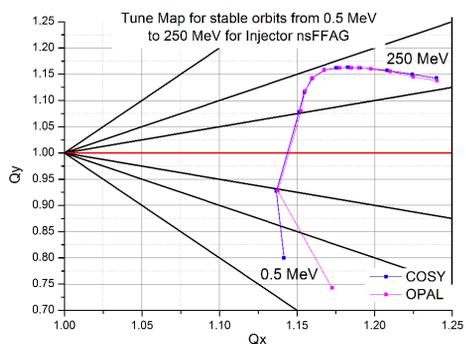
Figure 5: A tune map showing the tunes provided from COSY and OPAL. It can be observed the vertical tune crosses an integer resonance. This tune suppression is caused by the over lapping fringe fields near at the inner radius.

The beam was accelerated in OPAL, using two RF cavities with an operating frequency of 10.397 MHz. A single particle was used to find the ideal acceleration orbit, and the injection angle and radius were changed to optimise the orbit bunching. 320 turns were required to accelerate the beam up to 250 MeV. 10^5 particles with a spot size of 3mm were simulated without space charge and restricted by a vertical aperture of $+/-$ 1cm. No particles were lost and the RMS emittance in the x, y and z directions as a function of energy are depicted in Fig. 6. The emittances at 250 MeV were found to be 1.76 $\times 10^{-6}$ m rad, 6.26 $\times 10^{-6}$m rad and 8.69 $\times 10^{-8}$ m rad for x, y and z respectively.

DISCUSSION

The isochronicity of the machine is good enough for fixed RF acceleration, demonstrating that the integer tune crossing is non-destructive. Both the ToF and the tunes are effected by the overlapping fields at the inner radii of the magnets at lower orbits, which suppresses the vertical tune and decreases the path length. This is relieved as the spacing between the magnets increases and the vertical tune becomes stable. There are some unusual peaks in the y emittance which were not expected. The slight variation in the operating frequency to the revolution frequency is good enough to accelerate, but OPAL has dumped the beam when it is crossing the RF cavity. This causes the peaks in the y emittance and should be ignored. This has been confirmed by plotting the emittance as a function of angle. The peaks occur when the beam is at a 45 degree angle - directly over the cavity. Although only accelerated to 250 MeV the machine is capable of accelerating to 270 MeV. This may be necessary when designing the main ring in more detail where a higher extraction energy may be needed.

CONCLUSION

Cancer is a leading cause for mortality, and the benefits of using ions to treat this disease are well established. Helium ions hold the potential to be the stepping stone in delivering and biologically understanding ion therapy. We have
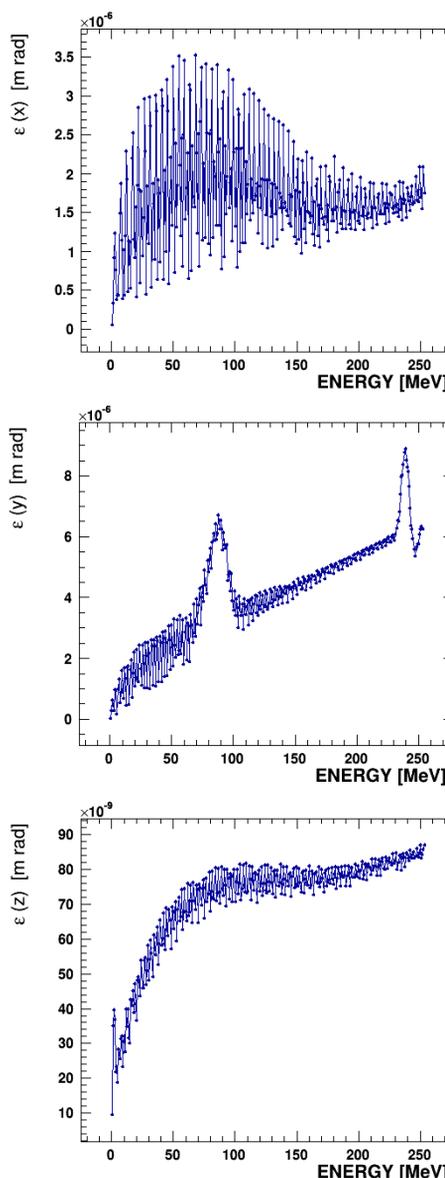

Figure 6: The RMS emittances without space charge from top to bottom for x, y and z respectively. The peaks in the y emittance are due to the non-perfect isochronicity which are caused by OPAL and should be ignored.

successfully demonstrated the isochronous acceleration of He^{2+} ions from 0.5 MeV to 250 MeV using a nsFFAG. Further work needs to be completed on the injector, such as the acceptance of the machine and the acceleration of H_2^+. Injection and extraction for the inejector ring will also be investigated. We now aim to work on the design of the main ring, and isochronously accelerate He^{2+} from 250 to 900 MeV.

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