HEATHER – HElium ion Accelerator for radioTHERapy∗

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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 superconducting rings, treating with helium ions (He\(^{2+}\)) and image with hydrogen ions (H\(^{+}\)). Currently only carbon ions are used to treat cancer, yet there is an increasing interest in the use of lighter ions for therapy. Lighter ions have reduced dose tail beyond the tumour compared to carbon, caused by low Z secondary particles produced via inelastic nuclear reactions. An FFAG approach for helium therapy has never been previously considered. Having demonstrated isochronous acceleration from 0.5 MeV to 900 MeV, we now demonstrate the survival of a realistic beam across both stages.

INTRODUCTION

The physical benefits of using protons over photons have been the cause for the growth of proton facilities for cancer treatment, and hence proton therapy becoming more prevalent over the past decade. These physical benefits increase with mass, which led to the development of carbon ion therapy. The use of heavier ions increases the absorbed dose in the tumour relative to the entrance dose, with range straggling and beam broadening reduced compared to protons. This effect is improved as the mass of the ion species increases, but consequentially with increasing mass ions become more difficult to accelerate and fragmentation becomes more prevalent [1–4].

Fragmentation is the breakup of the primary into lower Z particles, caused by inelastic nuclear interactions between the primary and the tissue. Most interactions occur at the Bragg peak, hence most secondaries are produced here. Clinically this means a dose tail of low Z secondaries is created beyond the tumour, and irradiate potentially critical structures [5]. Acceleration of carbon ions is difficult because of the increased beam rigidity as shown in Fig. 1. This difficulty in bending the beam translates into building larger machines. Clinically this makes it difficult to fit into current hospitals and requires the development of dedicated facilities. An example being HIT at Heidelberg, which accelerates carbon using a 65m circumference ring [6].

The use of an ion between protons and carbon would still deliver the physical benefits of ions over protons, and with a reduced beam rigidity allow for a smaller accelerator and ultimately a reduced cost. Current carbon facilities are the only facilities that are capable of accelerating helium ions,

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Figure 1: 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. This was calculated using SRIM/TRIM [7], a program dedicated to the stopping range of ions in matter and interest is rising, as work is being done in preparation to use helium at some of these facilities [8].

DESIGN

A non-scaling fixed field alternating gradient (nsFFAG) approach will be taken to investigate the feasibility of ion therapy using helium ions. FFAG accelerators have been previously identified as ideal candidates for ion acceleration, taking benefits from both the synchrotron and the cyclotron [9]. A non scaling design as opposed to a scaling design sacrifices tune control for a smaller machine, which for a medical accelerator is imperative.

HEATHER (HElium ion Accelerator for radioTHERapy) has been designed to be fully isochronous operating at fixed frequency RF acceleration from 0.5 MeV to 900 MeV over two superconducting stages, as depicted in Fig. 2. Particles with charge to mass ratio of \(\frac{1}{2}\) can be accelerated, enabling (He\(^{2+}\)) for treatment and (H\(^{+}\)) for imaging, improving accuracy and reducing treatment time. With the charge to mass ratio of \(\frac{1}{2}\), HEATHER has the ability to accelerate (C\(^{6+}\)) ions, however at the current design energies the reachable depth will be approximately 2cm.

Stage one is a superconducting ring, accelerating (He\(^{2+}\)) from 0.5 MeV to 400 MeV (100 MeV/u) using 4 identical multipole bending magnets. Stage 2 is a superconducting racetrack continuing the acceleration from 400 MeV through to 900 MeV (225 MeV/u); the necessary energy to reach a depth of 30 cm in water. The racetrack has been specifically designed with two straight sections to facilitate the injection...
and extraction of the beam, with the goal being to extract at variable energies.

**SIMULATIONS**

Initial design studies were completed using FACT, a UI for the COSY [10] Infinity particle tracking code. An initial field map was provided by C. Johnstone, and COSY was used to change the magnetic field parameters in order to improve isochronicity across all energies and reduce resonance crossings as much as possible. Once the field was optimised, it was extracted and input into OPAL [11], a charged particle tracking code capable of 3D space charge, and the same parameters were calculated and compared.

Once both stages were optimised, OPAL was used to accelerate a single particle through each machine. Stage one has a 600 KeV/turn energy gain across two cavities, and stage 2 has a 1 MeV/turn energy gain across two cavities. The operating frequency was varied for both machines whilst maintaining a reasonable phase slip, and an operating frequency for both stages selected. Having obtained a fixed frequency for acceleration, a realistic beam was accelerated in OPAL. This will identify any beam losses across both stages if any, and a likely beam size for extraction.

**RESULTS**

The isochronicity of HEATHER can be seen in Fig. 3, which compares the time of flight to the mean value for both COSY and OPAL. The isochronicity studies in COSY found the isochronicity to be within +/- 0.05 % beyond 150 MeV. Before this there is a variation of approximately 0.3% which causes an recoverable phase slip. The time of flight variation is caused by the fringe fields of the inner radii overlapping, suppressing the vertical tune and in turn decreasing the path length. The time of flight is not given explicitly by the COSY; the path length of a calculated orbit for a given energy is provided. Knowing the energy of the particle being tracked, one can calculate the velocity and hence the time of flight. A probe is used to calculate the time of flight in OPAL, data is recorded every time a particle crosses the probe, and the average time of many orbits is calculated for a given energy. Both codes are in strong agreement.
Figure 4: The comparison of the tune variation for COSY and OPAL, where the additional black text represents total beam energy. The initial overlapping fringe fields vertically suppress the tune which cause an integer resonance crossing; however the crossing is fast and is not destructive to the beam.

At Fig. 5, the total phase slip for stage 1 is greater than stage 2 at a given point, because of the initial isochronility variation, so the optimal operating frequency for HEATHER is dictated by that of stage 1: 10.0913 MHz. Stage 2 having an improved isochronility can operate off its ideal frequency more efficiently than stage one, with an improved total phase slip of $6^\circ$ compared to that of $10^\circ$ for stage 1. Operating at this frequency stage 1 reaches the desired energy in around 340 turns, and stage 2 reaches energy in around 260 turns.

Figure 5: The total change in phase slip across acceleration for stage 1 and stage 2 of HEATHER. At the overall optimal frequency the total phase slip is approximately $10^\circ$ and $6^\circ$ for stage 1 and 2 respectively.

OPAL was then used to accelerate a distribution of $10^4$ particles with a beam width 2.5 mm and divergence 50 mrad, based on the injection parameters for PAMELA; an ion therapy FFAG accelerator [13]. The same distribution was placed into both stages to look at growth across the different acceleration stages, and are depicted in Fig. 6. For stage 2 the beam experienced no losses and little growth. Stage one experienced losses of around 11% and large emittance growth is observed. The integer crossing can be observed in all 3 emittance planes for stage 1 as peaks occur at the same energy. Peaks are also present in two planes for the integer crossing at around 300 MeV.

Figure 6: Normalised emittance as a function of energy across all 3 planes for stage 1 and 2 of HEATHER.

CONCLUSION

Helium ions hold the potential to be the stepping stone in delivering, and biologically understanding, ion therapy. Interest in using helium ions is exponentially growing and we have successfully demonstrated the isochronous acceleration of He$^{2+}$ ions from 1 MeV to 900 MeV using HEATHER, a two stage nsFFAG. More work needs to be carried out regarding emittance growth, and using the beam that leaves stage 1, as opposed to the same initial distribution. Beyond this we aim to look at injection and extraction, specifically extracting the beam from stage 1.
REFERENCES


