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_2^+). 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 consequently 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, and interest is rising, as work is being done in preperation to use helium at some of these facilities [8].

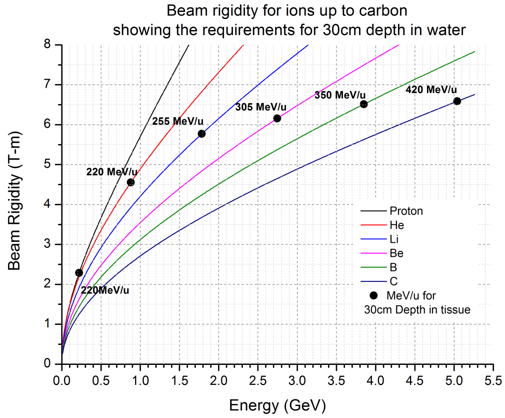

Figure 1: The beam rigidity required to bend the beam for varying kinetic energy for fully stripped ions up to carbon. The beam rigidity required to reach 30cm water depth is highlighted for each ion, and labeled with the energy required per nucleon. This was calculated using SRIM/TRIM [7], a program dedicated to the stopping range of ions in matter

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 ½ can be accelerated, enabling (He^{2+}) for treatment and (H_2^+) for imaging, improving accuracy and reducing treatment time. with the charge to mass ratio of ½, 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

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* Work supported by EPSRC

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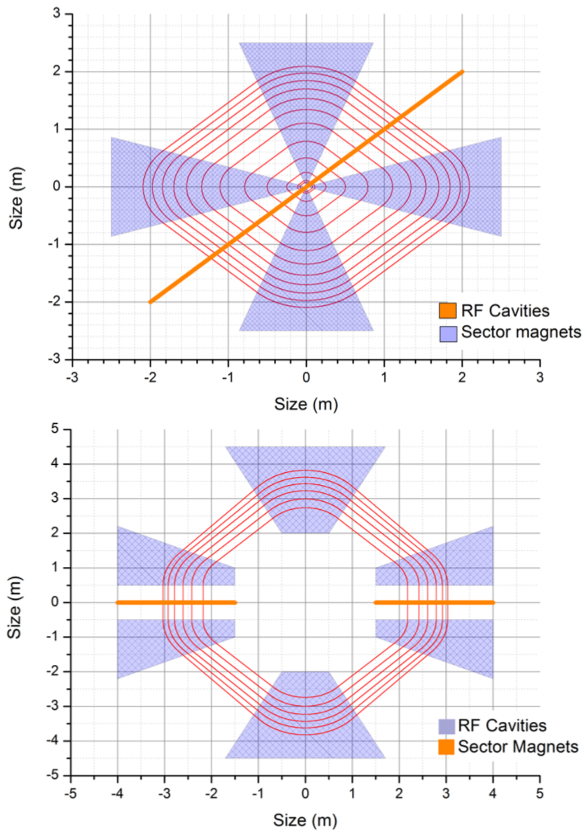

Figure 2: A representation of the magnet layout for both stages of HEATHER. Stage 1 is represented above and stage 2 below. For both stages the magnets are highlighted in blue, and the RF cavities highlighted in orange. The red ring represent stable orbits around the accelerators.

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 explicity 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.

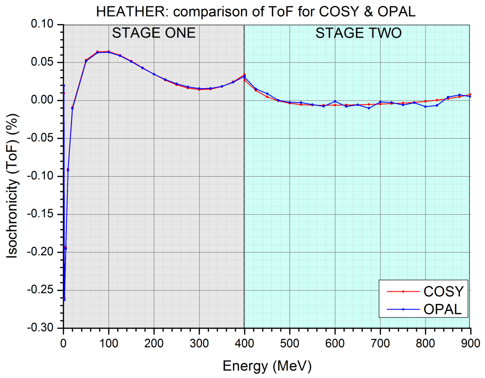

Figure 3: The comparison of isochronicity variation compared to the mean time of flight for COSY and OPAL (ToF). Overlapping fringe fields at the inner radii of stage 1 causes the orbits to be slightly faster, hence the 0.3% rapid change. The energy gain per turn allows this to be overcome quickly, and the ToF variation remains within ±0.05%.

A tune map highlighting the tunes for HEATHER are displayed in Fig. 4 for both COSY and OPAL. The vertical tune suppression previously mentioned causes many resonances to be crossed during stage 1. These resonances are crossed quickly, and should not be destructive to the beam. Resonance crossings occur regularly in cyclotron design, and integer resonance crossing has successfully been demonstrated by EMMA at Daresbury [12]. Stage 2 crosses less resonance lines compared to stage one, but crosses many at higher energies close together. Both COSY and OPAL again are in strong agreement.

Acceleration Studies

A single particle was accelerated through both stages of HEATHER using OPAL, and for each stage the injection angle and radius was optimised to deliver the most regular orbit spacing. The optimal operation frequency was found for each stage by and looking at the total phase slip across

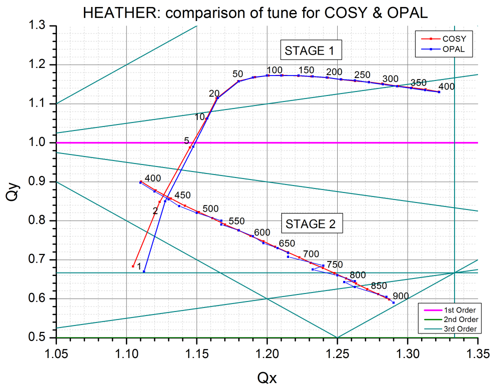

Figure 4: The comparison of the tune variation for COSY and OPAL, where the additional black text represents total beam energy. The initial overlapping fringe fields vertically suppress the tune which cause an integer resonance crossing; however the crossing is fast and is not destructive to the beam.

each stage for a given frequency as depicted in Fig. 5. The total phase slip for stage 1 is greater than stage 2 at a given point, because of the initial isochronicity variation, so the optimal operating frequency for HEATHER is dictated by that of stage 1; 10.0913 MHz. Stage 2 having an improved isochronicity can operate off its ideal frequency more efficiently than stage one, with an improved total phase slip of 6°compared to that of 10°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.

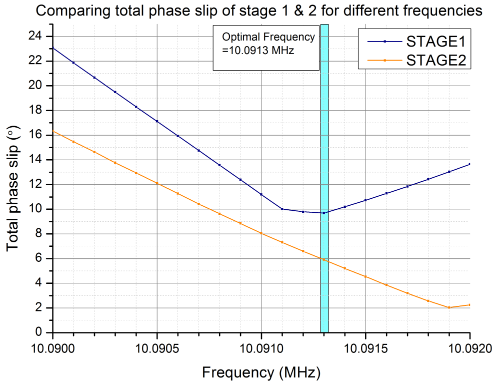

Figure 5: The total change in phase slip across acceleration for stage 1 and stage 2 of HEATHER. At the overall optimal frequency the total phase slip is approximately 10° and 6° for stage 1 and 2 respectively.

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.

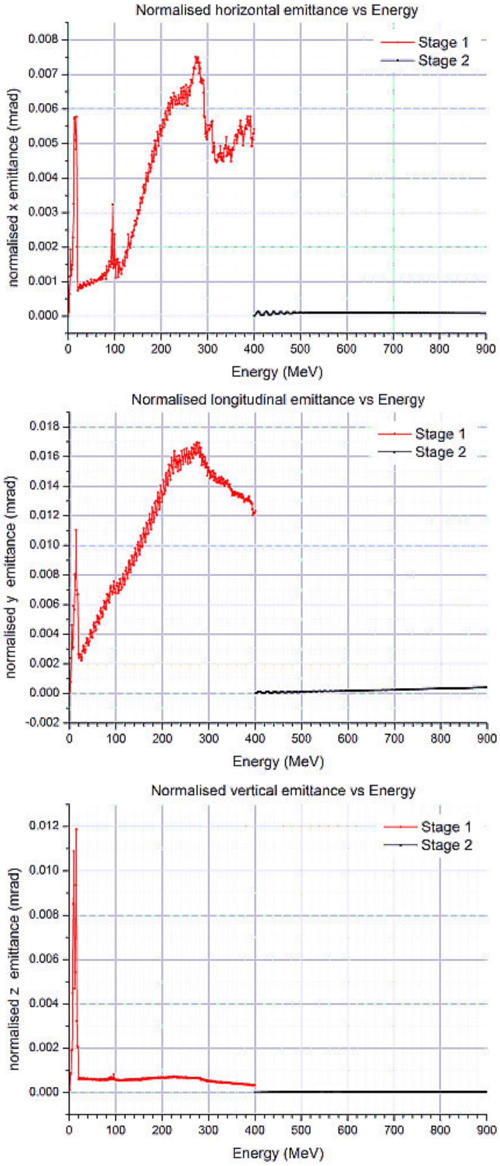

Figure 6: Normalised emittance as a function of energy across all 3 planes for stage 1 and 2 of HEATHER.

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

[1] I. Pshenichnov *et al.*, “Comparative study of depth–dose distributions for beams of light and heavy nuclei in tissue-like media”, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 266, no. 7, pp. 1094–1098, 2008.

[2] R. Grün *et al.*, “Assessment of potential advantages of relevant ions for particle therapy: a model based study”, *Medical Physics*, vol. 42, no. 2, pp.1037–1047, 2015.

[3] J. Ströbele *et al.*, “, Comparison of basic features of proton and helium ion pencil beams in water using GATE”, *Zeitschrift für Medizinische Physik*, vol. 22, no. 3, pp. 170–178, 2012.

[4] H. Fuchs *et al.*, “Implementation of spot scanning dose optimization and dose calculation for helium ions in Hyperion”, *Medical Physics*, vol. 42, no. 9, pp. 5157–5166, 2015.

[5] F. M. Khan and J. P. Gibbons, *Khan’s the Physics of Radiation Therapy*, 5th edition, Philadelphia PA, USA, Lippincott Williams & Wilkins, 2014.

[6] D. Ondreka *et al.*, “THE Heidelberg Ion Therapy (HIT) Accelerator coming into Operation”, in *Proc. 11th European Particle Accelerator Conference (EPAC’08)*, Genoa, Italy, Jun. 2008, paper TUOCG01, pp. 979–981.

[7] J. F. Ziegler *et al.*, “The Stopping and Range of Ions in Matter”, *Nuclear Instruments and Methods in Physics Research Section* B, vol. 268, no. (11-12), pp. 1818-1823, 2010.

[8] M. Krämer *et al.*, “Helium ions for radiotherapy? Physical and biological verifications of a novel treatment modality”, *Medical Physics*, vol. 43, no. 4, pp. 1995–2004, 2016.

[9] A. Ruggerio, *Fixed-Field Alternating-Gradient Workshop (FFAG’05)*, Osaka, Japan, Dec. 2008, pp. 9–13.

[10] M. Berz *et al.*, “COSY INFINITY *version 9.1 programmer’s manual*”, ’MSUHEP-101214’, Michigan State University, East Lansing, 2011, `http://cosyinfinity.org`

[11] A. Adelmann, *et al.*, “*The* OPAL *(Object Oriented ParallelAccelerator Library) Framework*”, ’PSI-PR-08-02’, 2008-2015, `https://amas.psi.ch/OPAL`

[12] S. Machida *et al.*, “Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA”, *Nature Physics*, vol. 8, no. 3, pp. 243–247, 2012.

[13] K. J. Peach *et al.*, "Conceptual design of a nonscaling fixed field alternating gradient accelerator for protons and carbon ions for charged particle therapy." *Physical review special topics-Accelerators and beams*, vol.16 no. 3, 2013.