ABSTRACT

A design of a Fixed Field Alternating Gradient (FFAG) [1] accelerator has been made for the production of radioisotopes, in particular \(^{99m}\)Tc and a number of therapeutic isotopes currently in short supply. As well as fixed magnetic fields, this machine is isochronous at the level of 0.3% up to at least 28 MeV and hence able to operate in continuous wave (CW) mode. Detailed tracking studies with the OPAL (Object Oriented Parallel Accelerator Library) code [2], including the effects of space charge, have demonstrated the ability to accelerate a beam with a current of up to 20 mA, significantly larger than achievable with any current cyclotrons. The accelerator is able to deliver beams of both protons and He\(^{2+}\) particles. Two options for the production of radioisotopes are being considered. The first uses a thin internal target. The huge acceptance of the accelerator allows the beam to be recirculated many times, the lost energy being restored on each cycle. In this way, the production of \(^{99m}\)Tc for example, can take place at the optimum energy. The second option is to use an electrostatic deflector and septum for extraction. This will allow the clean extraction of high current beams, for example He\(^{2+}\) for the production of therapeutic isotopes.

KEYWORDS

FFAG, radioisotope, \(^{99m}\)Tc, OPAL, cyclotron

1. INTRODUCTION

A compact non-scaling [3], non-linear, proton FFAG [1] was designed for the production of radio-isotopes for medical applications. A design energy of 28 MeV was chosen as many commonly used medical isotopes can be produced at this energy or below. Fig. 1, shows the general layout consisting of four sector magnets and two radio frequency (RF) cavities. The magnets are separate sector, allowing for the strongest possible edge focusing and leaving sufficient room in the drifts for RF cavities, extraction devices or targets. The magnet radius ranges from 0.1-1.7 m, making it small enough to fit into the basement of a hospital allowing direct on-site production, eliminating the need for distribution infrastructure. The injection energy is 75 keV, sufficiently low enough to allow injection directly from an ion source reducing costs by avoiding intermediate accelerators.
Beam focusing comes from three sources: edge focusing, weak focusing and the field gradient. Edge focusing occurs at the hill/valley transition where the magnet fringe fields create vertical focusing. The focusing is stronger entering than exiting the magnet creating an alternating gradient. Weak focusing comes from the distortion of the circular orbit due to the azimuthally varying magnetic field, resulting in the beam trajectory becoming non-perpendicular to the magnet edges. Gradient focusing comes from the magnetic fields radial variation. The gradient contains quadrupole and higher order components that focus the beam horizontally.

Although the field does not follow the isochronous condition times of flight vary by less than ± 0.5% allowing the use of fixed frequency RF. This was achieved through computationally optimising the field gradient with the magnet geometry.

The vertical and horizontal tune variation is broadly flat across the energy range. At very low energy however the magnets are close enough together that the fringe fields overlap and the fields no longer go to zero in the valley sectors. This reduces the strength of the edge focusing which in turn suppresses the vertical tune. As a result the vertical tune passes through an integer resonance. This resonance is passed very quickly, in a single turn or less for 200 kV/turn, restricting the growth of any instabilities.

He$^{2+}$ ions can also be accelerated in this design as they have almost identical beam rigidity in this energy range. The beam frequency is half that of protons ± 1%, opening up the possibility of running He$^{2+}$ on the first harmonic and protons on the second.

2. Studies with OPAL

Tracking studies using the OPAL [2] code have been carried out as part of wider design study of the machine to understand it’s feasibly and capabilities. OPAL is a particle optics tool including full 3D space.
charge calculations and was designed to make use of parallel processing and HPC (High Performance Computing).

2.1 Single Particle Tracking and Machine Characterization

Initial work was carried out with single particle tracking, looking to demonstrate that the machine is capable of acceleration and to find injection parameters. The closed orbits were found and injection conditions set to allow the beam to find a stable orbit and be accelerated. The accelerating cavity radial voltage profile was kept flat and the peak voltages varied to find the minimum necessary to accelerate to 28 MeV. An acceleration channel that reaches the design energy opens up at 140 kV/turn. In order to have a reasonable phase acceptance ($\Delta \varphi$) a minimum of 200 kV/turn is needed which gives a $\Delta \varphi = 40^\circ$. Fig. 2, shows the RF phase-space for 200 kV/turn. A cross crest acceleration regime is used with the initial phase set to between 20-40°. The phase slip then takes the particle phase across the crest twice before reaching the design energy.

![RF phase space for 200 kV/turn. Peak voltage is at 0°.](image)

He$^{2+}$ ions were successfully accelerated to 28 MeV without any changes to the magnetic field. The RF was changed to 3.785 MHz. This is 1-2% higher than half the frequency used for proton acceleration (7.43 MHz). RF cavities with up to 1-2% of frequency variation are currently used in some cyclotrons. This will allow both protons and He$^{2+}$ to be accelerated with the same RF system, He$^{2+}$ using the 1st harmonic and protons the 2nd.

Two possible injection methods are being considered, axial and radial. Axial injection is commonly used in cyclotrons often using a spiral inflector. This involves complex geometries and would require a specialist design. Radial injection is often used in larger, higher energy cyclotrons but rarely in low energy compact machines due to space limitations. This design has large drifts between magnets facilitating possible radial injection. To investigate this injection method a small counter bend magnet was...
added to the field map in one of the drift sectors at the radius of the injection energy. The beam is the injected from outside the machine towards the center and is then bent onto an accelerated orbit by the counter bend magnet. By the start of the second orbit the beam radius is sufficiently large as to avoid the counter bend magnet thanks to the large orbit separation at low energy. The simulated counter bend magnet has a uniform field of -1.15 Tesla and did not include fringe fields or account for any overlap from the fringe fields of the main magnets. Its size and position are arbitrary. A more detailed simulation and optimisation is needed to produce a realistic design.

For efficient production of radioisotopes a high beam current is needed. When running at high current, space charge effects cause emittance growth, the dynamic aperture therefore must be large in order to limit losses. A distribution was set up with particles displaced at 1 mm intervals in either the horizontal or vertical planes. This distribution was then tracked without acceleration for 1000 turns. This was repeated for energies up to 28 MeV. The acceptances are very large peaking at 60 $\pi \text{m mrad}$ at 1 MeV in the horizontal and 3.1 $\pi \text{m mrad}$ at 0.1 MeV in the vertical planes.

2.2 Space Charge Studies

Emittance growth due to space charge effects is likely to be the primary driver of losses in this machine when running at high current. Simulations were run to investigate these effects and the current limit of the design. Bunches of up to $10^6$ macro particles were run, however most simulation including the results show here were run with $10^5$ particles to keep the computational time reasonable.

The beam current was incrementally increased starting from 0.01 mA. Initially the beam would be lost in the first few turns at currents above 0.5 mA. It was found that the injection trajectory was miss-aligned resulting in misshapen orbits. This was corrected by adjusting the injection parameters and injecting directly into the RF. The simulation then showed acceleration to the design energy was possible with currents of up to 20 mA. At 20 mA significant emittance growth was observed shown in figure Fig. 3. Above approximately 15 MeV the horizontal emittance increases sharply. Analysis of the horizontal phase-space revealed significant filamentation resulting in halo growth and bunch fragmentation. Whilst space charge will have contributed to these effects, a beam mismatch at injection is the main cause. Optimisation of the injected distribution to match the twiss parameters at the injection point, combined with a new iteration of the field map better optimised for the higher energies, reduced these effects resulting in a more uniform and coherent bunch. As a result the emittances after matching, shown in Fig. 3, are an order of magnitude lower.

Losses in the machine were investigated by applying apertures to the simulation. In the horizontal plane the only apertures are the inner and out radii of the magnets. The vertical plane is restricted by the beam pipe, which in turn is limited by the magnet pole gap. Currently there aren't any detailed designs for the magnets so an aperture size of $\pm 2$ cm was selected based on gap sizes of currently operating cyclotrons. With this aperture applied simulations were run recording the losses. Approximately 1.7% of the simulated particles are lost before reaching 28 MeV with the most severe losses recorded at low energies. These levels of loss are currently too large, however further optimisation may reduce these. When a full magnet design study is undertaken the aperture may change effecting losses.
3. TARGET AND EXTRACTION

Extraction methods being considered include charge exchange and the use of an electrostatic deflector. Charge exchange requires the use negative ions which would exclude the running of He\textsuperscript{2+}. Electrostatic deflectors require large orbit separation in order to achieve clean extraction. The acceleration regime would have to be modified to ensure sufficient separation at the extraction energy. An alternative set up would be to use an internal target neglecting the need for beam extraction. A thick internal target could be placed directly in the beam path. With the target internalised the shielding becomes easier and more compact. Further benefits could be gained by using a thin internal target and recycling the beam as demonstrated by the ERIT FFAG [6] which used a recycled beam for the production of neutrons. The cross-sections for isotope production are energy dependent. The energy loss though the target $dE/dx$ means that in a thick target many particles will have moved of the cross-section peak before reacting. Using a thin target the particles that don't react whilst at the cross-section peak pass through the target and continue circulating round the machine. The beam can then be re-accelerated before passing through the target again. This setup could increase the efficiency of isotope production.

4. CONCLUSIONS

The design of a compact FFAG for isotope production has been studied. The separate sector magnets provide enhanced vertical focusing and leave large drifts for RF cavities, targets, and injection and
extraction devices. The field gradient provides horizontal focusing and is optimised with the magnet geometry to give stable tunes and sufficient isochronousity to allow the use of fixed frequency RF. Single and multiple particle simulations have been used to characterise the machine and investigate space charge effects. The design has been found to have large dynamic apertures and is capable of accelerating both protons and He$^+$ ions to 28 MeV. A minimum of 140 kV/turn peak accelerating voltage is needed to reach the desired energy. Injection could be achieved with either axial or radial setups. Beam currents of up to 20 mA have be simulated with 1.7% losses with a ± 2 cm aperture applied. Extraction setups, such as charge exchange and electrostatic deflector, are being considered as well as the possibility of using an internal target and recycled beam for increased production efficiency.

REFERENCES