A COMPACT AND HIGH CURRENT FFAG FOR THE PRODUCTION OF RADIOISOTOPES FOR MEDICAL APPLICATION

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Abstract

A low energy Fixed Field Alternating Gradient (FFAG) accelerator has been designed for the production of radioisotopes. Tracking studies have been conducted using the OPAL code [1], including the effects of space charge. Radioisotopes have a wide range of uses in medicine, and recent disruption to the supply chain has seen a renewed effort to find alternative isotopes and production methods. The design features separate sector magnets with non-scaling, non-linear field gradients but without the counter bends commonly found in FFAG's. The 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. Both protons and helium ions can be used with this design and it has been demonstrated that proton beams with currents of up to 20 mA can be accelerated. An interesting option for the production of radioisotopes is the use of a thin internal target. We have shown that this design has large acceptance, ideal for allowing the beam to be recirculated through the target 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.

INTRODUCTION

Radioisotopes are an important tool in health care with over 10,000 hospitals utilizing them for imaging and therapy globally [2]. The majority of radioisotopes are produced in a handful of reactors world wide. Recent unexpected shut downs of some of these reactors and subsequent radioisotope shortages have highlighted the fragility of the current supply chain and instigated a push to explore alternative production options.

A compact non-scaling [3], non-linear, proton FFAG [4] was designed as an alternative option for the production of common radio-isotopes such as ^{99m}Tc and other new isotopes that reactors are unable to produce. A design energy of 28 MeV was chosen as many commonly used medical isotopes can be produced at this energy or below. Separate sector magnets are used shown in Fig. 1, which create strong vertical focusing by maximising the magnetic field fluctuation at the magnet edges, and leaving sufficient room in the drifts for RF (radio frequency) 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. This allows direct on-site production eliminating the need for distribution infrastructure. The initial energy of 75 keV is sufficiently low to allow injection directly from an ion source, reducing cost by avoiding intermediate accelerators.

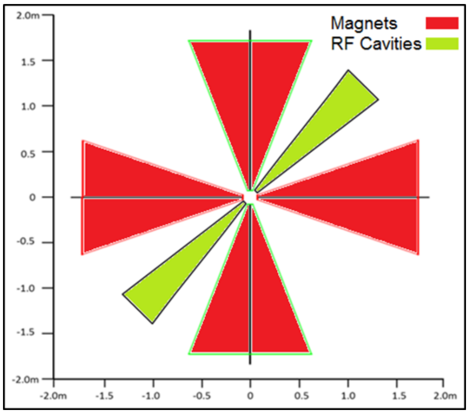

Figure 1: Plan view of magnet and RF layout.

Beam focusing comes from three sources: edge focusing, weak focusing and the field gradient. The edge and weak focusing are found in all separate sector cyclotrons, the gradient focusing however is enhanced in this design. The radial magnetic field profile has a larger variation than in a conventional isochronous cyclotron where the field scales as in Eq. (1) [5].

$$B_{(r)} = \gamma_{(r)} B_0 \tag{1}$$

Instead the radial field variation is described by a polynomial shown in Eq. (2) where B_0 is the dipole field strength and n_i are higher order field components. This is optimised with the magnet geometry to ensure isochronicity is maintained. This larger field gradient results in increased radial focusing.

$$B_{(r)} = B_0 + n_1 r + n_2 r^2 + n_3 r^3 \cdots \tag{2}$$

The field gradient can now be used to stabilise the machine tunes. As a result vertical and horizontal tune variation is small across most of the energy range. At low energies however the magnets are close enough together that the fringe fields overlap such that the fields become non-zero in the valley sectors. This reduces the strength of the edge focusing witch in turn suppresses the vertical tune. Figure 2 shows the vertical tune passing through an integer and third order resonance as a result this suppression. These resonances are passed very quickly, in a single turn or less for 200 kV/turn, which will restrict 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.

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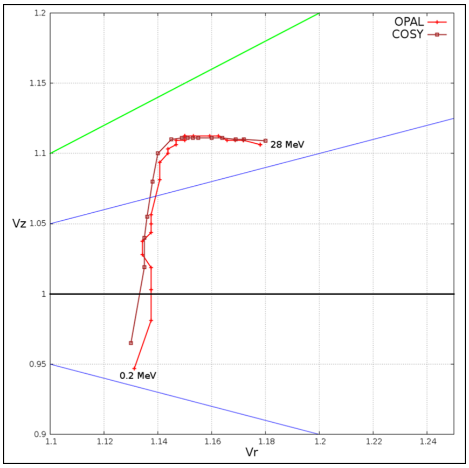

Figure 2: Tune diagram.

SIMULATIONS

Initial work was carried out looking to demonstrate the machine is capable of acceleration and investigate beam dynamics. A minimum RF voltage of 10 kV/turn is needed to reach the design energy. By 100 kV/turn the phase acceptance is $\Delta\phi = 100°$ which will allow for long beams to reduce space charge effects. Figure 3 shows the RF phase-space for 100 keV/turn. A cross crest acceleration regime is used where the phase slip takes the particle phase across the crest twice before reaching the design energy.

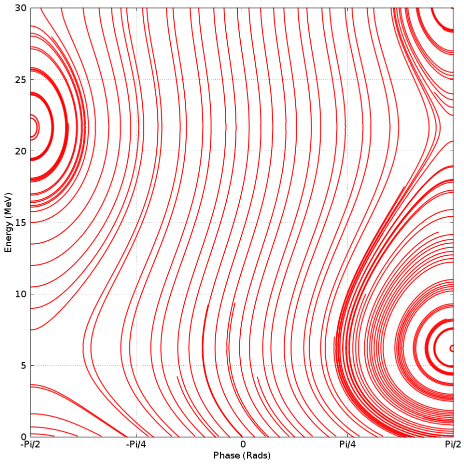

Figure 3: RF phase space for 100 kV/turn.

Efficient production of radio-isotopes requires a high beam current. At high current space charge effects can be destructive to the beam so large dynamic apertures are needed to limit losses. To investigate the dynamic aperture of this design 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 10000 turns. This was repeated for energies up to 28 MeV. The horizontal dynamic aperture at 1 MeV shown in Fig. 4 has an aperture size of 60 π m mrad. This is very large and you can see the distortion of the circular aperture at large amplitudes due to the sextupole component of the magnetic field gradient. The acceptances peak at 60 π m mrad at 1 MeV in the horizontal and 3.1 π m mrad at 0.1 MeV in the vertical planes.

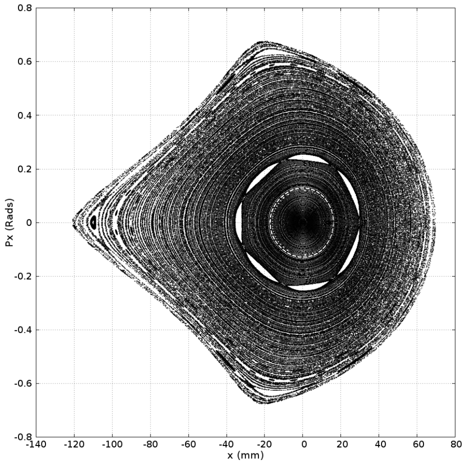

Figure 4: Horizontal dynamic aperture at 1 MeV.

In most compact cyclotrons axial injection is used as it is well suited to the tight confines of the central region. The additional space available in this separate sector design may allow radial injection which is simpler as it avoids the complex geometries of a spiral inflector. OPAL simulations in Fig. 5 show radial injection with a small magnet placed between the main magnets at the injection radius. Large orbit separation at low energy means that the second orbit is just large enough to miss the injection magnet.

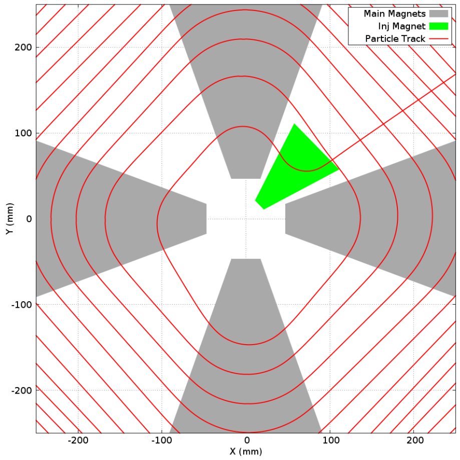

Figure 5: Track from OPAL simulation of radial injection.

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. Simulations were limited to bunches of up to 10^5 macro particles to keep the computational time reasonable.

Simulations initially showed acceleration to the design energy was possible with currents of up to 20 mA, however at high currents significant emittance growth was observed. Analysis of the horizontal phase-space revealed significant filamentation resulting in halo growth and bunch fragmentation. Beam mismatch at injection was identified as the main cause. Optimisation of the injected distribution to match the twiss parameters at the injection point reduced these effects resulting in a more uniform and coherent bunch and a reduction in the emittance in all three planes by an order of magnitude.

Losses in the machine were investigated by applying physical apertures. The horizontal plane 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. An aperture size of ± 2 cm was selected based on gap sizes of currently operating cyclotrons. With this aperture applied simulations were run recording the losses. At 10 mA 0.014% of macro particles were lost on the apertures increasing to approximately 1.7% at 20 mA.

THIN INTERNAL TARGET

Extraction could be achieved using conventional methods such as charge exchange or electrostatic deflector. Both these methods have disadvantages so an alternative set up would be not to extract and instead use an internal target. A thick internal target could be placed in the machine 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 shown in Fig. 6. As the cross-sections for isotope production are energy dependent the energy loss though the target (dE/dx) means that in a thick target many protons will have moved off the cross-section peak before reacting. Using a thin target the protons that don't react whilst at the cross-section peak pass through the target, continue round the machine and are re-accelerated before passing through the target again. The thin target set-up could increase the efficiency of isotope production as fewer protons will be lost without reacting and the energy of protons on the target can be kept closer to the ideal energy; keeping production on the cross-section peak and away from the cross-section peaks of other unwanted reactions. Possible problems for this set up are beam loss from multiple scatterings through the target, matching the energy lost in the target to the energy gain from the RF and space charge effects from the accumulation of charge on the final orbit.

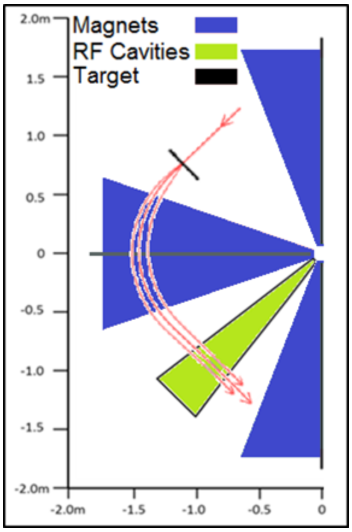

Figure 6: Schematic of thin target and recirculated beam.

CONCLUSION

The design of a compact FFAG for isotope production has been studied. Single and multiple particle simulations have been used to characterise the machine and investigate space charge effects. It has been found to have stable tunes, large dynamic apertures and is capable of accelerating both protons and He^{2+} ions to 28 MeV. A minimum of 10 kV/turn peak accelerating voltage is needed to reach the desired energy, however 100 kV/turn is preferable to facilitate long bunches. Injection could be achieved radially thanks to the additional space of a separate sector design. Beam currents of up to 20 mA have be simulated with 1.7% losses at 20 mA and 0.014% at 10 mA with a ± 2 cm aperture applied. The possibility of using an internal target and recycling the beam could increase production efficiency ensuring that all particles are at the optimum energy. This combined with the hight current capability of this design could result in a significant improvement over current commercial cyclotrons.

REFERENCES

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