DUAL PROTON – HELIUM ACCELERATOR FOR RADIOISOTOPE PRODUCTION

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ABSTRACT

A design of a compact accelerator has been made for the production of radioisotopes, in particular ^{99m}Tc and ^{211}At. As well as fixed magnetic fields, this machine is isochronous up to 28 MeV and able to operate in continuous wave (CW) mode for both protons and He^{2+}. Detailed tracking studies with the OPAL (Object Oriented Parallel Accelerator Library) code, including the effects of space charge, have demonstrated the ability to accelerate a proton beam with a current of up to 20mA, significantly larger than achievable with any current cyclotrons. The accelerator is able to deliver beams of both protons and He^{2+} particles through careful optimisation of the field, which would allow production of a wider range of isotopes including ^{211}At which is of interest for therapy. As well conventional target configurations the use of a thin internal target and recycled beam is being considered. The large acceptance of the accelerator allows the beam to be recirculated many times despite scattering through the target, 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 increasing yields and purity.

KEYWORDS
FFAG, proton, helium, radioisotope

1. INTRODUCTION

The majority of medical radioisotopes are produced by a handful of research reactors globally. This centralized infrastructure is vulnerable to disruption if there are any problems at one of these reactors. In 2009 two reactors, the National Research Universal (NRU) in Canada and the High Flux Reactor (HFR) in the Netherlands, were shut down for vital maintenance cutting off around two thirds of the world's supply of ^{99m}Tc, causing the delay or cancelation of many procedures [1]. This has resulted in a renewed effort from the scientific community to investigate new, more localized methods of production as well as using new isotopes. The use of compact accelerators for direct production of ^{99m}Tc is one option. The accelerators would be situated on hospital sites and would serve the local region only due to the short half-life of ^{99m}Tc (~6 hr). This would decentralize the distribution network, making it more robust.

1.1. Design of a Proton Accelerator

A compact proton accelerator was designed for the production of medical radioisotopes such as ^{99m}Tc. The design shown in Fig. 1 features four separate sector magnets and two radio frequency (RF) cavities. The separate sector design leaves plenty of room for injection/extraction and with an extraction radius of 1.7 m at 28 MeV is small enough to be place in the basement of a hospital. The 75 keV injection energy should allow injection strait from an ion source negating the need for pre acceleration.

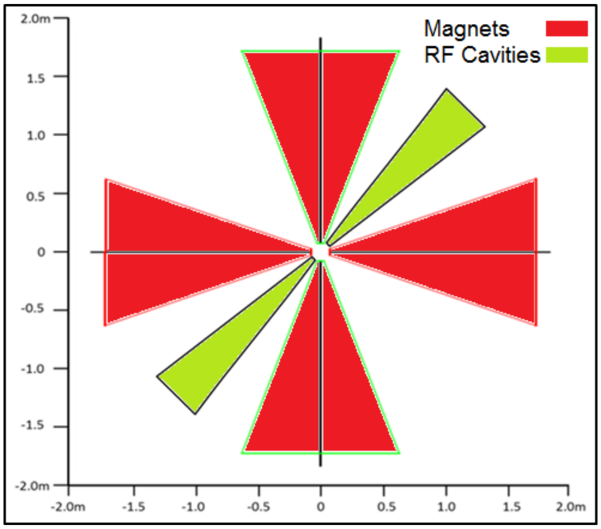

Figure 1. Plane view of the design with four sector magnets and two RF cavities.

The magnetic field profile is described by a polynomial and has components up to the sextapole term. It is optimized with the magnet geometry to maintain an isochronous field [2] with a time of flight variation of less than 0.15%. The tunes are stable across much of the energy range however the vertical tune is suppressed at low energy due to fringe field effects resulting in some resonance crossings. The resonances are passed very quickly which will limit instability growth. The small time of flight spread results in the RF phase space shown in Fig. 4 that gives a phase acceptance of approximately 100° for 200kV/Turn accelerating voltage.

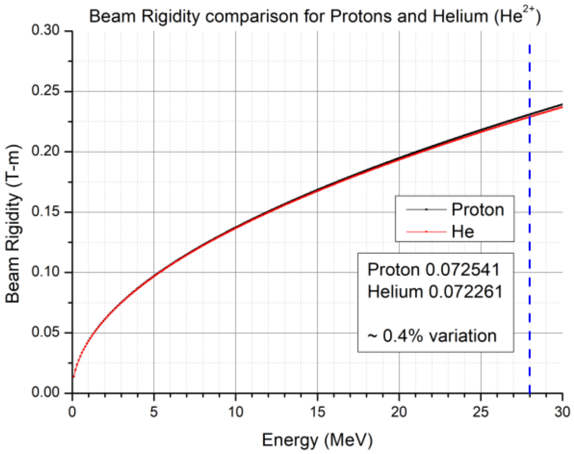

Figure 2. Beam rigidity of protons and He are very similar in this energy range.

1.2. Dual Proton-Helium Accelerator

Neither protons nor helium ions are highly relativistic in the energy range up to 28 MeV. Consequently the beam rigidity for protons and helium ions are very similar, as you can see in Fig. 2 they only vary by around 0.4% at 28 MeV. This opens up the possibility of running both protons and helium ions in the same machine. This would greatly increase the flexibility of the machine, allowing for the production of additional radioisotopes such as ^{211}At [3].

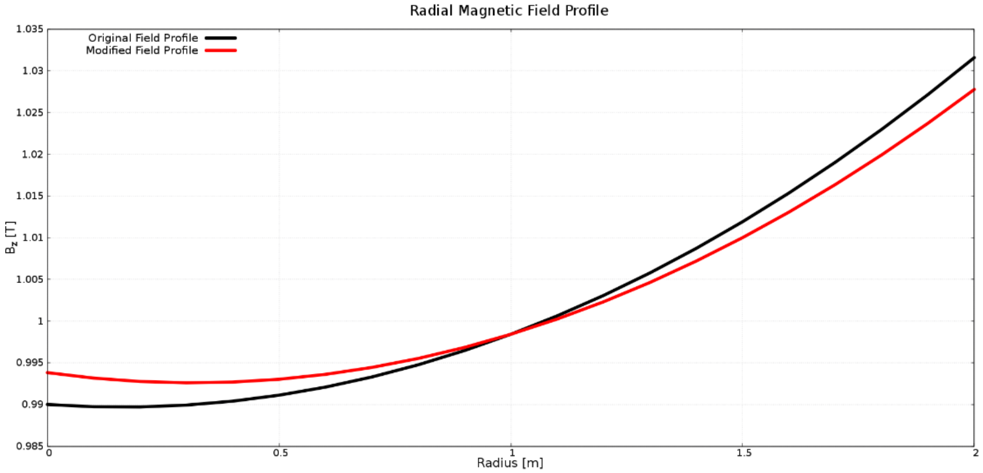

Figure 3. Comparison of the magnetic field profile before and after modification.

Using the same field map helium ion acceleration was investigated. The RF phase space for He^{2+} ions shown in Fig. 4 gives a phase acceptance of approximately 25°, significantly smaller than that of protons due to the divergence of the helium time of flight from the proton RF frequency. To improve the helium phase acceptance the magnetic field profile was modified by adjusting the quadrapole component of the magnetic field as in Fig. 3. The new RF phase spaces for protons and helium ions are shown in Fig. 4. With the field profile now somewhere between the ideal field for protons and that of helium ions the phase acceptance has changed, compromising the proton acceptance to improve the helium. The new phase acceptances are approximately 70° for protons and 55°.

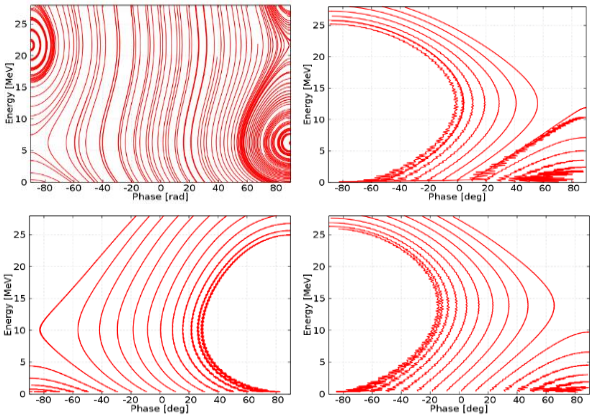

Figure 4. RF phase space for Protons (left) and Helium (right) before (top) and after (bottom) field modification.

2. SPACE CHARGE STUDIES

Simulations were run in OPAL [4] with full 3D space charge calculations to investigate the current capability of the design. Beam currents of up to 1mA were simulated for both protons and helium ions. For 1mA protons there was some initial emittance growth from a combination of beam mismatch and space charge blow up, before the stabilizing. The radial emittance at extraction was ≈3 mm mrad and the vertical emittance ≈0.6 mm mrad. He^{2+} ions at 1mA reached very similar emittances of 3 and 0.6 mm mrad. It's worth noting that due to its 2+ charge, 1mA of helium ions contains half the number of particles as 1mA of protons.

Helium ions are potentially highly activating at 28 MeV so clean, low loss extraction is vital. Good orbit separation is therefore important to allow just the final orbit to be extracted and minimize the losses on the septum to avoid heating and activation issues. This in turn limits the current that can be run as space charge effects broaden the beam width. Figure 5. shows the broadening of the radial profile of the bunch from space charge for the last two turns. At 0.5mA the last two bunches overlap slightly but this is mainly halo and large amplitude particles, the beam cores remain distinct. At 1mA however space charge effects have significantly broadened the beam to the point where the edges of the beam cores are now overlapping. Consequently the beam current is limited to around 0.5mA if clean extraction of He^{2+} is to be achieved.

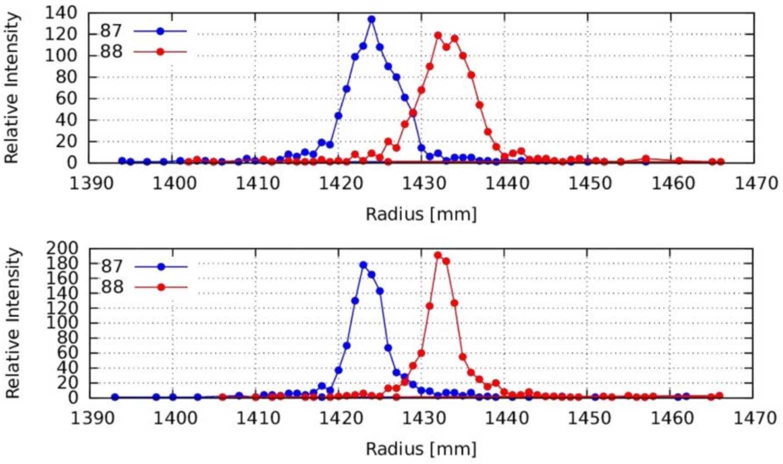

Figure 5. Orbit separation at extraction for Helium at 1mA (top) and 0.5mA (bottom) beam currents.

As well as broadening the beam radially, space charge also effects the longitudinal dynamics of the beam. Without space charge the bunch full pulse length is approximately 8 ns long. When running high currents in an isochronous accelerator the space charge effects actually work to break up long beams and shape shorter bunches into a sphere through shearing forces [3]. This effect shortens the pulse length of the beam core in these simulations, but also causes off momentum particles to be pushed out to larger amplitudes as shown in Fig 6. There are two options for dealing with this additional halo growth, reducing the energy spread of the beam, or collimating the off momentum particles. The energy spread could be reduced by injecting a shorter bunch and using less of the available RF phase space, but this would also worsen the space charge effects. A flat top cavity could be used to reduce energy spread but this would be an additional cost as well as an engineering challenge. Collimation is a more realistic option for controlling halo growth but would need a well optimized design to ensure only of momentum and halo particles were removed.

3. Extraction

The extraction options are slightly different for protons and He^{2+} ions. Protons could be run as either H^+ or H^- which allows extraction by either electrostatic deflector or by charge exchange. Helium however can only be run as He^{2+} excluding the use of charge exchange, so an electrostatic deflector is the only option. For dual proton He^{2+} operation, extraction devices for either particle could be placed in opposite sectors, with a stripping foil for charge exchange in one sector and deflector and septum in the other. The stripping foil could be movable to allow for variable energy extraction.

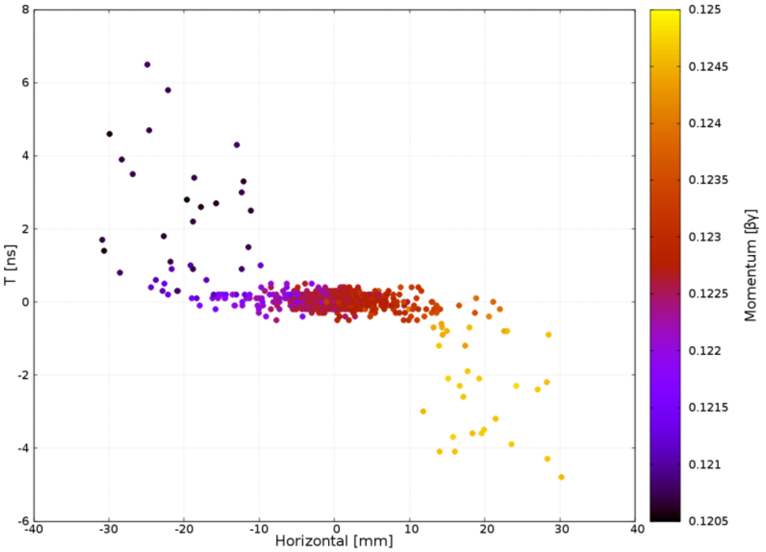

Figure 6. 2D Beam profile in (horizontal/longitudinal) showing that off momentum particles are major contributors to beam halo.

4. Conclusions

A design that could accelerate both protons and helium ions to 28 MeV is achievable by using a field gradient that is set between the optimal fields for either protons or helium. In doing so you compromise the accelerating efficiency of each, in order to be able to do both. At high current space charge effects cause beam broadening and emittance growth. This limits the current that can be run to around 0.5mA as the bunches start to overlap at higher current which results in unacceptable loss when extracting. Space charge also has an effect longitudinally, acting to make the bunch more compact and spherical but also increasing the extent of the beam halo which must be controlled. Different methods of extraction could be used for protons and helium and extraction devices for each could be placed in opposite sectors for ease of operation.

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