THIN INTERNAL TARGET STUDIES IN A COMPACT FFAG*

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Abstract

The production of radioisotopes using a thin internal target and recycled beam within a compact FFAG design has been studied. 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 FFAG design features separate sector magnets with non-scaling, non-linear field gradients which are optimized with magnet geometry to achieve isochronisity at the level of 0.3%, sufficient for Continuous Wave (CW) operation. Simulations have demonstrated that beam currents of up to 10mA can comfortably be achieved with this design. To further improve production efficiency a thin internal target, where the beam passes through the target and is recirculated, may be used. This setup ensures that production takes place within a narrow energy range, potentially increasing production rates and reducing impurities.

INTRODUCTION

Radioisotopes are a widely used tool in medicine, being utilised in both imaging and therapy. Most radioisotopes are produced by a small number of reactors and then shipped globally. Concern over the fragility of this supply chain along with interest in radioisotopes that can't be produced in reactors has led to renewed interest in other production methods.

Accelerator Design

A compact FFAG [1] has been designed for production of radioisotopes and ^{99m}Tc in particular. Figure 1 shows the layout of the design witch features four separate sector magnets and two RF cavities. The design has been optimised up to 28 MeV as a large number of commonly used isotopes can be produced at this energy or lower. The separate sector design allows plenty of space to facilitate the placement of targets or extraction devices in the valley sectors. The magnetic field gradient is optimised with the magnet geometry to make the machine isochronous while stabilising the tunes. As a result vertical and horizontal tunes do not cross any resonances across most of the energy range. However at low energies the magnets are close enough together that the fringe fields overlap and suppresses the vertical tune. Figure 2 shows that the tunes pass through an integer and third order resonance at low energy as a result of this suppression. Instability growth should be small however as these resonances are passed very quickly, in a single turn or less for an accelerating voltage of 200 kV/turn. The dynamic aperture is also restricted at low energy from the overlapping fringe fields. From 1 MeV and above however the dynamic apertures are very large, which is important for the performance of the internal target and beam recycling.

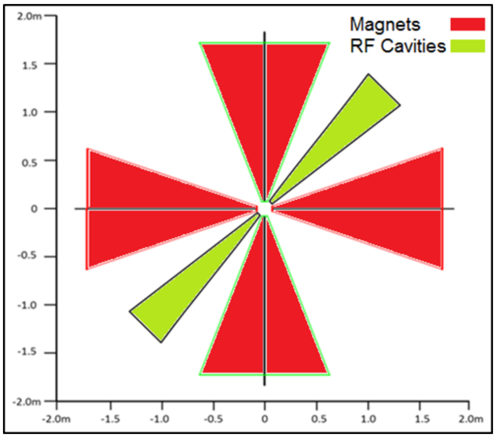

Figure 1: Layout of machine design featuring separate sector magnets and RF cavities.

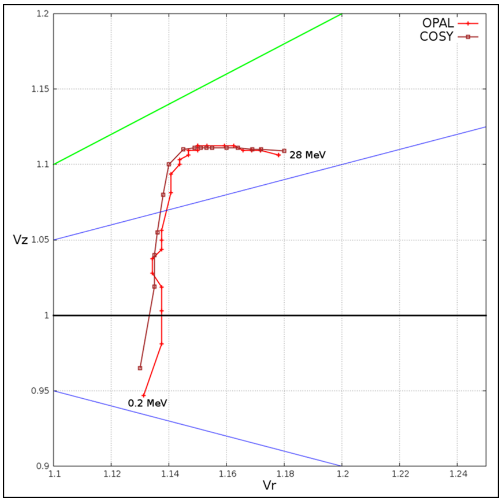

Figure 2: Tune map showing the crossing of an integer and third order resonance at low energy.

Internal Target and Ionisation Cooling

The reaction cross sections for isotope production are often highly energy dependent. As a result of energy loss though a thick target (dE/dx), many protons will have moved off the cross-section peak before reacting. In a thin internal target the protons that don't react at the cross section peak continue through the target and around the machine, being reaccelerated to the ideal energy before returning to the target. By controling the interaction energy in this way you can also keep it away from the peaks of other unwanted reactions. Potential issues for this set up are losses from scattering through the target

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and matching the RF voltage to the energy lost in the target.

Ionisation cooling [2] is a technique where by reaccelerating a beam after it has under gone energy loss and scattering through a material, the emittance can be effectively reduced. A particle has a momentum vector at an angle θ to the longitudinal axis. The beam then undergoes energy loss through the material (reducing the magnitude of the momentum vector), at the same time it scatters (rotating the vector). When it is reaccelerated the momentum is added only to the longitudinal component of the vector. The resultant vector has the same magnitude as the original vector but at an angle ϕ that is smaller than the original angle θ . The effectiveness of this technique is dependent on the ratio of scattering to energy loss being small. The energy loss is given by the Bethe-Bloch equation:

$$\frac{-dE}{dx}=Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2}\right)-\beta^2\right] \qquad (1)$$

and the multiple scattering by:

$$\theta_0=\frac{13.6\,MeV}{\beta cp}z\sqrt{x/X_0}\left[1+0.038\ln(x/X_0)\right] \qquad (2)$$

From equations 1 and 2 [3], you can examine the relationship between particular variables and the scattering/energy loss ratio. Figures 3-5 show the dependence of various factors on the scattering/energy loss ratio normalised between 0:1 over the ranges examined.

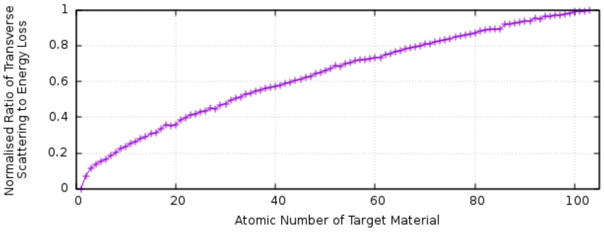

Figure 3: Dependence of the ratio of scattering/energy loss on atomic number of the target material.

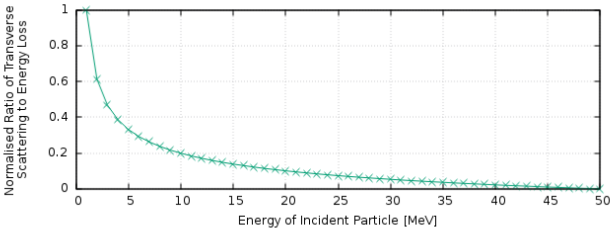

Figure 4: Dependence of the ratio of scattering/energy loss on total kinetic energy of incident particle.

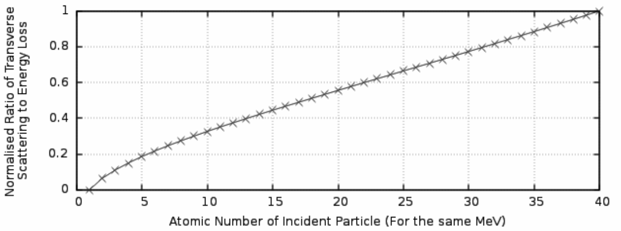

Figure 5: Dependence of the ratio of scattering/energy loss on the atomic number of the incident particle.

SIMULATIONS OF THIN INTERNAL TARGET

Simulations of the internal target and recycled beam were conducted using the OPAL code [4]. Initial focus was on direct production of ^{99m}Tc through the ^{100}Mo(p,2n)^{99m}Tc reaction [5], so a ^{100}Mo target was used in all simulations presented here. The cross section for this reaction peaks at 14 MeV, so protons of this energy were used.

To demonstrate the effect of ionisation cooling a comparison was conducted. A simulation was run with a 0.005mm thick target place half way between two of the sector magnets. Scattering through the target was simulated, but energy loss was not, and no RF cavities were used. This setup allows us to see the emittance growth from the scattering without ionisation cooling. Another simulation was run with the same setup but with energy loss and RF cavities turned on to simulate ionisation cooling. Figure 6 shows the emittance growth with and without ionisation cooling, demonstrating beam cooling effect.

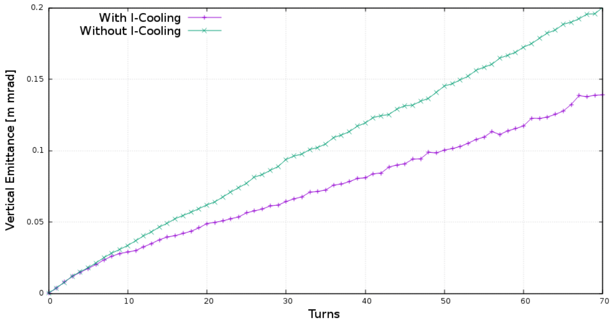

Figure 6: Emittance growth with and without ionisation cooling showing the emittance suppression effect.

Simulations were setup to investigate whether an internal target and ionisation cooling could be used to improve yields of ^{99m}Tc. The target was placed at the radius corresponding to 14 MeV, the beam injected at 75keV and accelerated to the target. A vertical aperture was applied and losses observed.

Simulations with different target thickness were conducted, with a ± 20mm aperture applied. The RF voltage was matched to replace approximately the energy lost through the target in a single pass. In Fig. 7 you can see increased beam survival with decreased thickness, such that the total average thickness of material traversed

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by the beam over all turns is approximately the same, hence producing similar yields. The differences in total average thickness observed in these simulations can likely be attributed to differences in how well the beam, target and RF have been optimised together in each case.

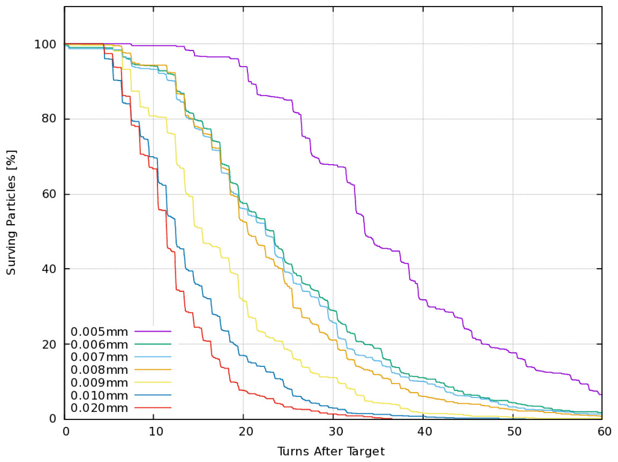

Figure 7: Beam survival for various different target thicknesses.

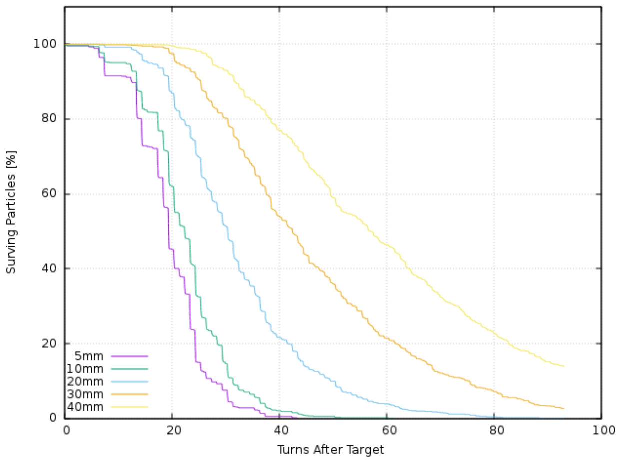

Figure 8: Beam survival for various different vertical apertures.

Figure 8 shows the effect of the vertical aperture on beam survival. The simulations were setup with a 0.005mm target and various aperture sizes applied. Larger apertures result in longer beam survival as expected. This shows that the dynamic aperture is large enough to allow for long beam survival, confirming that the physical aperture is the limiting factor.

The pattern of losses observed in all these simulations shows that the losses are largest around the magnet edges where the vertical beta function is at its largest. Reducing the peak vertical beta function in future designs may therefore improve beam survival.

CONCLUSION

A thin internal target could improve production yields by stabilising the interaction energy at the peak of the reaction cross section. Purity could also be improve by keeping the interaction energy away from the cross section peaks of other unwanted reactions. Ionisation cooling improves beam survival within a thin internal target system by surppressing the emittace growth from scattering through the target, and is most effective when using a low Z target material and low Z incident particle. The technique therefore is best suited to the production of light radioisotopes that are produced through proton interactions.

Simulations show that target thickness doesn't have a significant impact on yields as the total average thickness traversed by the beam is independent of target thickness. The dynamic apertures of the machine are very large so the limiting factor for beam survival is the physical aperture. Increasing the vertical aperture would improve beam survival but is limited by magnet engineering constraints and the effect it would have on the magnet fringe fields.

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