OPTIMIZING THE RADIOISOTOPE PRODUCTION WITH A WEAK FOCUSING COMPACT CYCLOTRON*

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Abstract

A classical weak focusing cyclotron can result in a simple and compact design for the radioisotope production for medical applications. Two main drawbacks arise from this type of machine. The energy limit imposed by the non RF-particle isochronism requires a careful design of the acceleration process, resulting in challenging requirements for the RF system. On the other hand, the weak focusing forces produced by the slightly decreasing magnetic field make essential to model the central region of the machine to improve the electric focalization with a reasonable phase acceptance. A complete analysis of the different beam losses, including vacuum stripping, has been performed. The main cyclotron parameters have been obtained by balancing the maximum energy we can obtain and the maximum beam transmission, resulting in an optimum radioisotope production.

INTRODUCTION

The growing demand of PET radioisotopes as diagnostic tools in hospitals makes interesting the design of compact cyclotrons. Superconducting magnets can be used to increase the magnetic field, minimizing the particle acceleration region and consequently reducing the overall cyclotron size. However, such strong magnetic fields, far beyond the iron saturation level, make difficult to obtain strong focusing forces by using azimuthally varying magnetic configuration, as it is typically used in synchronous cyclotron machines. To avoid moving to very expensive solutions with non-standard magnetic materials or auxiliary superconducting coils, classical cyclotrons, based on weak focusing forces, can result in an alternative for accelerating particles at relative low energies (<10 MeV) with a simple design.

AMIT CYCLOTRON

One of the main goals of the Spanish AMIT (Advanced Molecular Imaging Technologies) project is the development of a compact cyclotron of 8.5 MeV, 10μA proton beam for ^{11}C and ^{18}F single doses production for PET diagnostics. The superconducting AMIT cyclotron (Fig. 1) is a 180º Dee weak focusing machine, with a 60 kV accelerating peak voltage imposed by the non RF-particle isochronism and with stripping mechanism for beam extraction. A trade-off between machine size and cost results in a magnetic field of 4 T as an optimum value. In the same way an internal H^- ion source has been chosen to reduce the overall cyclotron footprint.

Figure 1: AMIT cyclotron overview.

The beam dynamics of the AMIT cyclotron is mainly determined by two features:

- **Weak focusing machine:** In this type of cyclotrons, beam focusing is obtained by using a slightly radial decreasing magnetic field. As a consequence, there is no synchronism between particles and the RF field, limiting the time that they can be properly accelerated and, consequently, the maximum beam energy we can achieve. In order to reach higher energies, high accelerating voltages are required.
- **Compact machine:** The compactness of the AMIT cyclotrons has resulted in the choice of a 4 T magnetic field and an internal ion source. On one hand, such a magnetic field results in very small orbits in the central region which, in combination with the high voltage, leads to a non-trivial design of the ion source and puller. On the other hand, the gas throughput needed for the internal ion source causes a low vacuum level in the cyclotron (~10^{-4}-10^{-5} mbar), resulting in a poor beam transmission through the cyclotron, stressed if the number of turns is not kept low.

This paper summarizes the most important beam dynamics features of the AMIT cyclotron. CYCLONE code [1] has been used for orbit simulations.

OPTIMIZATION OF RADIOISOTOPE PRODUCTION

The radioisotope production is determined by the properties of the beam hitting the target, namely, the beam energy and current. Although the dependence with the

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beam current is linear, the radioisotope production depends on the beam energy following the measured cross-section data [2]. It can be seen in the corresponding data for the ^{11}C production, shown in Fig. 2, that the optimum energy is about 8 MeV whereas below 5 MeV the production is negligible.

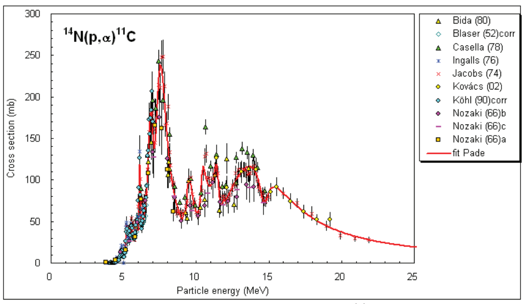

Figure 2: Measured cross-section of ^{11}C production for a proton beam impacting in a ^{14}N target.

To maximize the radioisotope production, two main features should be optimized in the cyclotron design. Firstly, a careful design of central region is required to optimize the phase acceptance and therefore the output beam current. Secondly, the cyclotron beam tuning, by slightly modifying the RF frequency choice and the stripping foil location, allows us to optimize the energy-current pair, resulting in the maximum radioisotope production.

Central Region Design

The central region determines most of the beam properties. The puller should be located close to the ion source to compress the electric field and to increase the energy gain in the first turn, and therefore the available space for the internal ion source. Additionally, stronger electric fields in the ion source slit result in a higher extracted current, being proportional to $(V sin\tau/d)^{3/2}$ [3], where V is the peak voltage, d is the ion source-puller gap and τ the initial RF phase seen by the particle. Although the 60 kV high voltage should result in a high beam current, the reduced dimensions required by the high magnetic field would lead to very high electric fields close to the central region, limiting, therefore, the minimum ion source-puller gap we can withstand without sparks, and consequently, the extracted beam current.

Furthermore, given the stripping extraction method, the final phase acceptance of the cyclotron is fully determined by the central region design. This phase acceptance should be optimized in order to:

- increase the output beam current with a central region configuration resulting in a wide range of initial phases which can be properly accelerated and with values close to the peak to increase the extracted beam current by the puller. For that goal, it is essential to reduce the ion source-puller distance as much as the sparks risk allows us.
- to move initial phases as a much delayed (after peak) as possible to increase the phase excursion and therefore the maximum output energy. Additionally, in a classical cyclotron, with weak focusing resulting from a slightly radial decreasing magnetic field, the beam at low energy is strongly influenced by the phase-dependent effects of the dee gaps. It is essential to move the initial phases to values after the peak (delayed particles) to improve the electric focusing and therefore to increase the transmitted beam current.

Taking into account those requirements, the AMIT central region configuration has been designed (Fig. 3) with an ion source-puller gap about 6 mm, a longer first half path to improve electric focusing forces and a devoted puller to improve the energy gain in the first turn and to kill non-desirable particles.

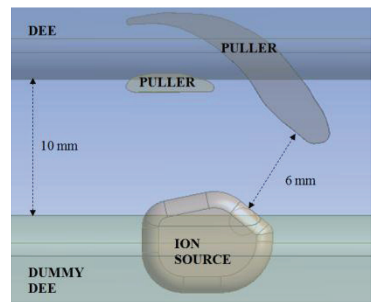

Figure 3: Central region configuration for AMIT cyclotron.

The ion source slit aperture has been chosen to increase the extracted current but keeping into account that particles starting far from the slit center will be probably lost (due to the large radial/axial oscillations) and the fact that the slit size will have a straightforward impact on the vacuum level and consequently on the stripping losses. Figure 4 shows the effect of the axial aperture of the ion source slit in the output beam current. A higher slit height will increase the number of particles extracted by the puller (red squares), although beyond 7 mm the output current remains the same due to vertical losses on the dee and dummy dee structures (12 mm height). The effect of a lower vacuum level due to a higher axial aperture (green triangles) will reduce the output beam current, resulting in an optimum slit aperture of 6 mm to maximize the output beam current. In the same way, a 0.5 mm radial width has been chosen for the ion source slit.

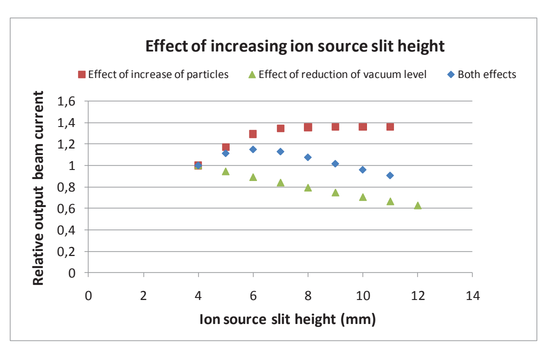

Figure 4: Effect of axial aperture of the ion source slit on the output beam current.

Beam Tuning: RF Frequency and Stripper Location

The beam acceleration pattern through the cyclotron will be determined by the RF-particle shift. It can be controlled with the RF frequency value choice and the stripping foil location to optimize the radioisotope production, balancing the mean energy and the final beam current. The RF phase seen by the particle at each accelerating gap (see Fig. 5) will be moved from the starting phase (given by central region configuration) to a maximum negative phase shift (where the RF field and the particle will be synchronous), determined by the chosen RF frequency, to a maximum positive phase shift given by the stripping foil location.

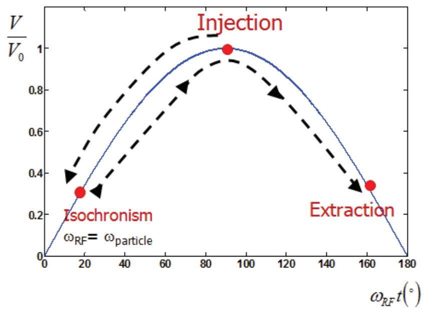

Figure 5: Voltage seen by the particle in the accelerating gaps at each turn. Particles will start, close to the peak at the injection, moving faster than the RF field. At a given radius, the particle and RF field will be synchronous and after that time, the particle will arrive at each gap later than the RF field until some point where the particle will be extracted by the stripping mechanism.

In order to optimize the final beam energy, such phase excursion should be maximized but the impact on beam current will limit the number of turns. Note that for those particles arriving to the accelerating gaps when RF phases are very far from the peak, their contribution to the output energy is very small but the beam current is reduced by stripping losses (a total about 30% due to the low vacuum level produced by the internal ion source). The time spent by particles at low energy should be controlled since the vacuum level at that region is worse and the stripping cross-section is higher. Additionally, the beam acceleration during negative phase shift (before peak) should be limited to reduce the electric defocusing forces and consequently the beam losses. Therefore the RF frequency value and the stripping foil location should be carefully chosen to get a phase excursion enough to get the required output beam energy but not too much to avoid current reduction.

Figure 6 shows the energy, current and radioisotope production as function of the stripping foil location and RF frequency choice. The activity production when the stripper is located at radius lower than 85 mm goes to zero because the output beam energy is below than 6 MeV and the cross section data (see Fig. 2) goes down to zero. Although the maximum stripper radius position, given by the outer cavity radius (115 mm) would result in high values for the radioisotope production, it could also imply high energy losses impacting in the Dee and vacuum chamber walls. Concerning the RF frequency, for low values most of particles will not arrive to the synchronism point and will start to be decelerated, resulting in a strong reduction of the output beam current. On the other hand for high RF frequencies, the synchronism occurs very early and the acceleration time is not enough to achieve the required energy to reach the stripping foil. Although results have been presented here for RF frequency tuning, an analogue effect can be obtained by keeping fixed the RF frequency and modifying the nominal magnetic field value, which allows a more fine tuning during operation.

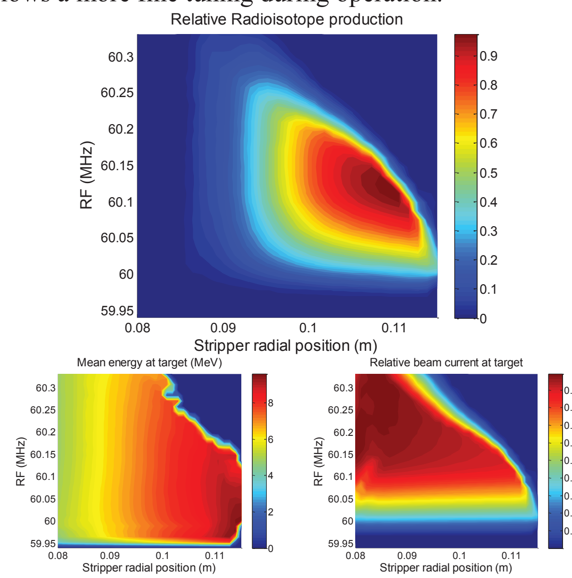

Figure 6: Effects of beam tuning (RF frequency and stripper location) on the mean energy and relative current at target (bottom figures, left and right respectively) and the impact on the relative radioisotope production (up).

CONCLUSIONS

In the optimization of the radioisotope production in a weak focusing compact cyclotron, two features have been shown to be important. From beam dynamics simulations the central region has been designed to optimize the beam transmission, taking into account the conditions imposed by the relative high magnetic field for compact reasons and the high peak voltage due to the weak focusing nature. On the other hand, the main effects of the RF frequency and the stripper location have been simulated in detail, resulting in the main design requirements of the different subsystems as well as a starting point for the fine tuning during cyclotron operation.

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