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AN IMPROVED CONCEPT FOR SELF-EXTRACTION CYCLOTRONS

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Abstract

A study is made for an improved concept of self-extraction in low and medium energy cyclotrons to be used for production of medical isotopes. The prototype of the self-extracting cyclotron was realized around the year 2001. From this machine, currents higher than 1 mA were extracted and transported to a Pd-103 production target. However, at the higher intensities, the extraction efficiency was dropping to about 70-75%, and the extracted emittance was rather poor, leading to additional losses in the beamline. Several improvements of the original concept are proposed: i) the beam coherent oscillation (as needed for good extraction) is no longer generated with harmonic coils, but is obtained from a significant off-centring of the ion source, ii) the cyclotron magnet has perfect 2-fold symmetry, allowing the placement of two internal sources and dual extraction on two opposite hill sectors, iii) a substantial improvement of the magnetic profile of the hill sectors. Simulations show an extraction efficiency up to almost 93% and emittances at least a factor 3 lower as compared to the original design. The new magnetic design is shown, and results of beam simulation are discussed.

THE PROTOTYPE

The principle of self-extraction is known already for almost 20 years [1]. During extraction, the beam crosses the region of decreasing magnetic field near the pole edge. In existing isochronous cyclotrons, the pole gap usually is large, leading to a gradual radial field fall-off and resulting in a loss of isochronism and ultimate deceleration of the beam. An extraction system is needed to transfer the beam from the limit of isochronous acceleration to the limit of radial focusing. Self-extraction is based on creating a sharp transition from the isochronous to the instable region such that the latter can be reached before falling out of RF accelerating resonance and such that the beam can escape spontaneously from the cyclotron. The prototype (Figure 1) was realized by IBA in the beginning of this century [2].

The cyclotron has unconventional features with respect to typical commercial machines. The pole gap decreases quasi-elliptically towards larger radii. The pole on which the beam is extracted, is radially longer than the others and in it, a groove is machined. This creates a field shape with a sharp dip that acts like a septum and at the same time provides optics for the extracted beam. In order to maximize the extraction, harmonic coils are used to enhance the turn separation at the entrance of the extraction path. A permanent magnet gradient corrector, is placed immediately at the exit of the pole to provide radial focusing to the diverging beam. The small part of the beam, which is not properly extracted, is intercepted on a beam stop (the beam separator) that is placed immediately at the pole exit, in between the circulating and the extracted beam. This beam separator (BS) is designed for low activation and high thermal load. The prototype successfull extracted beams almost up to 2 mA. However, rather poor beam quality was observed and also the extraction efficiency was limited to about 80% at low intensities and about 70% to 75% at higher intensities. This drop (partly) relates to an increase of the dee-voltage ripple resulting from the noisy PIG-source and beam-loading. Although encouraging, the prototype was not yet good enough for industrial applications. The measured beam-quality and extraction efficiency at low intensities agreed quite well with simulations.

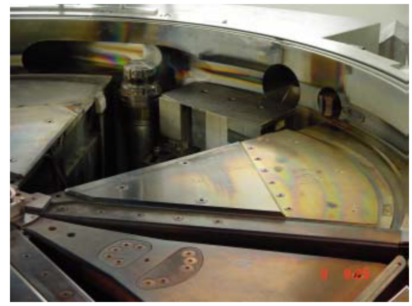

Figure 1: The extraction path in the prototype, showing the groove in the long pole, the gradient corrector and the beam separator. The harmonic coils are placed underneath aluminium pole covers.

Table 1: Cyclotron Main Design Parameters

Cyclotron Type	Compact Isochronous
particle	proton
injection	dual internal PIG-source
extraction radius/energy	52 cm; 14 MeV
rotational symmetry	2-fold (quasi 4)
B_{ave} and B_{max}	1.15 T; 1.9 T
quasi-elliptical gap	16 mm < g < 40 mm
minumum gap at extraction	18 mm
pole radius short/long	54 cm/57 cm
number of dees/angle	2; 36°
RF frequency/mode	69.1 MHz; h = 4
dee-voltage	55 kV
available RF power	200 kW

IMPROVEMENTS OF THE DESIGN

Table 1 shows the main design parameters of the cyclotron. Several improvements of the prototype are proposed [3]: i) The groove is replaced by a plateau. This lowers the strong magnetic sextupole component in the extraction path and

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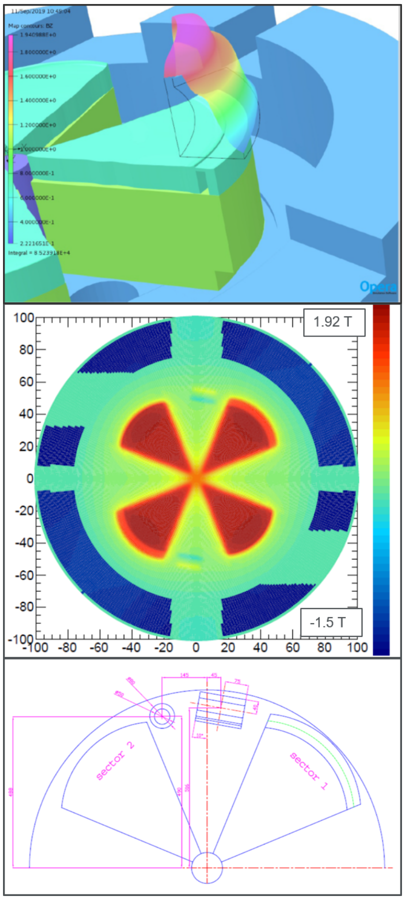

Figure 2: Lower: principal design features of the magnetic structure with the long pole and its plateau, the short pole, the permanent magnet gradient corrector and the beam separator. Middle: a zone plot of the median plane magnetic field. Upper: Finite element model of the cyclotron, showing design features of the extraction pole and the magnetic field histogram in the plateau region. At the plateau radius, the vertical gap changes from 18 mm to 28 mm.

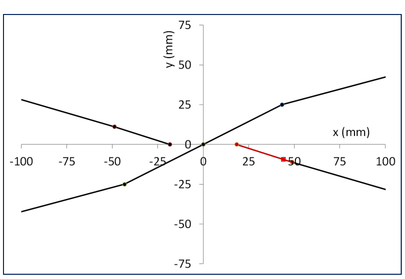

Figure 3: For the beam-simulation, the accelerating gaps were represented as a series of connected straight lines.

thereby strongly enhances the quality of the extracted beam. ii) The varying quasi-elliptical pole gap is no longer constant along circles but is constant along the equilibrium orbits of the particles. Such, the transition from the internal stable towards the non-stable extracted orbit becomes steeper, enhancing extraction efficiency. iii) The enhanced turn separation at extraction is no longer created with harmonic coils, but by an off-centring of the ion source. This substantially increases the extraction efficiency. iv) Strategic collimators are placed immediately on the first turn. This lowers the undesired beam losses at extraction. v) The cyclotron is designed with 2-fold rotational symmetry (with two long poles and two shorter poles). At the same time, two identical internal PIG ion sources are placed at opposite angles in the cyclotron centre. This allows to (simultaneously) accelerate two beams and to extract those on the two opposite longer poles. Beam produced at the first (second) ion source extracts only towards the first (second) exit port. In this way it can be chosen to irradiate only one of the production targets or both simultaneously. We note that in the prototype, currents up to 13 mA could be extracted from the ion source [1]. Figure 2 illustrates the main design features.

DESIGN OPTIMIZATION

For a given magnetic design, many beam simulations were carried out in order to find an optimum central region, resulting in highest extraction efficiency and beam quality. For this purpose the accelerating gaps were represented by a series of connected straight lines (see Figure 3) and the electric fields perpendicular to these lines by Gaussian distributions. The most important optimization parameters in this layout are the position of the ion source (r, θ) and the angle of the first gap with respect to the x-axis.

About 600 different central region geometries were evaluated. For each case a beam of 3000 particles was injected from the PIG-source in the first gap, accelerated up to full energy and then extracted. The injected phase space (see Table 2) was very large such that it filled the full central region acceptance. Figure 4 shows a typical central region beam pattern. The ion source is off-centered so much that the

Table 2: Initial beam properties used in the simulations

number of particles	3000
energy	100 eV
RF-phase	$0° < \Phi_{RF} < 110°$
half-beam width/height	1 mm; 2 mm
normalized/emittance (100%)	0.23/500 π mm-mrad

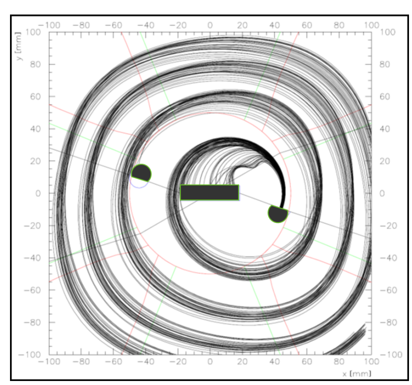

Figure 4: A typical injection simulation, showing the two ion sources, the beam passing in between them, the accelerating gaps and the beam stop removing unwanted orbits.

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first turn passes in between the two (symmetrically placed) ion sources. A beam stop is placed at this position, that removes the part of the beam that is not properly accelerated or extracted. In the simulations, the second ion source also serves as an additional collimater that further cleans the beam. In a practical design, this collimator may be placed elsewhere and further optimized in order to futher improve the extraction. Figure 5 shows a 3D simulated extracted beam super-imposed on the FEM-model of the magnet.

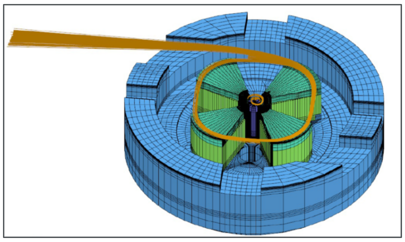

Figure 5: A simulated extracted beam also showing the part that is intercepted on the beam separator.

RESULTS

The best ion source position found in the optimization process is at the radius of 45 mm with the first accelerating gap angle at -20 degrees. This position results in a beam coherent oscillation of about 20 mm. Figure 6 shows a simulation of a differential probe track taken at an azimuth of 120° (just beyond the beam separator BS1). The beating

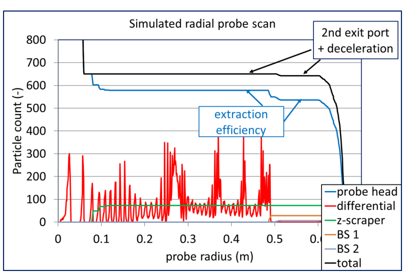

Figure 6: Simulation of a differential probe track showing turn-pattern, accumulated beam losses and beam transmission as function of radius.

Table 3: Simulated Extraction Efficiency and Beam Losses

number of injected particles = 3000 CENTRAL REGION LOSSES		
2nd ion source (18 mm)	398	
dee-connection block	1462	
vertical on dees	497	
vertical beam scraper	73	
number of particles accelerated	578	
EXTRACTION LOSSES		
beam separator 1	28	4.8%
beam separator 2	6	1.0%
second exit port	4	0.7%
back-accelerated	4	0.7%
EXTRACTION EFFICIENCY = 92.7%		

behavior seen in the turn pattern (red curve) is due to the beam off-centering. The blue curve represents the particle count on the integral part of the probe. Also shown are the losses on a vertical beam scraper (gap=12 mm) in the center, and the losses on the beam separators BS1 and BS2 (4.8% and 1.0% respectively). The black curve shows the sum of all signals. The slight dip in this curve at 50 cm is due to i) loss of isochronism and deceleration of a small fraction of the particles (0.7%) and ii) extraction towards the opposite exit port (0.7%). Table 3 shows an account on all losses. The considerable loss in the central region is due partly to the oversized injected phase space and partly to beam cleaning by collimation.The second ion source diameter is used for fine-tuning this collimation. Figure 7 shows that

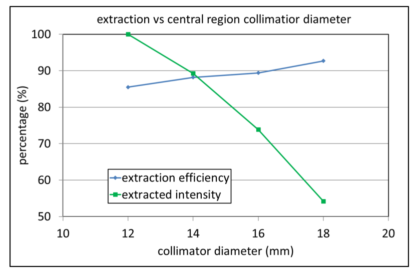

Figure 7: Dependence of extraction efficiency and intensity on the central region collimator size.

the extraction efficiency improves from about 87% to 93% by increasing this diameter from 12 mm to 18 mm. Figure 8

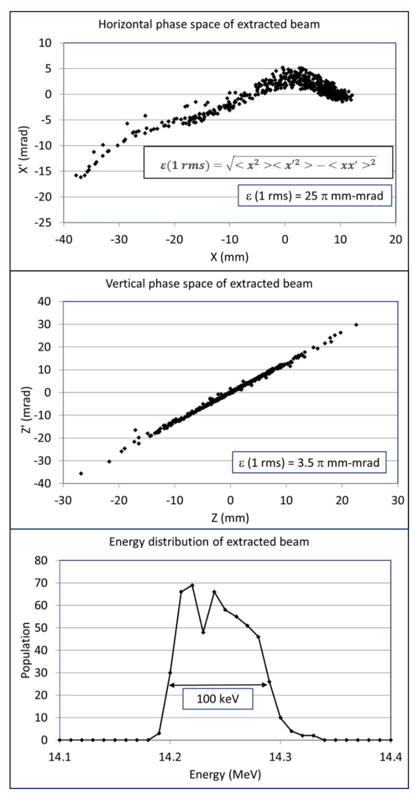

Figure 8: Horizontal phase space (upper), vertical phase space (middle) and energy spectrum (lower) of the simulated extracted beam.

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shows the phase space properties and the energy spread of the extracted beam. The emmitances are at about a factor 3 better as compared to the prototype [2]. Such a beam can easily be transported to an isotope production target within a beamline with quadrupole apertures of 100 mm.

CONCLUSION

The improved design looks promissing: compared to the prototype it shows a substantial increase of extraction efficiency and also a much better beam quality. It is foreseen to continue this study. The following routes may lead to further improvements: i) increase of the extraction radius, ii) reduction of the elliptical gap in the long poles, iii) an improved positioning of collimators in the central region and iv) improvement of the dee-voltage regulation loop.

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