DESIGN STUDY OF A SUPERCONDUCTING CYCLOTRON FOR HEAVY ION THERAPY

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1 Introduction

Radiation therapy with high Linear Energy Transfer (LET) ions such as carbon has been preferred for the treatments of some radioresistant tumours. Currently one accelerator facility is dedicated to heavy-ion therapy[2], while several proposals have been made to construct heavy-ion medical accelerator facilities[3-5]. After the demise of the EUropean Light Ion Medical Accelerator (EULIMA) proposal[3], a major accelerator option under consideration has been synchrotron as it has the advantage of active energy variation. Energy tuning on beam-pulse basis is considered to better-fit ion-beam treatment modality. However, sophistication in varying beam energy during slow or fast extraction may entail complications in the control system e.g. in the aspect of ensuring beam position. On the other hand a fixed-energy cyclotron can produce more stable CW beams, and the beam energy could be varied by well-defined mechanical system of energy degrader.

The design of a heavy-ion medical cyclotron in fact has been extensively studied some years ago through the EURIMA project. Its cyclotron was composed of a pair of circular superconducting coils and four separated flux-return yokes to produce 3 T at the extraction radius of 2.1 m for the acceleration of 400 MeV/u, q/A=0.5 ions. This separated-sector configuration has advantages in beam acceleration and extraction, but open coils produce large fringe fields, which requires more complicated shielding scheme in the facility.

According to our recent design studies, a high-field fixed-energy compact cyclotron with pillbox yoke and circular coils appears to be a viable candidate as a heavy ion medical cyclotron. Our main efforts have been paid to visualizing a practical magnet configuration, and to optics study. Many useful design concepts have been adopted from those of existent variable energy cyclotrons built at the NSCL, the K500 and K1200. The magnet and cyclotron elements have been optimized to suit the features of fixed energy and single q/A machine.

2 Magnet Design

The overall configuration of the magnet is similar to that of the K1200 magnet. Two key differences besides the magnet size lie in 1) four sectors instead of three to avoid harmful resonance of ν_r=N/2 (N is the number of sector), and 2) one pair of epoxy-potted coil instead of two pairs of cryostable coil. The pole size was scaled up to the level where adequate beam focusing is provided with spiralled sectors and where beam extraction is achievable with realistic electric fields on deflectors. It is generally true that a larger magnet and thus lower field will benefit the beam acceleration and extraction, but at the cost of magnet compactness and accordingly facility cost. The current study is not yet extended to include the size and cost relationship.

After preliminary studies on beam optics of the extraction, the extraction radius was chosen 1.33 m as the specifications of necessary cyclotron components become acceptable. The magnetic field profile for the 200 MeV/u ions with q/A=0.5 in the K1200 cyclotron is compared to the 400 MeV/u field in Fig. 1. The magnetic field at the center is about the same, but higher in the extraction region, which makes the extraction task more challenging.

The sector spiral edges for adequate vertical focusing and the focusing tunes are plotted in Fig. 2. The isochronous field was obtained using POISSON and saturated iron approximation, which has been used for the construction of high-field NSCL cyclotrons. One fourth of the magnet cross-section used in POISSON is plotted in Fig. 3 to show the configuration and dimension. A 3-d model was also made with TOSCA [7], which yielded approximately the same field map within a few percents. For rapid optimization of the overall magnet configuration, the 2-d method serves the purpose better, but for detailed shaping of the magnet steel in 3-d, TOSCA will be the final tool.

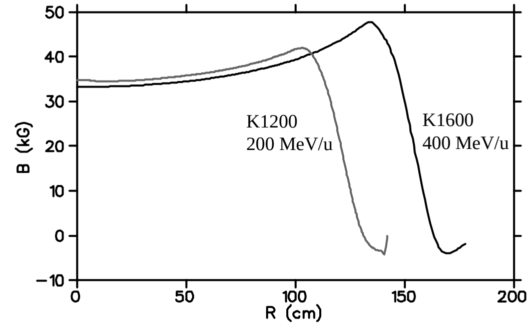

Figure 1: Radial profiles of the isochronous magnetic fields in the K1200 and K1600 cyclotrons for q/A=0.5 ions.

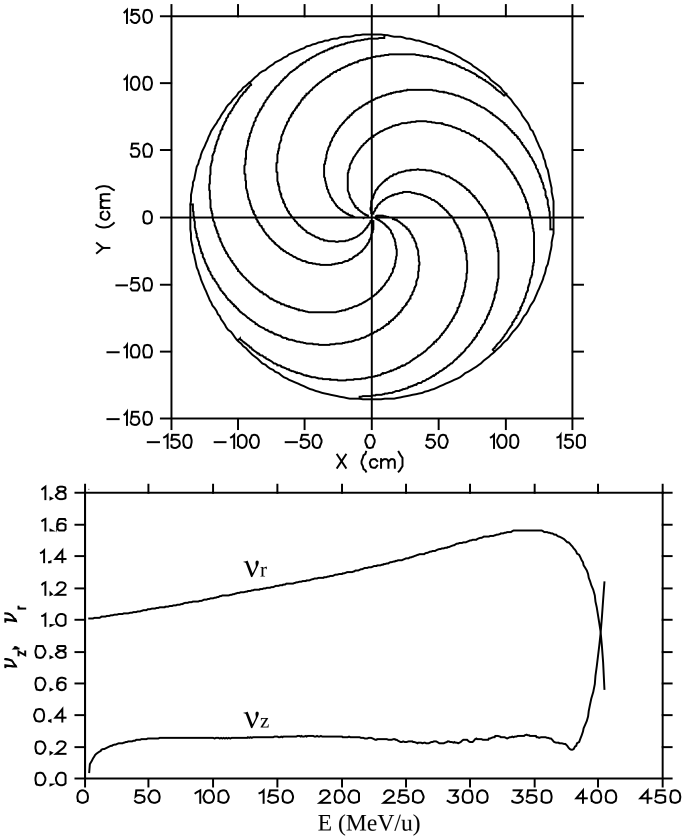

Figure 2: Hill spirals drawn on the pole-base and the focusing tunes.

Major cyclotron parameters are listed in Table 1. The detailed coil parameters were attained considering for the epoxy-potted coil package to sustain high internal stresses, and they are subject to change according to modifications of the overall coil and magnet configurations. The radial distributions of stresses in the coil are calculated by STANSOL[8] for the high field region inside the coil as shown in Fig. 4. The maximum circumferential (hoop) stress is suppressed below the yield strength of copper by 6 cm thick aluminium banding enforcement and winding preload.

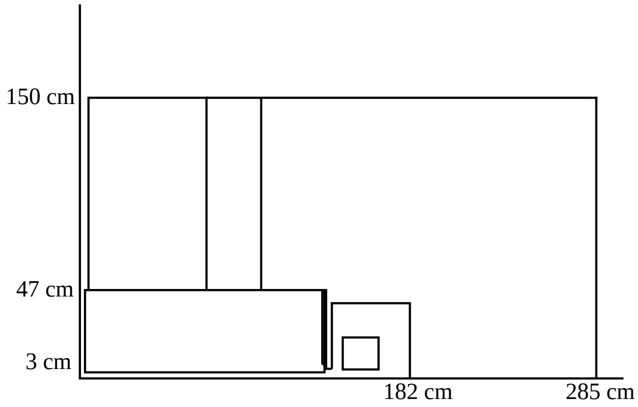

Figure 3: Cross-sectional view of one fourth of the magnet

Table 1: Major design parameters

Ion		Magnet	
Charge	Q/A=1/2	B(T)	4.8 T
Energy	400 MeV/u	R_{ext}	1.3 m
RF system		Sector #	4
Frequency	52 MHz	Weight	550 tons
V_{peak}	120 kV	J_{ave}	4100 A/cm^2
Harmonic	2	I_{op}	400 A
		Wire size	2×4 mm

Beam Extraction

The beam extraction was a main issue in optics study and consequently in choosing the magnet size. The focus of this computational work was to ensure that a usual extraction scheme is acceptable, in which electrostatic deflectors are used and followed by passive magnetic focusing channels. Figure 5 shows the layout of extraction elements and trajectory of an extracted orbit. The extraction process takes slightly over one turn as its maximum angular span is limited by the presence of penetration holes. The deflector field is set to 130 kV/cm with a gap of 5 mm, and the magnetic fields used in the channels are realistic. The beam envelopes in the course of extraction are shown in Fig. 6. The arrangement of the elements is not yet fully optimized, and a further work should produce better beam envelopes.

If a single-ion machine such as carbon-only cyclotron meets medical requirements, charge stripping could be an attractive alternative method of extraction. The beam optics has been checked for the scheme to be feasible. The extraction is done in a single turn, and the stripping should be performed in the valley region to restrain the vertical beam growth.

The turn separation at the entrance of first deflector can be enlarged by adjusting the phase of beam precession when the beam passes through ν_r=1. Figure 7 shows the radial phase space motions when a first harmonic component of 6 gauss is present at the resonance. The rf voltage is assumed 120 kV, and normalized radial emittance is 0.1 π mm mrad. The figure shows a sufficient turn separation to allow a single turn extraction. Because the beam passes through the $\nu_r=2\nu_z$ resonance prior to the extraction the effect of coupling resonance was evaluated for different radial emittances, and it turned out to be not so serious if the emittance is kept roughly less than 0.4 π mm mrad.

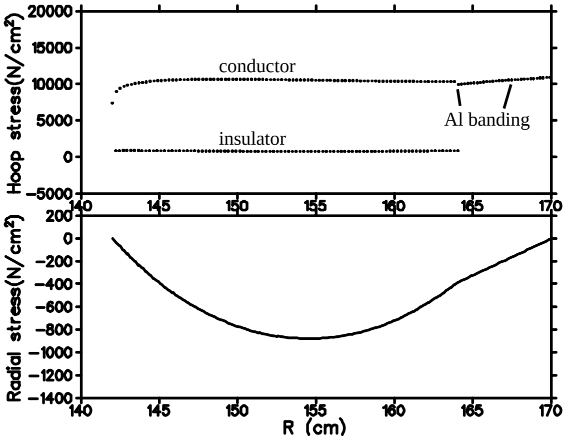

Figure 4: Radial distributions of stresses in the coil.

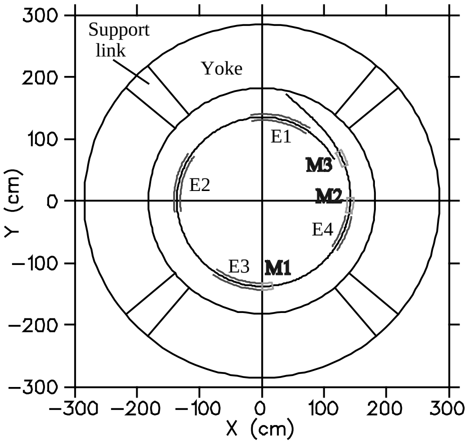

Figure 5: A layout of extraction elements and the central ray before reaching the yoke.

4 Ion source and Injection Scheme

Modern ECR ion sources can produce fully stripped light heavy-ions with q/A=0.5 sufficiently to serve the therapeutic purpose. The beam current required is in the range of 1 pnA to limit the treatment period typically to less than 5 min.

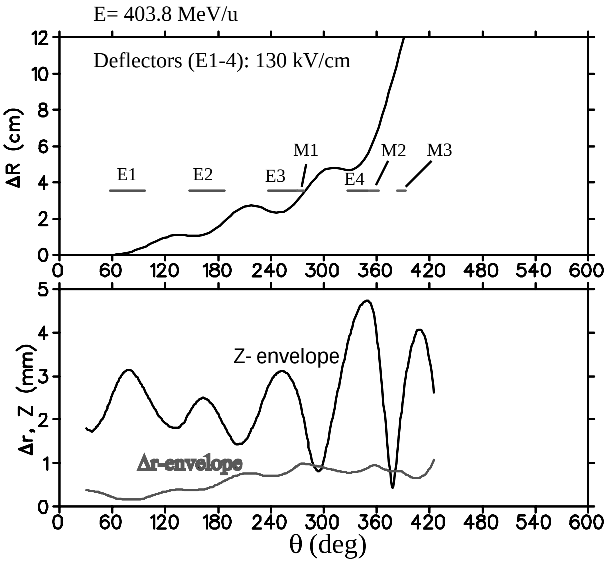

Figure 6: Upper: Separation of an extracted turn from the previous turn as a function of azimuth. Lower: Radial and axial beam envelopes.

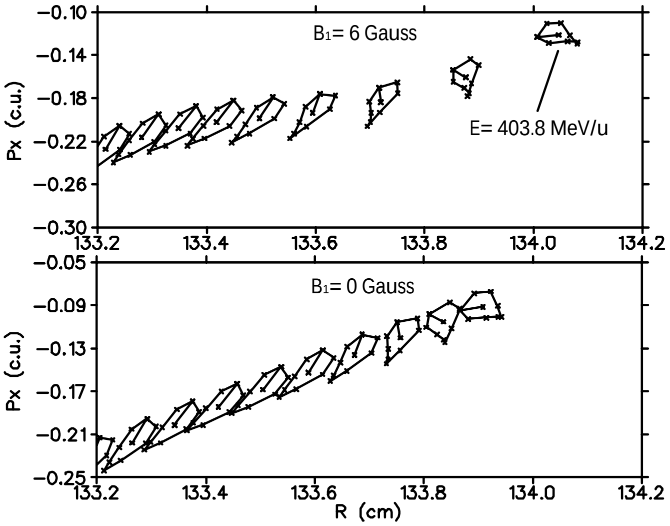

Figure 7: Radial phase space motions prior to extraction with and without first harmonic applied.

The extracted ions from the source will be axially injected into the cyclotron through a spiral inflector as in the NSCL cyclotrons[9]. With an extraction voltage of 20 kV the magnetic banding radius is 0.86 cm, and an inflector parameter, defined as $K=A/(2\rho_m)$ where A is the vertical distance for 90^o bending, is 1.16. The central region enclosing the inflector is not yet designed.

Concluding remarks

This design study has been carried out to show that a superconducting cyclotron should be a serious candidate as a heavy-ion medical accelerator. The cyclotron is more compact than synchrotron and simpler to operate. The cyclotron elements specified in the current design are realistically achievable. More complete design will be pursued, and the result will be written in other article.

References

[1] H. Blosser, PAC’89, (1989) p742.
[2] E. Takada et al., EPAC’2000, (2000) p2557.
[3] P. Mandrillon et al., Int’l Conference on Cyclotrons and Their Applications, (1989) p152.
[4] E. Eickhoff et al., EPAC’2000, (2000) p2512.
[5] G. Arduini, NIM A 365, (1995) p542.
[6] J. Alonso, EPAC’2000, (2000) p235.
[7] Vector Fields Limited, England
[8] N. Johnson, Adv. Cryo. Eng. V.22, (1976) p490.
[9] F. Marti et al, Int’l Conference on Cyclotrons and Their Applications, (1987) p484.