OPTIMIZED MAGNET FOR A 250 MEV PROTON RADIOTHERAPY CYCLOTRON

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1. Introduction

The design of a K250 superconducting cyclotron has been recently improved from the original design of early 90's as a private company ACCEL may be involved in actual construction for the PSI in Switzerland. Several critical design aspects have been reconsidered especially on the sector spiral angle and the dee configuration to achieve minimal rf losses without excessive increase in total number of turns while keeping the adequate spiral-edge focusing strength. The radial voltage profile on the dee is also being optimized by adjusting the dee stem location to meet optics requirement and to reduce rf losses.

The central region, which affects the entire acceleration characteristics for a given magnetic field, has been studied using new magnetic and electric field maps. Detailed study is currently underway in search of a source-to-puller design for larger acceptance and higher beam quality.

To estimate the energy gain and beam behaviours more precisely, 3-d electric field maps have been used throughout the acceleration region in the orbit tracking code CYCLONE[2]. In earlier studies the code utilized an impulse energy gain approximation at the middle of dee gaps when the beam is outside of the central region typically after 5-10 turns. The results of new simulations should better match with empirical beam profile measurements.

Most of major design parameters remain essentially the same as in the original design. The rf frequency is 72 MHz in second harmonic of the particle rotation frequency. The azimuthally averaged magnetic field at the extraction radius of 81 cm is 3 T. The peak voltage in the central region is lowered from 100 kV to 80 kV.

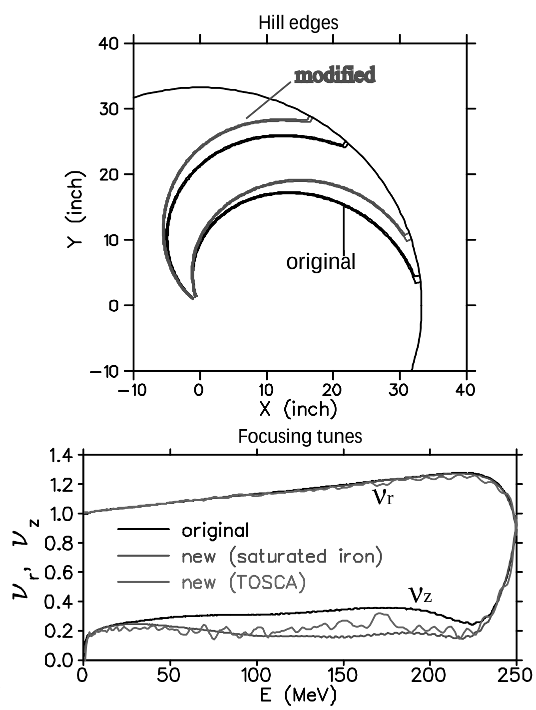

Figure 1: Original and modified hill spiral lines drawn on the pole base and the corresponding focusing tunes.

2. Magnet design

The sector spiral angle in isochronous cyclotrons is determined to yield sufficient vertical focusing. The vertical focusing tune is usually set to be greater than 0.15. The previously chosen spiral line was rather prudent in that the tune was over 0.2. The hill-edge line is thus unspiraled, which benefits in reducing capacitive load to lower rf power losses. The hill spiral-lines of the two designs and the corresponding focusing tunes are shown in Fig. 1. The magnetic field was computed using POISSON[3] and saturated iron approximation in 2-d, and with TOSCA[4] in 3-d for a final configuration. Noise in the tune plot for the TOSCA field comes from irregular meshes in finite-element analysis.

In the injection and extraction regions, focusing tunes and isochronism sensitively depend on detailed iron configuration of cyclotron components. TOSCA was the main tool to shape the steel in those important regions and to identify the parts to shape the field without major modifications when the field mapping-correction process begins. Crosshatches in Fig. 2 indicate added iron in the central region and a field-shaping element in the extraction region.

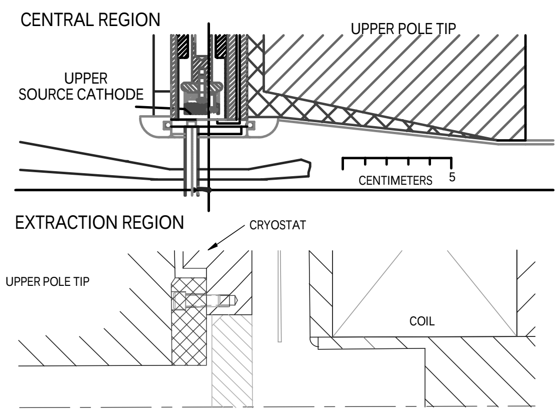

Figure 2: 3-orbit tracking study and central region design. Cross hatches indicate the parts for modification to control the average field and field flutter.

In pursuit of an optimal design of the central and extraction regions in the cyclotron, we have studied optics of a beam starting from the ion source exit to 250 MeV with CYCLONE. The rf electric field maps used cover the entire beam acceleration region for enhanced realistic simulation. The electric field map was computed with the 3-d relaxation code RELAX3D[5] including the radial dee voltage profile attained with transmission line analysis. We have a future plan to use MAFIA[6] to generate more accurate field map.

The design of the central region adopting an internal ion source needs to assume some parameters such as zero-potential plasma boundary at the source opening and the initial ion energy because they are not clearly defined with respect to the rf voltage wave. Based on experiences gained from the K50 and the Harper hospital cyclotrons built at the NSCL, we chose the reference rf starting phase as 210° (the peak is at 270^{o}) and the starting energy 10 eV. The validity of these choices has been tested with experiment[7]. The source tube has 6.35 mm OD, and the opening for an outgoing beam has a horizontal width of 0.5 mm and an axial height of 6 mm. The relaxed equipotential contours in the source-to-puller region are shown in Fig. 3 with some ion trajectories. The starting locations of the ions are indicated in the inset. The locations of the posts in the puller region need an adjustment for a better beam centering.

To extract ions from the cyclotron, which predominantly start around 210^{o} initial rf phase, the fully accelerated beam energy should be a maximum for that starting phase. Figure 4 shows the energy versus rf starting phase. Another condition imposed to the beam is to minimize the energy spread with the following requirement:

$$\int \sin\phi(E)dE = 0\,,$$

where $\phi(E)$ is phase excursion. These conditions of peak energy gain and minimum energy spread can be met by adjusting the rf frequency and isochronism of the magnetic field. A first few turns of ion trajectories in the central region are plotted on equipotential contours in Fig. 5. The peak puller voltage is 80 kV. We have to further work on this region as the magnetic field modelling gets improved.

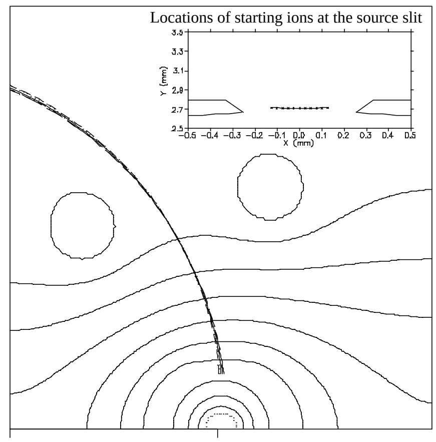

Figure 3: Equipotential lines in the source-to-puller region plotted with ion trajectories. The inset shows starting ion locations on zero plasma potential.

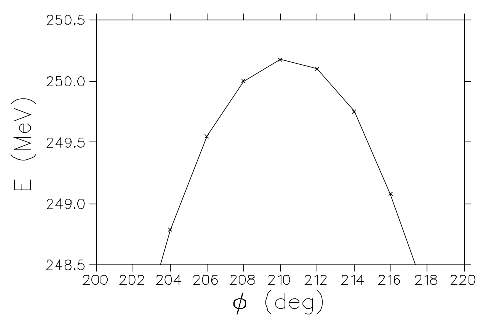

Figure 4: Final energies versus rf starting time. The peak is at 270^o.

The centering of a beam is required to avoid the vertical beam blow-up induced at coupling resonance. It is planned to produce the centering bump field with field- trimming rods that are movable to control the strength and phase of first harmonic component. In current simulations, an ideal gaussian field bump was used, and more realistic TOSCA field bump will be adopted later.

The phase space motions of a beam have been investigated starting from the beam energy of 10 eV at the source to 250 MeV. This study aims to optimize the magnetic field profile and to produce the radial beam profile matching with beam probe measurement. The result is yet preliminary as the work is ongoing. Figure 4 shows the final five turns well centered before the extraction when the initial rf phase spread is $\pm 1^o$ around 210^o, radial beam spread at the source opening ± 0.13 mm, and angular spread $\pm 30^o$. The energy spread at 250 MeV given by the rf phase spread is about 4×10^{-4}, which sets the radial beam width. The curling in phase spaces mainly comes from non-isochronism and finite transverse emittance. The field needs to be better isochonized to achieve smaller radial beam spread especially when the beam is in precession. For extraction, precession induced at the ν_r=1 is of course needed to enlarge turn separation.

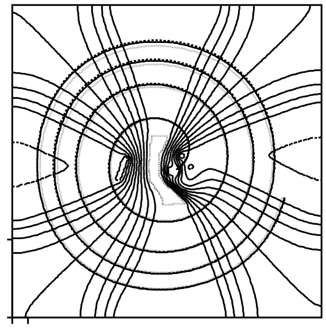

Figure 5: Ion trajectories in the central region. The starting rf phase for solid line is 210^o, for dotted line 200^o, and for dashed line 220^o.

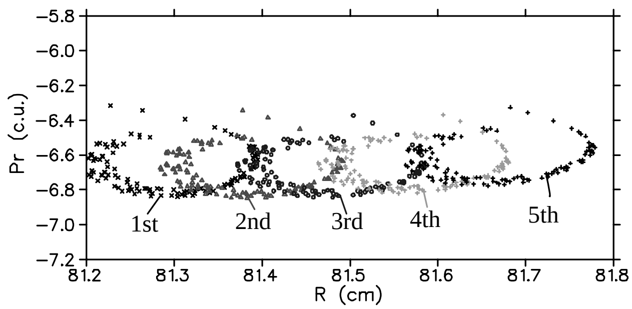

Figure 6: Radial phase space motions of a well-centered beam plotted for last five turns before extraction.

3 RF Power loss in relation with dee gap width

The gap profiles between the dee and dee-liner are often chosen without much optimization efforts so far as sparking is not a concern. According to the relationship between energy gain per turn and gap width as written in equation below, the energy gain is inversely proportional to the dee gap width ($g \approx (45^o - \Delta\vartheta)/2$):

$$\Delta E = 2 n_{dee} V_{dee} \frac{\sin\eta}{\eta} \sin\frac{h\Delta\theta}{2},$$

where $\eta = (\pi g)/(\beta\lambda)$, $\beta = v/c$, dee number n_{dee} is 4, angular dee width $\Delta\vartheta$ is around 40^o, and h is 2. On the other hand the rf power loss has higher-power dependence on the gap width. This means that an optimum gap width exists for a given total number of turns, and may be larger than usually prescribed. For a systematic study quasi-uniform gap profiles were used as shown in Fig. 7 in the calculations of energy gain and rf power loss. The total turn number increases from dee1 to dee2 by 10 % for the same voltage profile, and from dee2 to dee3 by 15 %, while the power loss is reduced by 50 % in the first step according to the transmission line analysis and 30 % in the second step roughly estimated by scaling, which implies dee3 may be close to an optimum considering square dependence of power loss on rf voltage. Further computational studies are needed to finalize the dee gap profile.

Summary

The sector spiral angle has been optimized to improve the rf properties under the criterion that the vertical focusing tune remains above 0.15. The optics study involving more realistic fields have been carried out to help in designs of the central and extraction regions as well as in final beam tuning. We have searched for an optimal dee gap width to reduce the rf power loss, and have found the gap should be larger than usually defined as in existing cyclotrons. The work is ongoing, and the design will be complete, suitable for the actual construction in the near future.

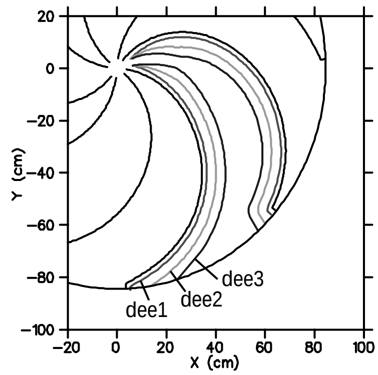

Figure 7: Dee profiles in the valley to compute energy gains and rf power losses.

References

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