DESIGN STUDIES ON THE MAGNET AND CENTRAL REGION OF A 10 MEV HIGH CURRENT COMPACT CYCLOTRON

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Abstract

A compact four sector 10 MeV, 5 mA proton cyclotron is being developed at VECC. Proton beam at 100keV from a 2.45 GHz ion source (under testing) will be first collimated and bunched. It will be injected axially in the central region where a spiral inflector will place the beam on the orbit. Two delta type resonators located in the opposite valleys will accelerate the beam and an electrostatic deflector will be used for the extraction. In this paper we present the design study carried out for the main magnet. We have also carried out the optimization of the central region in the computed magnetic field to get well-centered orbits.

INTRODUCTION

The development of a 10 MeV, 5 mA compact radial sector proton cyclotron [1, 2] is a part of the considerably larger activity undergoing in the field of high intensity accelerator development for ADSS applications. A 2.45 GHz microwave ion source presently under testing will produce ~30mA of proton beam at 100keV. The extracted beam will be first collimated using slits and then it will be bunched using a sinusoidal buncher. It will be injected axially in the central region of the cyclotron where a spiral inflector will place the beam on the proper orbit. Two delta type resonators, each having ~ 45 degree angle located in the opposite valleys, will be used for providing acceleration to the beam. Finally, this beam will be extracted using an electrostatic deflecting channel. The main aim of this project is to study and settle various physics and technological issues associated with the production, bunching, injection, acceleration and extraction of the high intensity beams.

We have chosen the configuration of the magnet having four sectors with maximum magnetic field of 1.5T at the hill centre, and an average magnetic field of 0.689T. This corresponds to a revolution frequency of ~10.5 MHz for proton. The harmonic mode h of operation is equal to 4. The hill gap is 4 cm and the valley gap is 64 cm, same as the distance between the upper and lower return yokes. For the injection system, one hole is provided at the center. We have provided four holes in the four valleys, two of them will be used for vacuum pumps and the rest two will be used for the RF cavities vertically. Apart from using a high dee voltage, we have chosen a low average magnetic field and hence a large extraction radius of ~65 cm for 10 MeV cyclotron to have a reasonable turn separation at the extraction radius. Though this method increases the cost of the cyclotron, it gives more flexibility and a clear advantage for injection and extraction. A high flutter provides strong focusing in the vertical direction. The main idea was to provide the vertical betatron tune > 0.5 at all radii. This is necessary for handling the beam space charge defocusing force at the average beam current of ~ 5mA. In order to meet the isochronism, the shaping of the azimuthally averaged magnetic field was done with the help of varying the sector angular width along the radius.

The primary size of the magnet was estimated using two-dimensional code. Finally a 3D code was utilized for the field calculation and optimization. The profile of magnet sectors was optimized based on the computed results to get the desired values of isochronous field and the betatron tunes. We have carried out the optimization of the central region in the computed magnetic field to get well-centered orbits and also estimated the behavior of the beam envelope along the accelerated orbit using K-V beam envelop equations.

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MAGNET DESIGN

The conceptual dimensions of the magnet and the properties of the equilibrium orbits (EO) were first determined by a computer code based on hard edge approximation and matrix method [3, 4]. A preliminary estimate using analytical calculations indicated the transverse and longitudinal current limit > 10mA [5]. Finally a 3D computer code was used to optimize the sector shape and achieve the isochronous magnetic field. We obtained the shape of the magnet sector and properties of the equilibrium orbit such as focusing frequencies using an iterative process. Extreme care was taken to keep the betatron tunes υ_r and υ_z sufficiently away from the dangerous resonances. The optimised parameters of the magnet are listed in Table 1.

Table 1:Optimized parameters of the magnet

Injection energy	100 keV
Final energy	10 MeV
Number of sectors	4
Hill gap	40 mm
Valley gap	640 mm
Sector angular width	16-34 deg
Hill field at extraction	1.5 T
Valley field at extraction	0.15 T
Extraction radius	65 cm
Pole radius	72 cm
Ampere turns	315 × 200
Iron weight	25 ton

Fig. 1 shows the model of the magnet. In order to improve the accuracy we have used one eighth model and divided the hill in several parts to give different mesh sizes appropriate with the dimension i.e., smaller mesh sizes at lower radii. One of the most difficult problems to solve was the shaping of the magnetic field in the central region. In our case the estimated height of the spiral inflector is ~10cm (100 keV injection energy), which requires a reasonably large space and, therefore, a careful optimisation of the central plug was needed. The required isochronous field within the tolerances was obtained after several iterations by shimming the angular width of the hill as a function of radius as shown in Fig. 2. Initially the sector radius was chosen to be equal to the extraction radius plus one pole gap, however, during the iteration it was modified to provide good field region up to the final closed equilibrium orbit.

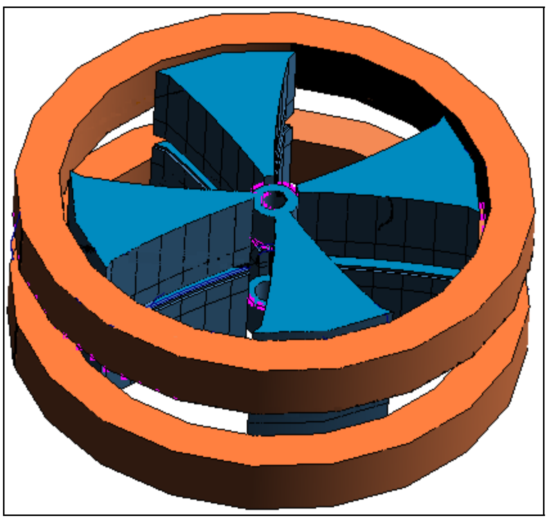

Figure 1: Model of the magnet (only hills, coils and central plug) used for the calculation of magnetic field.

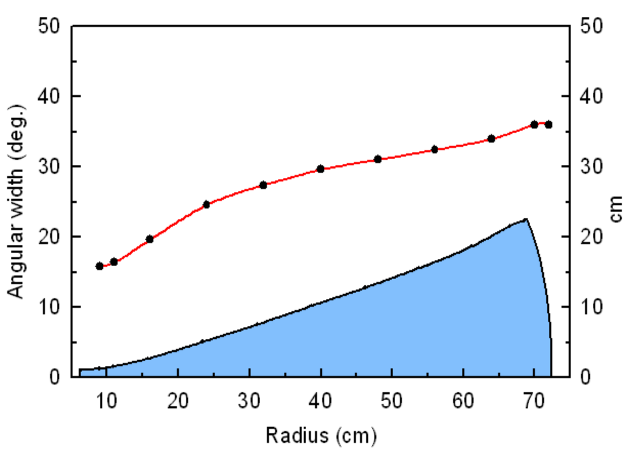

Figure 2: Optimised angular width of the sector as a function of radius and a half model of the hill.

ORBIT PROPERTIES

The properties of the equilibrium orbit i.e., the radial and axial tunes, frequency error, integrated phase shift, and average magnetic field etc. were optimized after several iterations using the equilibrium orbit program GENSPEO [6]. All the equilibrium orbit calculations were done at the energy intervals of 200 keV starting from 100 keV. Fig. 3 shows the integrated phase shift as a function of radius. The analysis shows that the phase excursion in the entire region is limited within ± 10deg. The radial and axial betatron tunes are plotted in Fig. 4 and are compared with the analytical calculations.

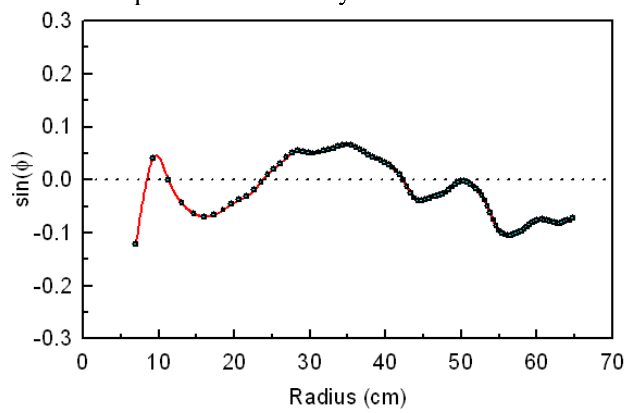

Figure 3: Variation of integrated phase shift with radius. The phase excursion is within ± 10 deg.

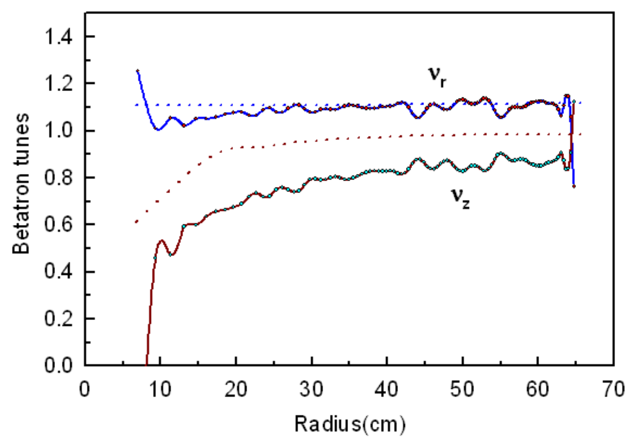

Figure 4: Variation of radial and axial betatron tunes with radius. Dotted curves represent the analytical results.

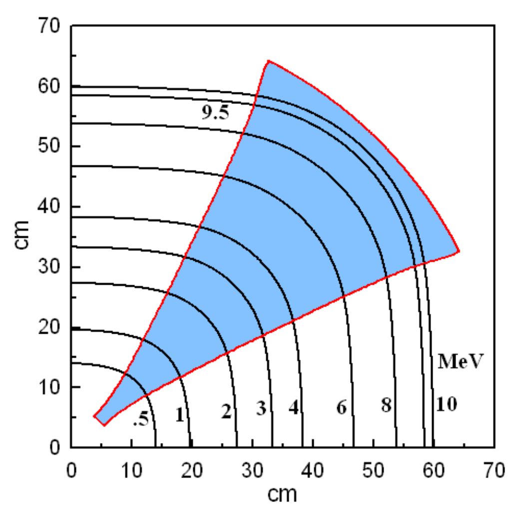

Figure 5: Equilibrium orbits for different energies. The separation between the last two orbits is ~1.8 cm.

CENTRAL REGION

We have done some preliminary studies on the central region to find out the condition for beam centering. All calculations of the beam centering have been performed with following parameters: injection energy 100keV, Dee Voltage 125kV, gap width between dee and dummy-dee 2cm, dee height 3cm. Initially we used a homogeneous magnetic field 0.5 T in the plug region but later on it was replaced with the field obtained from 3D calculations. We have used a gaussian distribution function for the electric field in the four accelerating gaps. Fig. 6 shows the position of the accelerating gaps (G-1 to G-4) in the median plane and orbits of the beam. A more detailed analysis and optimisation of central region with computed electric and magnetic fields are in the process.

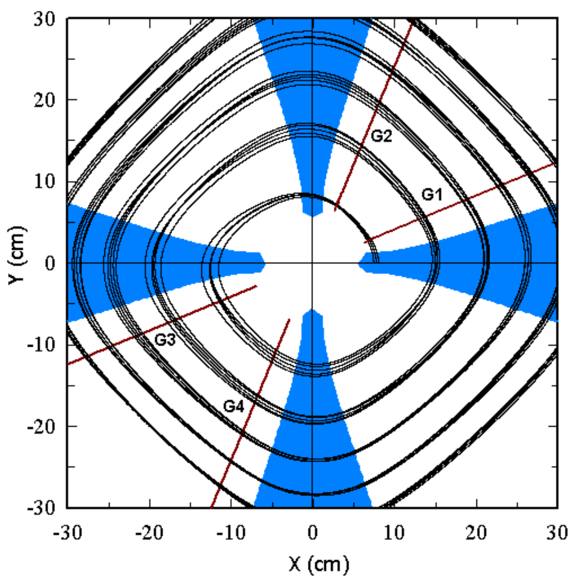

Figure 6: Optimised orbits for protons having radial width of ± 4 mm and phase acceptance of ± 15^0 of rf at starting. Injection energy=100keV and dee voltage =125keV.

We have also estimated the radial and vertical acceptance of the cyclotron in the presence of space charge. For this we have solved numerically the well known coupled K-V beam envelope equations along the accelerated orbit of beam. The K-V beam envelope equations are

$$\frac{X''}{R^2} + \frac{\nu_r^2}{R^2}X - \frac{4I}{(X+Z)I_0\beta^3\gamma^3}\cdot\frac{2\pi}{\Delta\phi} - \frac{\varepsilon_x^2}{X^3} = 0 \qquad (1)$$

$$\frac{Z''}{R^2} + \frac{\nu_z^2}{R^2}Z - \frac{4I}{(X+Z)I_0\beta^3\gamma^3}\cdot\frac{2\pi}{\Delta\phi} - \frac{\varepsilon_z^2}{Z^3} = 0 \qquad (2)$$

In equations (1) and (2) the integration variable is azimuth angle θ and R is the location of the orbit from the machine centre. $I_0 = 3.1\times10^7\ A$. The radial dependence of tunes was obtained from the equilibrium orbit data. The effect of axial electric focusing at the gaps in our case was calculated using first order theory [7] and was included in the vertical tune during calculations. In order to take care of acceleration the values X' and Z' were modified suitably at each integration step by multiplying them with the ratio of old $\beta\gamma$ to the new $\beta\gamma$. Fig. 7 shows the radial and axial beam envelops along the accelerated orbit up to 16 turns for two different values of beam current. We have observed that 5 mA beam can be easily controlled in the vertical plane within the 5mm beam radius.

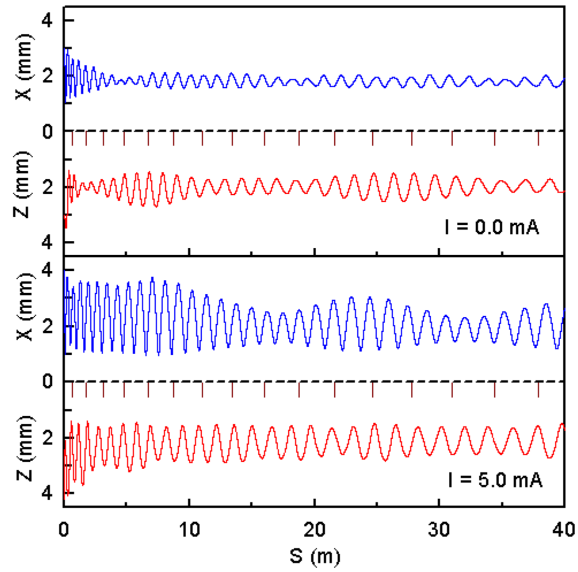

Figure 7: Radial (X) and axial (Z) beam envelopes along the accelerated orbit up to 16 turns. Normalised emittance ε_n=0.8π mmmrad in both the planes.

CONCLUSION

In this work we have presented the modelling of the magnet and 3D calculations of the magnetic field of the 10 MeV compact cyclotron. The 3D magnetic field calculation has been found to be utmost useful for the optimisation of the hill shape near the central part. We have also presented the studies carried out on the optimisation of central region using the calculated magnetic and also estimated the vertical acceptance. Studies related to the design optimisation of the spiral inflector to match the starting conditions in the central region are in progress.

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