MAGNETIC FIELD CALCULATIONS OF A 10 MEV HIGH CURRENT COMPACT CYCLOTRON

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Abstract

In this paper we present the design study of the main magnet of the 10 MeV compact cyclotron. The preliminary dimensions of the magnet and the properties of the equilibrium orbits were first obtained using hard edge approximation. The primary size of the magnet was estimated using two-dimensional POISSON code. Finally a 3D code was utilized for the field 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.

INTRODUCTION

Under the ADS development programme of the DAE, a 10MeV, 5-10mA compact radial sector proton cyclotron, is being developed at VECC in Kolkata [1, 2]. A 2.45 GHz microwave ion source 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, acceleration, injection, extraction, etc. of the high intensity beams.

In our design there are four magnet sectors. We have tried to keep a maximum magnetic field of 1.5T at the hill centre, and an average magnetic field of 0.689T, which correspond to a particle revolution frequency of 10.5MHz for proton. 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. The harmonic mode h of operation is equal to 4. The magnet design combines the advantages of solid pole cyclotron and separated sector cyclotron. 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.

CYCLOTRON PARAMETERS

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]. Here we outline the procedure briefly. Details are given in reference [5]. For an N sector cyclotron with magnetic fields B_H and B_V in the hill and valley respectively, the angles of turning of orbits η and ξ can be given as

$$\eta = \frac{B_H B_V}{B_H - B_V} \cdot \frac{2\pi}{N} \cdot \left(\frac{1}{B_V} - \frac{1}{\gamma B_0} \right), \; \xi = \frac{2\pi}{N} - \eta \qquad (1)$$

where γ is the usual relativistic term and B_0 is the central magnetic filed. One can easily obtain the angular widths of the hill and valley η_0 and ξ_0 on an equilibrium orbit for a given energy by solving

$$\cot(\frac{\eta_0}{2}) = \cot(\frac{\pi}{N}) + \frac{B_H}{B_V}\left(\cot(\frac{\eta}{2}) - \cot(\frac{\pi}{N}) \right),$$

$$\xi_0 = \frac{2\pi}{N} - \eta_0 \qquad (2)$$

In order to calculate betatron tunes we need entry and exit angles to the hill (which becomes the exit and entry angles for the valley), which are given by

$$\phi_1 = \varepsilon_1 + \frac{\eta - \eta_0}{2} \; , \; \phi_2 = \varepsilon_2 - \frac{\eta - \eta_0}{2}$$

$$\tan \varepsilon_2 = \tan \varepsilon_1 + R \cdot \frac{d\eta_0}{d\gamma} \cdot \frac{d\gamma}{dR} \qquad (3)$$

Here ε_1 is the spiral angle at the entry of the hill, which is zero in the present case. The effective spiral angle ε_2 at the exit of the hill includes spiral angle as well as flaring effect [4]. We have used the well-known matrix method to estimate the betatron tunes. Here hills and valleys are treated as bending magnets of lengths $\eta\rho_H$ and $\xi\rho_V$ having focusing strengths of $1/\rho_H$ and $1/\rho_V$, ρ_H and ρ_V being the radius of curvature in the hill and valley respectively. The

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flaring and the edge effects are introduced by using thin lens matrices at each hill-valley boundary. Since the vertical focusing frequency is quite sensitive to the fringe field at the hill-valley boundary, we have modified the classical hard edge formula to include the soft edge effect. The radial and vertical betatron tunes υ_r and υ_z can be easily obtained from:

$$\upsilon_r = \frac{N}{2\pi}\cos^{-1}\left[\tfrac{1}{2}Tr\left(\mathbf{V_R}\cdot\mathbf{H_R}\right)\right]$$

$$\upsilon_z = \frac{N}{2\pi}\cos^{-1}\left[\tfrac{1}{2}Tr\left(\mathbf{V}_V\cdot\mathbf{H}_V\right)\right]$$

Here $\mathbf{H_R}$, $\mathbf{H_V}$ and $\mathbf{V_R}$, $\mathbf{V_V}$ are the transfer matrices for horizontal and vertical motions in the hill and valley respectively. We have obtained the initial shape of the magnet and properties of the equilibrium orbit using an iterative process. Care has been taken to keep betatron tunes υ_r and υ_z sufficiently away from the resonance.

MAGNET DESIGN

A 3D computer code was used to calculate and achieve the isochronous magnetic field. 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 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 EO.

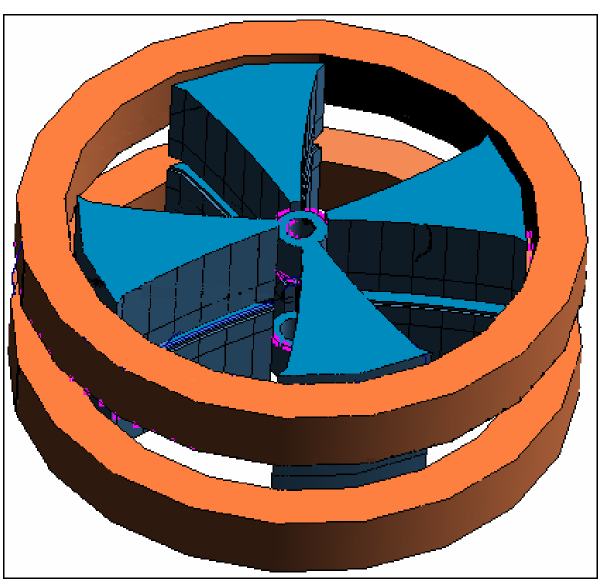

Figure 1: Model of the magnet used for field calculation.

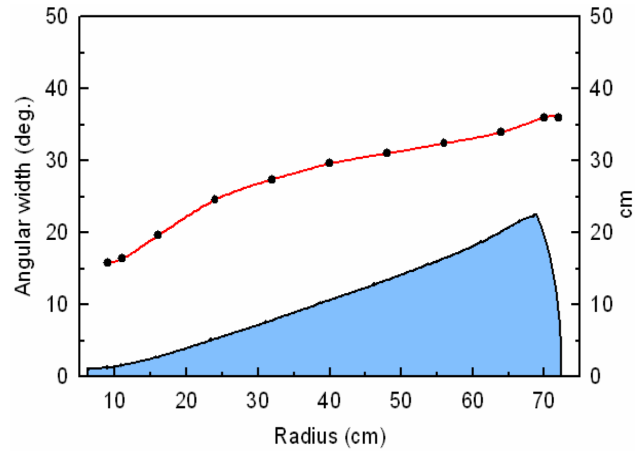

Figure 2: Optimized angular width of the sector as a function of radius and a half model of the hill.

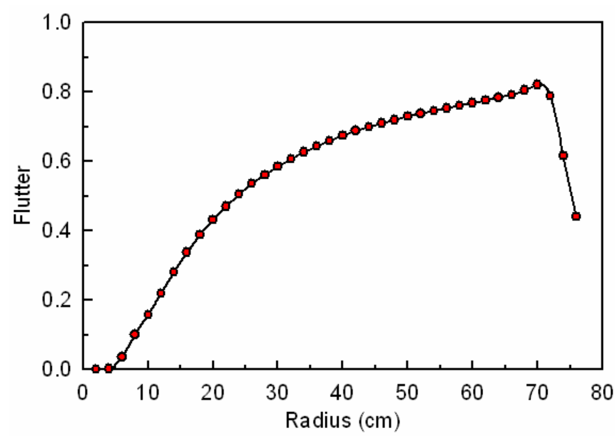

Figure 3: Flutter as a function of the radius.

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

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]. Fig. 3 shows the variation of calculated flutter with radius whereas Table 1 presents the optimized important parameters of the magnet. All the EO calculations were done at energy intervals of 200 keV starting from 100 keV. Fig. 4 presents the frequency error $\Omega(\omega)$ between the calculated field and the isochroous field as function of radius whereas Fig. 5 shows the integrated phase shift. 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. 6 and compared with those of the analytical calculations.

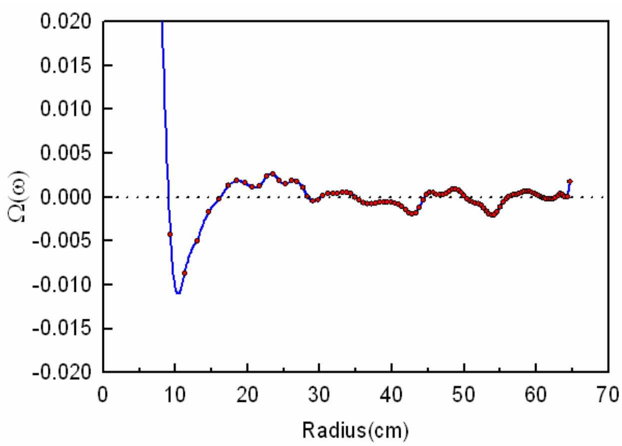

Figure 4: Variation of frequency error $\Omega(\omega) = (\omega_0-\omega)/\omega$ as a function of the radius.

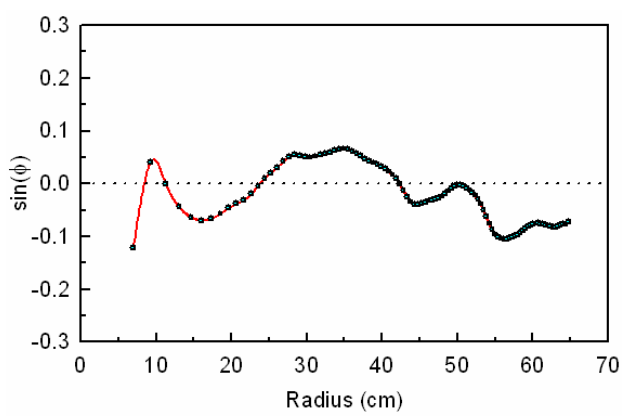

Figure 5: Variation of integrated phase shift with radius. The phase excursion during the entire region is within reasonable limit of ± 10deg.

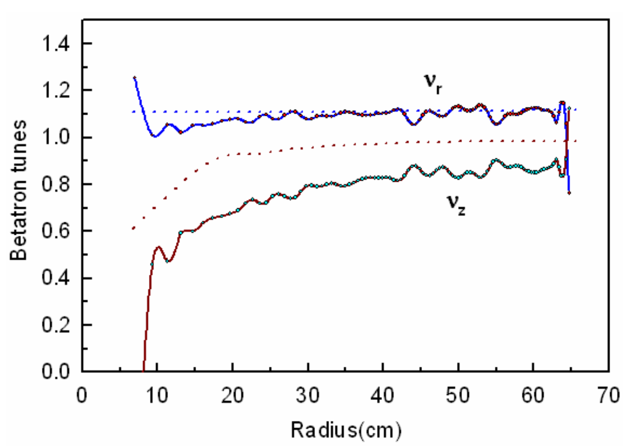

Figure 6: Variation of radial and axial betatron tunes with radius. Dotted curves represent the analytical results.

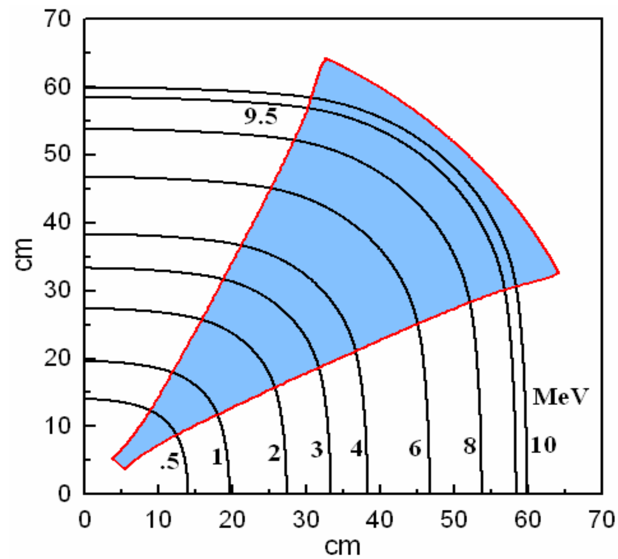

Figure 7: Equilibrium orbits for different energies. The separation between the last two orbits is ~1.8 cm.

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. The detailed interpretations of the results and further detail modelling, particularly in the central region, are in progress. Studies related to the design optimization of the RF system are in progress.

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