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DESIGN OF THE TRIM COIL FOR THE SUPERCONDUCTING CYCLOTRON EXTRACTION

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Abstract

A proton therapy system is being developed at Huazhong University of Science and Technology (HUST). A 250 MeV superconducting cyclotron with an average magnetic field of 3.1 T in the extraction region is selected, which creates difficulties for beam extraction because of the small turn separation of the beam orbits in the extraction region. To obtain high extraction efficiency, a carefully controlled magnetic perturbation is introduced to excite resonance when beam passes through the ν_r =1 resonance. The first-order perturbation in the magnetic field is generated by trim coils within confined regions. The profile of the trim coil and the resultant perturbation fields are optimized iteratively with orbit tracking. Simulation shows that sufficient turn separation can be obtained with the proper setting of trim coils.

INTRODUCTION

The average magnetic field in the extraction region of the SCC-250 MeV superconducting cyclotron is 3.1T [1]. It makes the turn separation smaller than the beam size, which will cause the low extraction efficiency. In order to increase the turn separation, processional extraction method [2] driven by the imperfect magnetic field with the 1-harmonic during passing the ν_r=1 resonance is used. The 1-harmonic can be generated by active or passive method. In active method, trim coils are usually used to generate the 1-harmonic. In passive method, the 1-harmonic is generated by trim rod in the pole. In order to ensure that the amplitude adjustment range of the first harmonic covers 0-10 Gs, the depth of the trim rod should be design more than 15 cm depth [3]. The radius spread of the first harmonic is about 6cm, which is much higher than that of the active method.

In this paper, the accelerator is still in the commission stage, in order to make the adjustment more flexible. Trim coils are designed to generate the 1-harmonic, there are four harmonic coils distributed on top of the four hills of the main magnet pole. The hard edge model is used to adjust the coil current. The phase of the 1-harmonic is optimized to obtain a large turn separation. Finally, the coil is designed to cover a radial range of 2 cm, and the amplitude of the generated 1-harmonic is 11.2 Gs

MODEL OF THE TRIM COIL

Hard Edge Model

The angular distribution of the trim coil along the track is shown in Fig. 1. Due to the location relationship between the spiral angle sectors and the trim coil, the installation coverage angle of the trim coil cannot be taken as 45°, where the installation angle of 30° is taken here. By continuously controlling the current of the four coils, a continuously adjustable first harmonic amplitude and phase can be obtained.

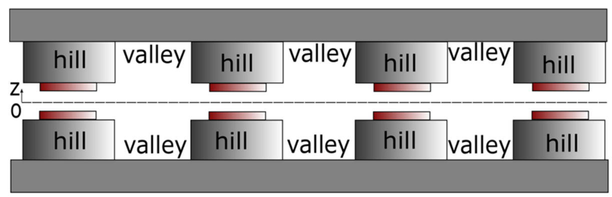

Figure 1. Distribution of the trim coils.

The length of the coil in the azimuthal direction is of 21 times than that of the radial direction, so the magnetic field can be approximated as flat top square wave in the azimuthal direction using the hard edge model. Thus, the analytical result of the magnetic field can be given.

Square wave with the Phase of 0°, the duty cycle of 1/12 and the amplitude of 1 is written in the form of Fourier series

$$u(t)=\begin{cases}1(0<t<\frac{\pi}{6}) \\ 0(\frac{\pi}{6}<t<2\pi)\end{cases}=a0+\sum_{1}^{+\infty}[an\cos(n\theta)+bn\sin(n\theta)] \quad (1)$$

The constant a_n and b_n contain the amplitude and phase value of each harmonic, they can be calculated as

$$\begin{cases}a0=\dfrac{1}{12} \\ an=\dfrac{\sin(\frac{n\pi}{6})}{2n\pi} \\ bn=\dfrac{1-\cos(\frac{n\pi}{6})}{2n\pi}\end{cases} \quad (2)$$

using Eq. 2, the amplitude and the phase of the 1-harmonic is 0.08 and -5/27π separately.

Magnetic field generated by the 4-bump coils are given as

$$\begin{cases}B_1=A_1u(\theta-\pi/12) \\ B_2=A_2u(\theta-7\pi/12) \\ B_3=A_3u(\theta-13\pi/12) \\ B_4=A_4u(\theta-19\pi/12)\end{cases} \quad (3)$$

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$$\begin{cases} A1 + A2 + A3 + A4 = 0 \\ A1\cos(-\frac{29}{108}\pi) + A2\cos(-\frac{83}{108}\pi) + A3\cos(-\frac{137}{108}\pi) + A4\cos(-\frac{191}{108}\pi) = A\cos(\varphi) \\ A1\sin(-\frac{29}{108}\pi) + A2\sin(-\frac{83}{108}\pi) + A3\sin(-\frac{137}{108}\pi) + A4\sin(-\frac{191}{108}\pi) = A\sin(\varphi) \end{cases} \quad (4)$$

where A_n is the magnetic flux density amplitude of each coil. To obtain the 1-harmonic with the given amplitude A and phase φ, the magnetic flux density amplitude of each coil satisfies the 3 equations contain 4 variables, so an additional constrain can be satisfied. For example, zero value of the 2-harmonic.

Phase Optimization of the 1-Harmonic

To find the largest turn separation with the lowest 1-harmonic, the harmonic field phase is searched in range of 0-2 π. Figure 2 shows the phase plot of the radial motion of the beam under the 1-harmonic with different phases. It can be seen from the figure that in the phase range 20° ~ 45°, turn separation reaches more than 5 mm.

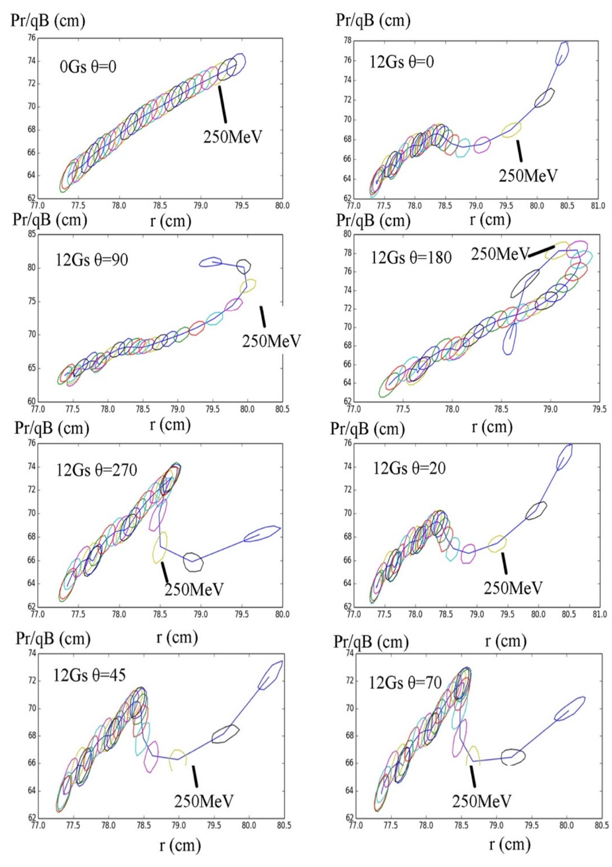

Figure 2: Phase ellipse of the extracting beam under different 1-harmonic phases.

DESIGN OF THE TRIM COIL

Figure 3 shows the shape of one pair of trim coil. Coil size in the azimuthal direction is much bigger than that in other directions, so the ampere turn of the coil can be estimated using 1D model where d is the distance between the coil and the median plane of the cyclotron. To get the 1-harmonic with the amplitude of 12 Gs, ampere turn is calculated as 150.

$$NI = \frac{8\pi \mathrm{d} B_0}{\mu_0} \quad (5)$$

Considering the current density limitation of 3A/mm^2 and the coil filling factor between 0.6-0.8, the coil cross section size of 10 × 10 mm can meet all this conditions. The magnetic field is evaluated using TOSCA as shown in Fig. 3. When the number of ampere turns is set to 150, the variation of the magnetic field B_z in the azimuthal direction along the radius is shown in Fig. 4, and its radial coverage is about 2 cm. The 1-harmonic produced by one coil is 11.2 Gs in the peak.

Figure 3: 3D model of one pair of trim coil.

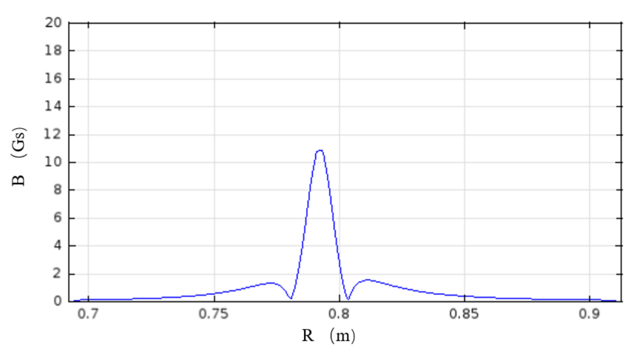

Figure 4: 1-harmonic magnetic field contributed by the trim coils.

After obtaining the ampere-turns of the coil, the power supply for the coil is calculated. For different wire diameters, the impedance parameters can be calculated and the supply current of the coil can be evaluated according to the ampere-turns. Finally, the diameter of 1 mm is selected to make the coil the total loss of a pair of trim coil is 8.076 W.

CONCLUSION

In this paper, processional extraction method driven by the imperfect magnetic field with the 1-harmonic during passing the ν_r=1 resonance is used to obtain a large turn separation before the beam extraction from the HUST

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250 MeV superconducting cyclotron. On the basis of the hard edge trim coil model, an optimized 1-harmonic with the phase of 20-45° is selected, which contributes a turn separation of 5 mm. Then, the structure of the trim coil is designed. The 1-harmonic is limited in a radial coverage of about 2 cm, and the total loss of a pair of trim coil is 8.076 W.

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