PHYSICAL DESIGN OF THE EXTRACTION TRIM-RODS IN A 230 MeV SUPERCONDUCTING CYCLOTRON*

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Abstract

In order to increase turn separation and accordingly extraction efficiency in a superconducting cyclotron CYCIAE-230, a first harmonic bump is required to introduce beam processional motion. Eight trim-rods of variable position are employed at the extraction region to generate the desirable field bump. The amplitude and phase of first harmonics can be adjusted by changing the position of trim-rods to meet the requirements of extraction beam dynamics. However, its side effect on the isochronous field in acceleration region is inevitable. Therefore, the rest positions of trim-rods need to be determined and the re-shimming procedure of main magnet model needs to be implemented interactively. The effects of trim-rods and its influence on the isochronous field in a new model will be presented.

INTRODUCTION

CYCIAE-230, a superconducting cyclotron aims for proton therapy, is under design and construction at China Institute of Atomic Energy [1,2]. Beam dynamics and processional extraction design of CYCIAE-230 are studied for years. First harmonic bump is the source of procession in the extraction region, it could be generated from trim-coils as our former machine [3], but trim-rod field is more predictable and stable in the saturated pole region, and trim-rod method is proved effective in field shimming [4] and field excitation [5]. Extraction efficiency is the key parameter of extraction system, which related to radial oscillation amplitude, turn separation of particle motion and septum width of deflector. Trim-rods which located at the central line of each pole introduce first harmonic bump to provide enough processional motion and turn separation with the help of $\nu_r = 1$ resonance. In former extraction design stage, we adopted ideal Gaussian first harmonic field bump with fixed phase [6]. But real trim-rod field distribution should be employed for a precise result. And real field has effect on main magnet isochronous field which can be analysing by same model.

In this paper, two main magnet models, a 90 degree folded and a 360 degree one, are introduced. Trim-rod field is studied in detail with the 90 degree model, and the procedure of eight trim-rod position design to provide first harmonic bump with certain amplitude and phase is accomplished. Trim-rod field of 90 degree and 360 degree model with the same trim-rod position are compared. And finally, real trim-rod field effect on the isochronous field and the re-shimming results are presented.

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MAIN MAGNET AND TRIM-ROD MODEL

As the spiral sector pole model of CYCIAE-230 is complicated in trim-rod design, a straight sector pole model is used instead for simplicity. A 90 degree sector model (Fig. 1) is used in preliminary design to analyse the physical properties of trim-rod field and a full 360 degree model is used to determinate final trim rods parameters. The pole angle width and spiral angle had been well designed to get isochronous field and working diagram.

The extraction trim-rods are rod shaped with diameter of 30 mm and length of about 80 cm, located at the central line of each pole with radius 79 cm. Trim-rods are driven by electric motors separately. When a trim-rod is elevated, an air-rod is generated inside the pole, leading to a field bump which decrease main magnet field locally. First harmonic field with amplitude less than 10 Gauss and arbitrary phase can be achieved by positioning eight trim-rods. For simplicity, the trim-rods are replaced by square rods with same cross section area in models.

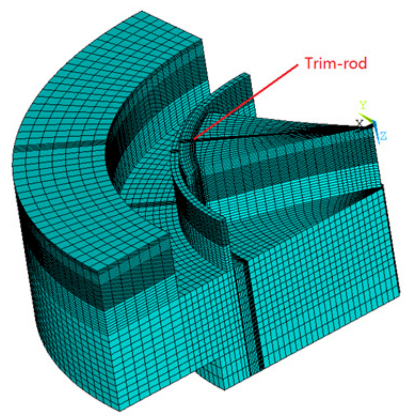

Figure 1: 90 degree straight sector model.

TRIM-ROD POSITION DESIGN

Main task of trim-rods physical design is to determine the height of each air-rod and the rest position of trim-rods. Design process is based on 90 degree sector model and the requirements of extraction beam dynamics. The oscillation amplitude at extraction point is mainly dependent on the amplitude and phase of the first harmonic bump, the FWHM of amplitude radial distribution $B_1(r)$ also has accumulative effect on oscillation amplitude, but the FWHM is hard to adjust.

It had been tested that first harmonic bump with following parameters reaches the highest extraction efficiency: 2.74 Gauss amplitude at 79 cm, 337 degree phase and the Gaussian fit of $B_1(r)$ has $\sigma = 6$ cm, and second harmonic amplitude should be less than 1 Gauss to minimize the effect of second order resonance. About 10% change of

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first harmonic amplitude or 30 degree of first harmonic phase shift would not change extraction efficiency clearly. In design stage, trim-rods are designed to provide 5 Gauss amplitude first harmonic bump with arbitrary phase, and second harmonics vanishes in theory.

The trim-rod position design started with trim-rod field analysis in 90 degree model with one trim-rod. The maximum first harmonic amplitude of different trim-rod position is shown below. The travel length of trim-rod is estimated to be 15 cm. In order to meet the requirements of amplitude and phase, the adjusting range of single trim-rod should cover 5 Gauss range, which means that the travel length of trim-rod could be strict to smaller length to reach better linearity of the curve.

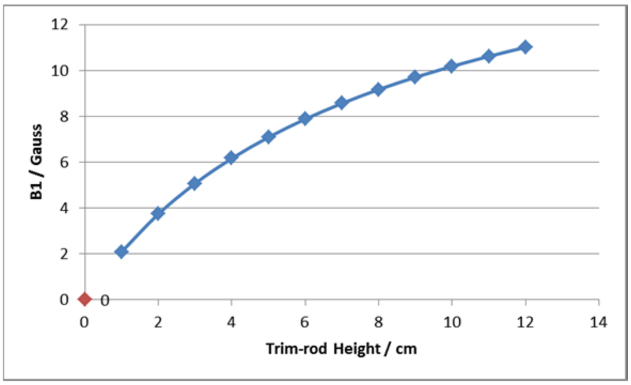

Figure 2: First harmonic amplitude vs trim-rod position.

Three groups of trim-rod travel length cover 5 Gauss range are designed, group 1: 1-5 cm height, group 2: 2-8 cm height, group 3: 3-11 cm height. Group 2 has proper range and margin and it is selected to present design procedure.

The travel length center with height 5cm is determined as the baseline of trim-rods and two steps are used for generate first harmonic bump. 1) Lift or drop eight trim-rod to the baseline, which induce isochronous field change but the first harmonic bump remains zero. 2) Lift or drop opposite four trim-rods to generate first harmonic bump with fixed phase, which would not change isochronous field because of good linearity of curve in Fig. 2.

In the range of 2-8 cm, we assumed that the radial distribution shape of amplitude is independent of trim-rod position, while first harmonic amplitude is linear with trim-rod height, also we supposed that the peak of amplitude distribution lies at 79 cm, and harmonic field phase around 79 cm does not change observably, which have been verified in later simulation result. Then harmonic field at 79 cm can be represented by the equation

$$B(z) = C(z)(0.4961 + 1.0000\cos\theta + 1.0198\cos 2\theta + ..)$$

While the constants are solved from baseline field and $C(z) = az + b$ is linear fitting of curve in Fig. 2 in range 2-8 cm.

In consideration of trim-rod location and first harmonic phase, the total first harmonic field can be written as:

$$\begin{aligned} B_1 =& C(z_1)\cos(\theta-45^\circ) + C(z_2)\cos(\theta-135^\circ) + \\ & C(z_3)\cos(\theta-225^\circ) + C(z_4)\cos(\theta-315^\circ) \\ =& \frac{\sqrt{2}}{2}a[(z_1-z_2-z_3+z_4)\cos\theta \\ & +(z_1+z_2-z_3-z_4)\sin\theta] \end{aligned}$$

and the total second harmonic field is

$$\begin{aligned} B_2 =& 1.0198[C(z_1)\cos(\theta-90^\circ) + C(z_2)\cos(\theta-270^\circ) + \\ & C(z_3)\cos(\theta-450^\circ) + C(z_4)\cos(\theta-630^\circ)] \\ =& 1.0198a(z_1-z_2+z_3-z_4)\sin 2\theta \end{aligned}$$

Synthesize all the constrictions: The phase of first harmonic field need to be $\theta_0 = 337°$, the second harmonic field vanishes in theory, the first harmonic amplitude should be as large as possible, and the position of four trim-rods lies in designed travel length, we get a linear programming dependent on the position of four trim-rod sets :

$$max \quad (z_1-z_2-z_3+z_4)/\cos\theta_0$$
$$\begin{cases} \dfrac{z_1+z_2-z_3-z_4}{z_1-z_2-z_3+z_4} = \tan\theta_0 \\ z_1-z_2+z_3-z_4 = 0 \\ z_1,z_2,z_3,z_4 \in [2cm, 8cm] \end{cases}$$

The result of problem is $z_1 = 3.788$ cm, $z_2 = 8.000$ cm, $z_3 = 6.212$ cm, $z_4 = 2.000$ cm, which could produce 5.78 Gauss first harmonic amplitude in theory. The first harmonic amplitude used in extraction is 2.74 Gauss, and trim-rod position should regression to the baseline according to the amplitude proportion. The theoretical values are $z_1 = 4.425$ cm, $z_2 = 6.422$ cm, $z_3 = 5.575$ cm, $z_4 = 3.578$ cm, respectively.

The solved trim-rod heights are examined by 90 degree model field with rotation and linear interpolation of the field data. The first harmonic has amplitude 2.66 Gauss, and phase 336.78 degree, which lies in the error bound, and the second harmonic amplitude is 0.25 Gauss, isochronous field at 79 cm is dropped by 13.9 Gauss. Error analysis shows that 0.1cm positioning precision would induce 0.24 Gauss first harmonic amplitude error and 4.9 degree first harmonic phase error at the worst case.

TRIM-ROD POSITION VARIFICATION IN 360 DEGREE MODEL

A new 360 degree model is designed to verify trim-rod position, this model contains upper half of the cyclotron, including 4 air-rods of different height. The result in 360 degree model is beyond expectation, while first harmonic amplitude is 2.98 Gauss, first harmonic phase is 339.91 degree. First harmonic amplitude is larger than 90 degree model result, and exceeds 10% limit on error, but the first harmonic phase and second harmonic amplitude is in the bound. The increase of first harmonic amplitude is intelligible, in 360 degree model, trim-rod at quad-

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rant 1 induce minus field in other quads, but in 90 degree model, all the minus field are superposed in quadrant 1, which can reduce the first harmonic amplitude.

The proportional regression method is used again, the positions of four trim-rod sets in 360 degree model are: $z_1 = 4.465$ cm, $z_2 = 6.347$ cm, $z_3 = 5.544$ cm, $z_4 = 3.653$ cm. Calculation executed with new position gives anticipated result, the first harmonic amplitude is 2.74 Gauss, first harmonic phase is 339.94 degree, and the Gaussian fit of first harmonic amplitude radial distribution has $\sigma = 7.40$ cm, the isochronous field drop at 79 cm is 14.02 Gauss, and second harmonic amplitude is 0.21 Gauss. Harmonic amplitude and phase are shown in Fig. 4 and Fig. 5. The results show that after one iteration of trim-rod position, ideal first harmonic amplitude and phase is obtained, the linear assumption and linear programming method is robust.

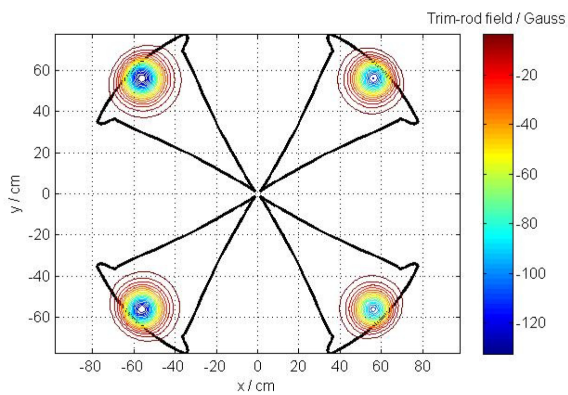

Figure 3: Trim-rod field in straight sector model.

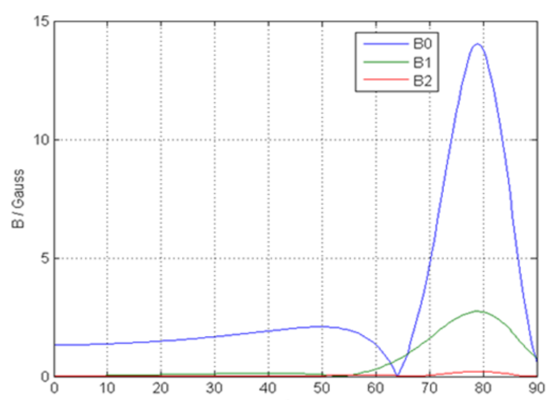

Figure 4: Harmonic amplitude radial distribution.

ISOCHRONOUS FIELD RE-SHIMMING

As shown in Fig. 4, four sets of trim-rod will generate 14 Gauss isochronous field drop at 79 cm, and about 2 Gauss field elevation in whole acceleration region. The frequency error due to trim-rod field is small but keeps negative in acceleration region and positive in extraction region, which can reduce accumulative effect to shift the phase slip curve. The phase slip is shown in Fig. 5. Although the maximal phase slip in acceleration region is about 15 degree, which is in the bound of error limit from acceleration beam dynamics, applying re-shimming process would lead to a smaller phase slip and accordingly a quicker acceleration process.

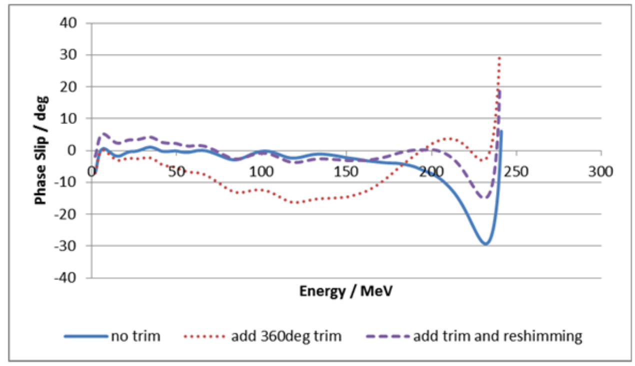

Figure 5: Phase slip and re-shimming effect.

Re-shimming is a negative feedback process of magnet pole angle width to minimize frequency error, and after two times of iteration the re-shimmed phase slip is shown in Fig. 5. And the variation of angle width is less than 0.1 degree.

In view of the trim-rod field effect on isochronous field, we recommend that in preliminary shimming process, the trim-rod effect on the isochronous field could be ignored, and in last time of shimming iteration, trim-rod sets should be placed at baseline.

CONCLUSION

Physical design of trim-rod position aims for providing first harmonic bump with fixed amplitude and phase is introduced in this paper. Linear programming method with linear assumption is used to reach the solution and present high robustness and accuracy. The trim-rod field has a small effect on isochronous field but can not to be reckoned with. And a re-shimming process is adopted to rectify frequency error and phase slip.

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