

# RESEARCH ON THE EFFECT OF MAGNET PARAMETERS ON THE ISOCHRONOUS FIELD OF A SUPERCONDUCTING CYCLOTRON

by

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It is a complicated task to obtain an isochronous field of a cyclotron magnet. Due to non-linear property of iron, iterated simulation of magnet design takes a long time to get an isochronous field. As an example, for a magnet design of a 240 MeV (SC240) superconducting cyclotron, the effect of main parameters of a magnet system on the magnetic field was studied, among them the azimuthal sector width, the spiral sector angle, the gap between sectors, the depth of valley region, the position of the coil, the shape of the coil and the excited current of the superconducting coil. It was found that the azimuthal average magnetic field can be increased by any of the following methods, including enlarging azimuthal width, increasing excited current of the superconducting coil, narrowing of the gap between sectors, reducing the depth of the valley region or decreasing the distance between the coil and the mid-plane. In addition, axial oscillation frequency can be improved by increasing the spiral angle, the depth of the valley region, or decreasing the gap between sectors.

*Key words:* isochronous field, superconducting cyclotron, spiral sector angle, azimuthal sector width

## INTRODUCTION

The strategic emerging and healthy industries in China, as well as the first grounding project among seven platforms of Hefei Comprehensive National Science Center, Hefei CAS Ion Medical and Technical Devices Co., Ltd. are devoted to research, development and manufacturing of the Superconducting Isochronous Proton Cyclotron with extraction energy of 200 MeV (SC200) [1], which promotes the localization and industrialization process of proton therapy in Anhui, China.

In the period of manufacturing SC200, the requirement of a cyclotron with higher extraction energy has become extremely urgent. Internationally, VARIAN/ACCEL in America has installed a cyclotron of 250 MeV [2, 3] and applied it successfully in medical treatment. Sumitomo Heavy Industries, Ltd. in Japan also proposed the conceptual design of a 230 MeV cyclotron [4]. For improving industrialization development of proton medical equipment in China, during the construction of SC200 physical design of our second superconducting isochronous cyclotron of 240 MeV (SC240) had already begun.

A magnet system which mainly consists of sectors, yokes and superconducting coils is a significant part of primary cyclotron design. The basic parameters of these components determine not only the distribution of a magnetic field but also the quality of the beam inside the cyclotron. Due to the fact that the beam moves in the proximity of the median plane of a cyclotron, the axial magnetic field in the median plane is particularly vital, which affects the phase slip and work diagram (namely the transverse betatron oscillation frequencies  $Q_r$ ,  $Q_z$ ) [5-11]. Furthermore, it has been established that the azimuthal width and spiral angle of sectors, the gap distance between the upper and the lower sectors, the depth of the valley region, the axial position and shape of superconducting coils and the coil current can affect the distribution of axial magnetic field on median plane. As a result, it becomes important to research and eventually verify the effects of changing these parameters on the magnetic field.

For this paper, the effects of sector azimuthal width and its spiral angle, the gap between magnet poles, the depth of the valley region, the position of the coil, the shape of the coil and the excited current on the isochronous field were studied and calculated based

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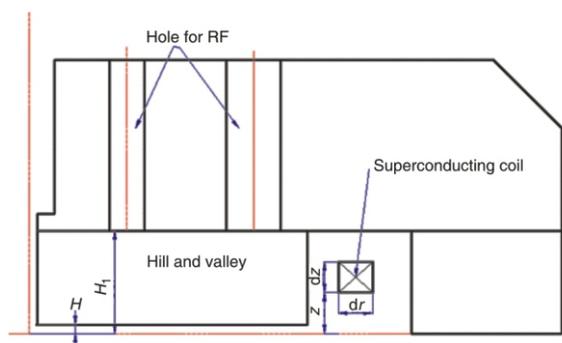


Figure 1. Schematic presentation of a quarter cross-section of the superconducting cyclotron magnet

Table 1. Parameters of Cyclotron SC240

Parameters	Value
Extraction energy	240 MeV
Injection/extraction field	2.4/3T
Pole gap at hill	50 mm
Pole gap at valley	600 mm
Pole diameter	1.68 m
Dimension (diameter/height)	3.3/1.68 m
Excited current	560000 A
Coil size	11.5 8.2 mm <sup>2</sup>

on the SC240 magnet model. The geometry of the magnet is shown in fig. 1. The main parameters of the magnet are shown in tab. 1.

### THE EFFECT OF SECTOR WIDTH ON MAGNETIC FIELD

Sector width controls the adjustment of the magnetic field along the azimuthal direction. It also determines the installed space of radiofrequency (RF) cavity, ion source and other components in the valley [5]. Once the dimensions of the magnet structure are fixed, the sector width,  $\phi$  (see fig. 2), is the main parameter for optimizing magnetic field design.

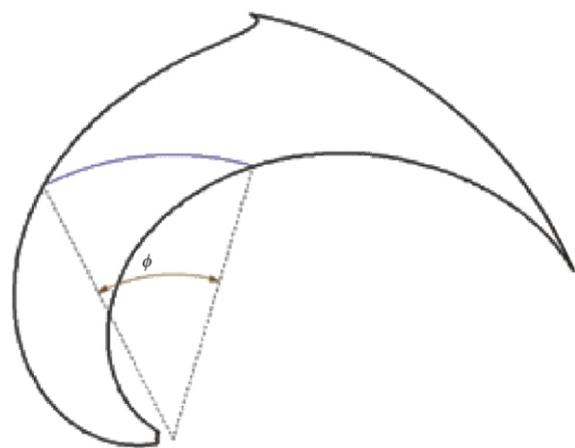


Figure 2. The azimuthal width of the sector

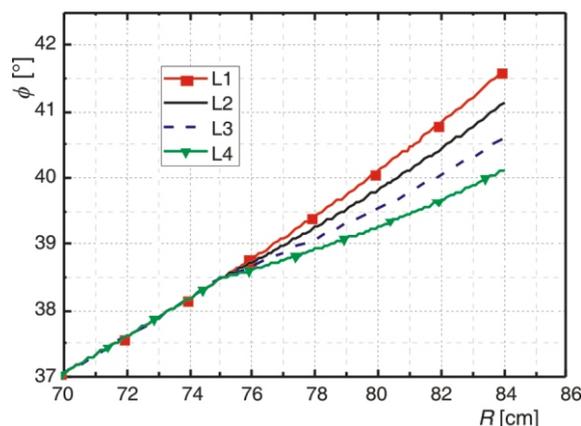


Figure 3. The values of sector azimuthal width

Four models, L1, L2, L3, L4, with different azimuthal width of sectors were simulated, see fig. 3. The averaged magnetic fields in the middle plane for four different models are obtained by MAXWELL [12] using the same meshing size. Symbols L2-L1, L3-L1, L4-L1 are used to mark magnetic changes of L2, L3, L4 based on L1. The effect of sector azimuthal width on the averaged field is shown in fig. 4. The averaged field lowers when azimuthal width of the sector decreases. With a large radius of the sector, the increment of the magnetic field caused by the increment of azimuthal width of the sector is relatively small. As shown in tab. 2, with the radius of 82 cm, the azimuthal width of the sector widens by 1.2° and the magnetic field increases by 147 Gs (1 Gs = 10<sup>-4</sup> T), when the ra-

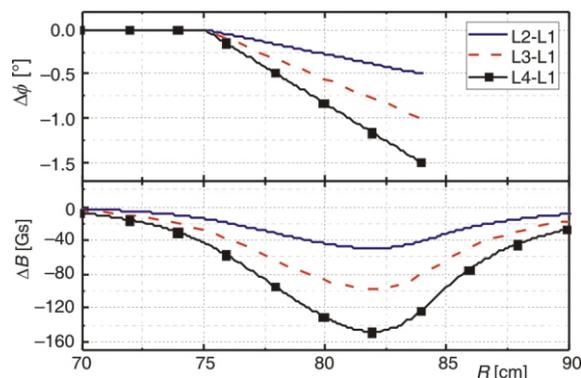


Figure 4. Variation of sector azimuthal width and average magnetic field

Table 2. The variation of sector azimuthal width and the corresponding magnetic field at R 82 cm/84 cm

Variation of sector azimuthal width		Variation of average magnetic field [Gs]
R = 82 cm	0.38°	49
R = 82 cm	0.78°	98
R = 82 cm	1.2°	147
R = 84 cm	0.5°	40.4
R = 84 cm	1°	80
R = 84 cm	1.5°	121

dus is 84 cm, the azimuthal width of the sector widens by  $1.5^\circ$  and the magnetic field increases by 121 Gs. Therefore, the method of enlarging the azimuthal width of a sector to strengthen the magnetic field is not effective in the extraction area.

However, as the result of an extremely small azimuthal width of the sector, the deformation of sectors due to the action of the magnetic force would be greater and this would affect the distribution of the magnetic field and make magnetic field shimming more difficult in the future. Generally, in order to improve the efficiency of accelerating particles, the azimuthal width of the sector should be below  $45^\circ$ .

### THE EFFECT OF THE SPIRAL ANGLE ON MAGNETIC FIELD

In addition to an adequate azimuthal average field, a reasonable working diagram composed of transverse betatron oscillation frequencies  $Q_r$ ,  $Q_z$  is also indispensable for cyclotrons. Brief expressions of  $Q_r$ ,  $Q_z$  are as follows [13]

$$Q_r^2 = 1 - n \frac{3N^2}{(N^2 - 1)(N^2 - 4)} F(1 - \tan^2 \xi) \quad (1)$$

$$Q_z^2 = n \frac{N^2}{N^2 - 1} F(1 + 2 \tan^2 \xi) \quad (2)$$

where  $n = (r/B)(dB/dr)$  is the field index and  $B(r)$  – the azimuthal average field in respect to radius  $r$ ,  $\xi$  – the spiral angle,  $F$  – the field flutter which represents the azimuthal variation of the magnetic field. In these two equations, field flutter  $F$  of the superconducting cyclotron is very small with the value below 0.1 due to the highly saturated iron pole [14]. Therefore, it is obvious that the changes of spiral angle,  $\xi$ , and field index,  $n$ , play a dominant role in the adjustment of work diagram.

The spiral angle can be defined by the following formula

$$\xi = \arctan r \frac{d\theta}{dr} \quad (3)$$

where  $\theta$  is the azimuth of sector central line and  $r$  – the polar radius of the corresponding position. Due to another calculation of  $\theta$  by the phase of  $B_z$  4<sup>th</sup> harmonic field, the spiral angle can be divided into the spiral angle of geometry model  $\xi_{GM}$  and the spiral angle of magnetic field  $\xi_{MF}$  (calculated by the phase of  $B_z$  4<sup>th</sup> harmonic field), which is presented in fig. 5. In the acceleration region ( $R < 70$  cm),  $\xi_{MF}$  rises almost equally as  $\xi_{GM}$ , but declines drastically after the radius of 70 cm. This indicates that the effect of the geometrical spiral angle on the magnetic field is limited in the extraction region.

Models S1, S2, S3, S4 with digressive sector spiral angles were simulated to analyze their effect on axial oscillation frequency  $Q_z$ . Combined with the

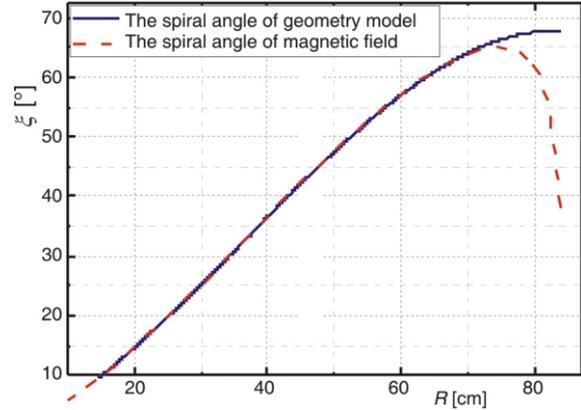


Figure 5. Comparison between magnetic and geometrical spiral angle

change of field flutter,  $F$ , the results are shown in fig. 6. One can see from fig. 6 that the incremental spiral angle at each radius can slightly weaken the field flutter and strengthen the  $Q_z$  along the radius.

It is determined that the larger spiral angle is beneficial for the provision of a stronger axial focusing force, but makes designing of RF cavity and beam diagnostic system difficult. In the commissioning period, the beam probe needs to be inserted into the central region from outside. Considering that the movement trajectory of beam probe is usually a straight line, and the large spiral angle can make the beam probe move along a curved line, the maximum spiral angle is always limited to less than  $70^\circ$ .

### THE EFFECT OF GAP ON THE MAGNETIC FIELD

#### The effect of sector gap on the magnetic field

The half gap between the sectors is represented by symbol  $H$  as shown in fig. 1. In order to study the influence of sector gaps on the magnetic field, the magnetic fields of four models with different sector gaps were calculated.

Figure 7 shows the distribution of the magnetic field in azimuthal direction at radius of 0.4 m. When sector gap is narrowed, the peak value of the magnetic field increases and the valley value of the magnetic field decreases. When  $H$  is reduced from 25 mm to 18 mm, the peak value of the magnetic field is enhanced by 1266 Gs, and the valley of the magnetic field declines by 300 Gs. This shows that the peak value of the magnetic field is more sensitive to sector gap than the valley value. Figure 8 shows the average field, the flutter, and the field index for different sector gaps. Reducing the sector gap enlarges the average magnetic field. The increment of the magnetic field in the extraction region is larger than that in the acceleration area, so that the field index in the extraction region is significantly increased. At the same time, the reduction of sector gap can also increase field flutter.

Figure 6. The spiral angle,  $\xi_{GM}$ , the flutter,  $F$ , and the axial oscillation frequency,  $Q_z$ , for different models

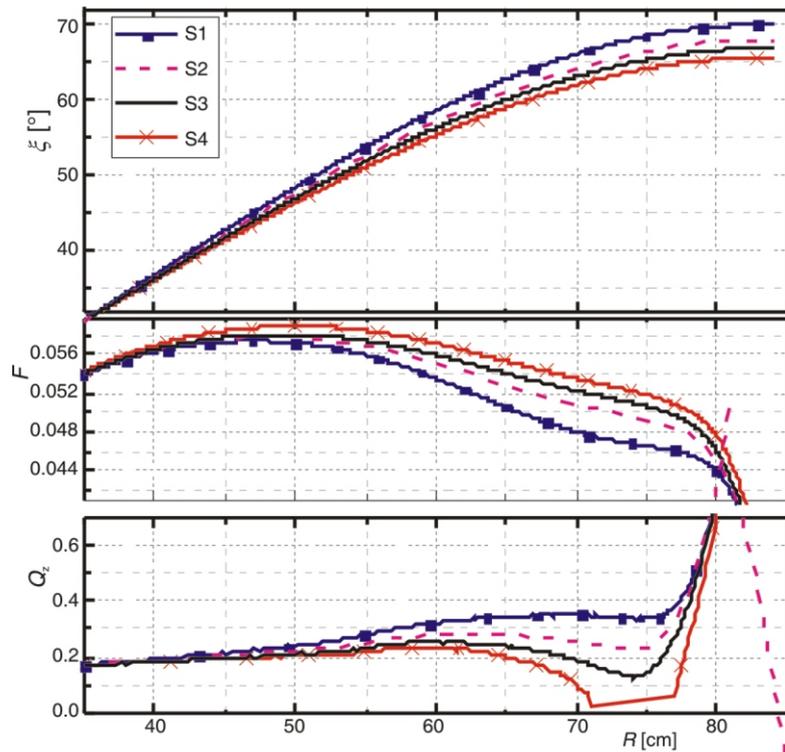


Figure 7. Magnetic field in azimuthal direction for different sector gaps  $H$ , with a radius of 0.4 m

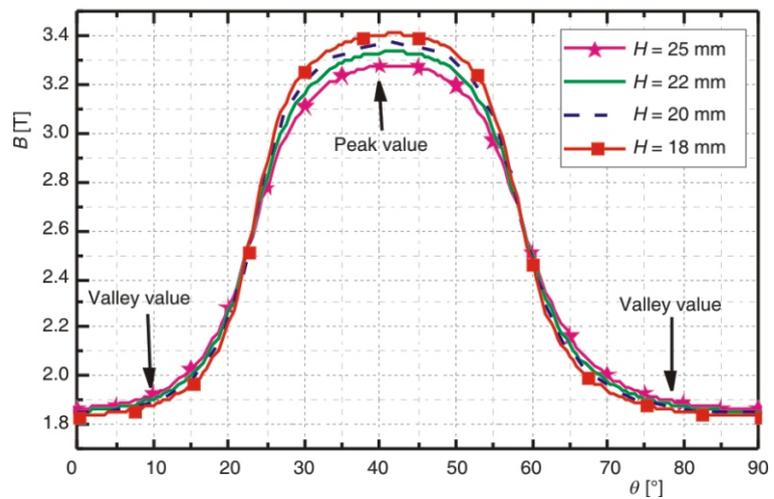
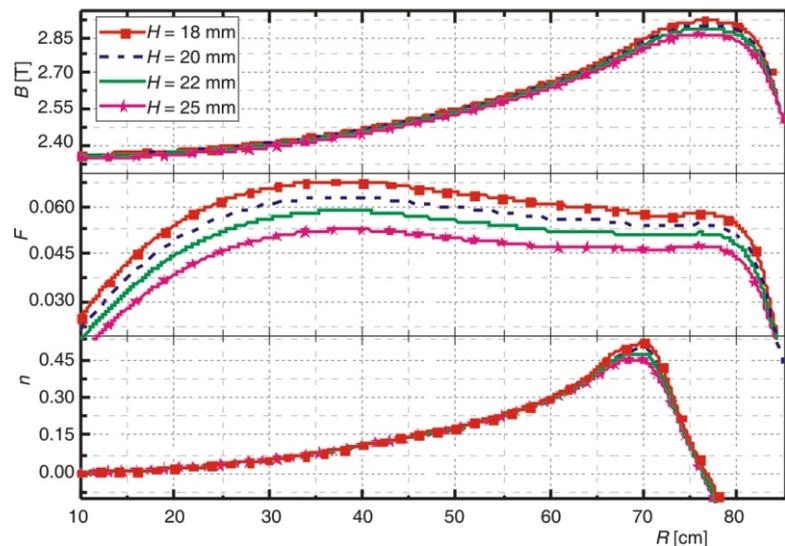


Figure 8. Variation of average field, field flutter and field index for different sector gaps  $H$



Due to the requirements of high magnetic field gradients and beam focusing in the extraction region, a small gap is beneficial for the design of the isochronous field of a cyclotron.

However, a small gap decreases the available space for beam oscillation in the axial plane, and makes the design of the magnetic field measuring device more challenging. Therefore, it is necessary to balance the difficulties caused by the design of a magnetic field measuring device.

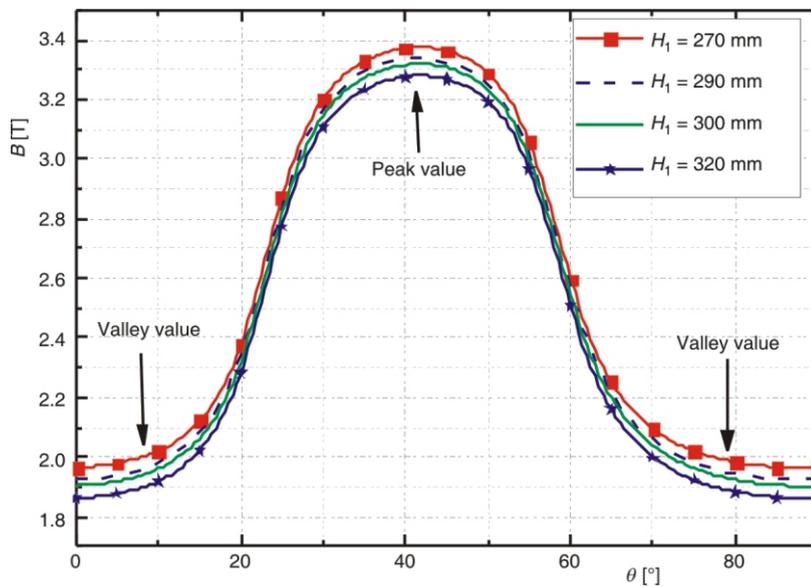
**The effect of valley depth on the magnetic field**

The valley depth refers to the distance from yoke to mid-plane in fig. 1, which is represented by the symbol  $H_1$ . In order to study the influence of valley depth

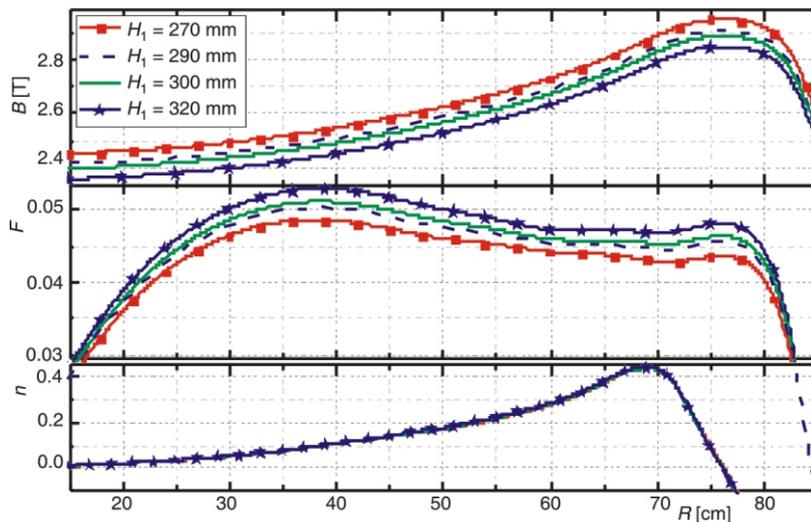
on the magnetic field, four models with different depths of 270 mm, 290 mm, 300 mm, and 320 mm, respectively, were simulated.

Figure 9 shows the magnetic fields along the azimuthal direction for different valley depths with a radius of 0.4 m. With the digressive valley depth, the hill and the valley values of the magnetic field both drop. Figure 10 shows the variation of the average field, the flutter and the field index for different valley depths. Although increasing of valley depth reduces the average field, it increases the flutter. The field index is hardly affected by valley depth, which indicates that valley depth affects the average magnetic field in mid-plane with a full radius.

For a superconducting compact cyclotron with requirements concerning its weight, it is suitable to select a magnet system with a shallow valley, which can reduce the requirement for coil excitation. For some

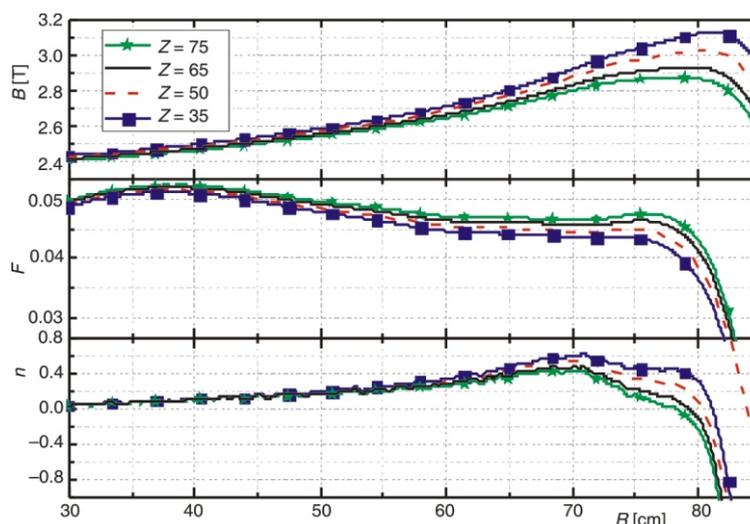


**Figure 9. Distribution of magnetic field in azimuthal direction for different  $H_1$  with a radius of 0.4 m**



**Figure 10. Variation of average field, field flutter and field index for different  $H_1$**

**Figure 11. Comparison of average field, field flutter and field index at different parameter  $z$**



accelerators that require a large field flutter of the magnet and a low hill magnetic field, it is advantageous to use a magnet system with a deep valley.

According to the research on the influence of sector gap and valley depth on the magnetic field, the average magnetic field can be increased by reducing sector gap or reducing valley depth. However, the decrease of the sector gap increases the radial magnetic field index of the extraction region, while the radial magnetic field index is basically unchanged after valley depth is changed. It is evident that sector gap has a great influence on the magnetic field with a large radius, while the change of valley depth affects the average magnetic field as a whole from the central region to the extraction region. So, it is more effective to adjust valley depth when the magnetic field needs changing with full radius. The variation of sector gap is more effective than the adjustment of the magnetic field at the extraction area.

### THE EFFECT OF SUPERCONDUCTING COIL ON THE MAGNETIC FIELD

The main coil of the cyclotron is located between the magnet pole and the yoke, mainly providing the magnetic fields for the cyclotron. To obtain the required magnetic field, it is important to determine the position and the size of the coil, and the excited current of the coil. How to select these parameters is analyzed in the following paragraphs.

#### The effect of axial position of the coil

The axial position of the coil is the distance from the bottom of the upper coil (or the top of the lower coil) to mid-plane, which is marked by symbol  $z$  in fig. 1. The magnetic fields are calculated at different axial positions of the coil including 35 mm, 50 mm, 65 mm,

75 mm. Figure 11 shows the effect of coil position on the magnetic field. When the coil is close to mid-plane, the average magnetic field is increased especially in the extraction region. The position of the maximum magnetic field when the radial magnetic field index is zero is closer to the edge of the pole. The flutter is weakened by reducing the distance of the coil to mid-plane.

In order to obtain a larger magnetic field gradient at the end of the pole, reducing the axial position of the coil is an effective method for increasing the magnetic field of the extraction region. However, the axial position of the coil is also determined by the required space of the beam diagnostic device, the cooling channel and the magnetic channel and so on. Hence, the coil axial position is usually confined to more than 65 mm.

#### The effect of coil shape

The effect of coil shape on the magnetic field is studied by changing  $d$  which is the ratio of  $dz$  and  $dr$ . The parameters  $dz$  and  $dr$  are shown in fig. 1. The parameters of coil cross-section are shown in tab. 3.

Figure 12 shows the variations of the average field and the field flutter with different parameter,  $d$ . Coil shape also mainly affects the magnetic field in the extraction region. Reducing  $d$  is beneficial to the rise of the magnetic field but decreases magnetic field flutter. In order to provide high flutter and facilitate the winding of the coil, a large  $d$  is usually chosen.

**Table 3. Parameters of section size superconductor coil**

$dr$ [mm]	$dz$ [mm]	$d = dz/dr$	$z$ [mm]	Excited current of one coil [A]
77	122.5	1.6	70	560000
82	115	1.4	70	560000
88	107.2	1.2	70	560000
97	97.2	1	70	560000
108.4	87	0.8	70	560000

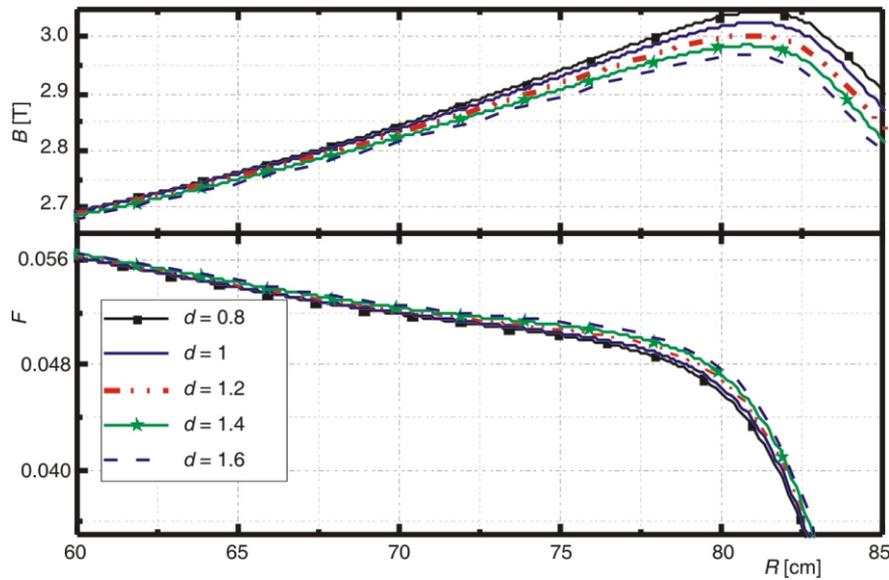


Figure 12. Variations of average field and field flutter for different parameter  $d$

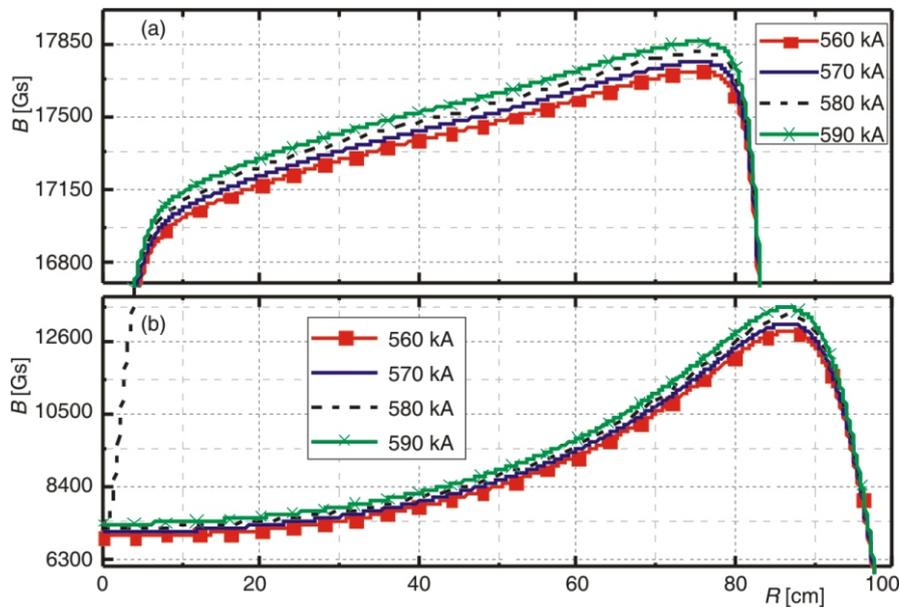


Figure 13. Field components produced by superconducting coils and iron

### The effect of the excited current on the magnetic field

The coil current mainly depends on the required magnetic field for a cyclotron. In addition, it is known that the higher the proportion of iron in the cyclotron, the larger the magnetic field in median plane. Hence, two methods are available to strengthen the magnetic field: increasing the coil current and the iron. However, the extent to which these two methods increase the magnetic field need further discussing.

The total magnetic field in a cyclotron is provided by a superconducting coil and iron. Setting different coil currents at 560 kA, 570 kA, 580 kA, 590 kA, the magnetic field component produced solely by the superconducting coil (namely coil field) is shown in fig. 13(b). On the other hand, the magnetic

field component produced by the iron pole (namely iron field) is shown in fig. 13(a), which is calculated by subtracting the magnetic field in fig. 13(b) from the total magnetic field in median plane. It is clear that the gradient of azimuthal average magnetic field in fig. 13(b) is higher than that in fig. 13(a), which is largely reflected in the radial region between 20 cm and 80 cm. Therefore, the required gradient of a magnetic field is mainly provided by coil field.

Figure 14 illustrates the increment of the iron field and the coil field with the increase of coil current by 30 kA. It is obvious that the increment of the coil field is larger than that of the iron field along the radius and more remarkable in the extraction region (around 80 cm). Therefore, increasing the current after a saturated iron pole is more effective to enhance the magnetic field in extraction.

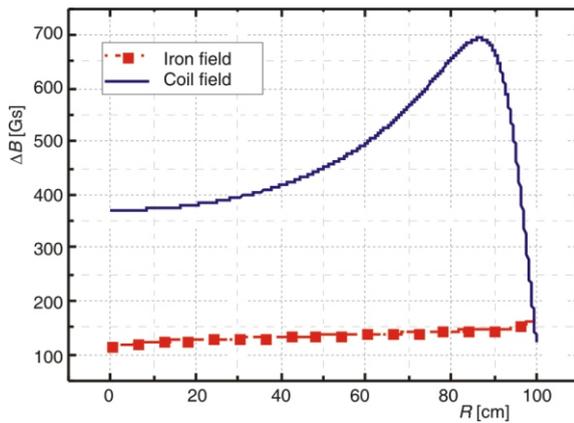


Figure 14. The increment of iron field and coil field with the increase of coil current by 30 kA

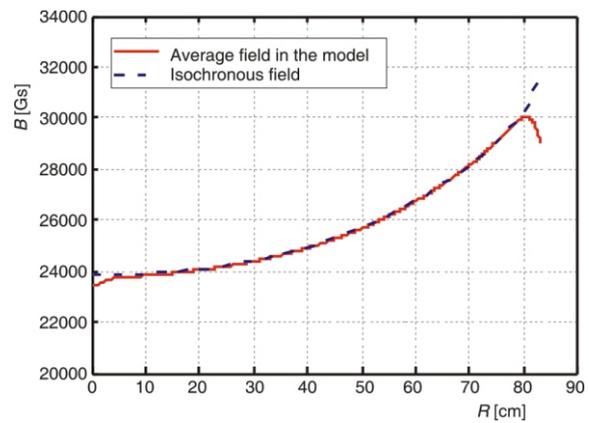


Figure 15. Average field with initial isochronous shaping

## CONCLUSION

In the process of magnet design, a number of important factors of the magnet were adjusted to obtain an isochronous field, among which are the azimuthal width of sectors, the spiral angle of the pole, valley depth, sector gap, coil shape and coil current. Taking the magnet system of SC240 cyclotron as an example, the aforementioned factors were analyzed and their effects on the magnetic field were summarized with the help of a large number of calculations. First, field index,  $n$ , was pre-determined to maintain isochronism. Then, flutter was optimized by choosing a suitable ratio between sector gap to valley depth and a suitable coil shape. Coil position is reasonably selected according to the requirements of the magnetic field in the extraction area. Moreover, the excited current needs to be adjusted to provide the required magnetic field gradient. Finally, the spiral angle and the azimuthal width of the sector along the radius need to be adjusted to obtain the isochronous field. In the end, the difference between the achieved magnetic field of SC240 cyclotron by appropriate magnet parameters and isochronous field for protons is shown in fig. 15. The total phase slip of  $20^\circ$  in the main acceleration region was achieved as shown in fig. 16, which meets beam dynamics requirements of particle acceleration.

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## AUTHORS' CONTRIBUTIONS

The theoretical work was done by P. Zhou, J. Li, and S. Xu, and all the authors took part in planning the work and in discussions during all phases of its elaboration. The manuscript was written by J. Li, P. Zhou and S. Xu.

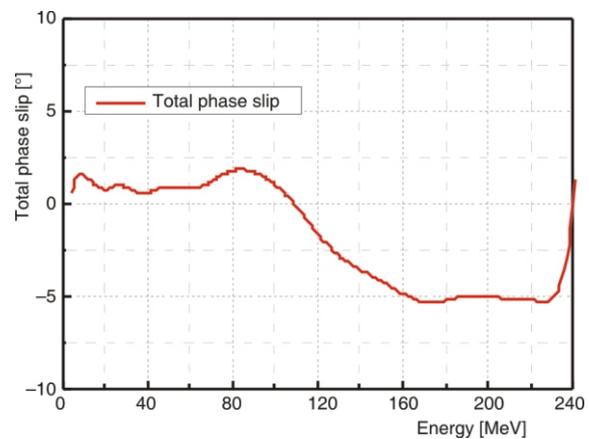


Figure 16. The total phase slip with the change of energy

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#### ИСТРАЖИВАЊЕ УТИЦАЈА МАГНЕТНИХ ПАРАМЕТАРА НА ИЗОХРОНО ПОЉЕ СУПЕРПРОВОДНОГ ЦИКЛОТРОНА

Успостављање изохроног поља магнета циклотрона представља компликован задатак. Због нелинераних својстава гвожђа, итеративна симулација дизајна магнета захтева дуго време за постизање изохроног поља. На примеру дизајна магнета за суперпроводни циклотрон од 240 MeV (SC240), испитани су утицаји главних параметара магнетног система на магнетно поље, међу којима су: ширина азимутног сектора, угао спиралног сектора, размак између сектора, дубина области долине, позиција и облик завојнице и побуђена струја суперпроводне завојнице. Уочено је да се азимутно средње магнетно поље може повећати било којом од следећих метода: повећањем азимутне ширине, појачавањем побуђене струје суперпроводне завојнице, смањењем размака између сектора, смањењем дубине области долине, или смањењем растојања између завојнице и средње равни. Додатно, учестаност аксијалних осцилација може се побољшати повећањем спиралног угла, дубине области долине, или смањењем растојања између сектора.

*Кључне речи:* изохроно поље, суперпроводни циклотрон, спирални угао сектора, ширина азимутног сектора