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Magnetic Field Design of a KIRAMS-K120 Superconducting Cyclotron

Joonsun Kang*, **Yu-Seok Kim**

Laboratory of Accelerator Development, Korea Institute of Radiological & Medical Sciences, Seoul 139-706, Korea

***Abstract*--** **Korea Institute of Radiological & Medical Sciences (KIRAMS) has been developing a K120 superconducting cyclotron. We have designed the magnetic field of a K120 superconducting cyclotron. Two pairs of superconducting NbTi coils have been introduced to accelerate variable ions ($0.125 \leq Z/A \leq 0.5$). The spiral sector has been designed for stable beam acceleration. The basic design parameters of the magnet geometries are calculated by analytic equations. The magnetic fields and the geometries are simulated by TOSCA and are verified by GENSPEO. We use Carbon ions during the design process as the criteria. The main parameters and properties of the K120 superconducting magnet are presented.**

1. INTRODUCTION

In recent years, a superconducting cyclotron has been focused as a heavy-ion accelerator. A superconducting cyclotron is widely used to produce various heavy ion beams for use in medical, biological, and physical researches [1]-[8]. KIRAMS has started development of a superconducting cyclotron since 2007. The first goal of this project is to accomplish superconducting cyclotron development technology. The remarkable difference between a superconducting cyclotron and conventional one is a magnet system. Employing the superconducting magnet, we can achieve the strong magnetic field and reduce the size and weight of the magnet by a factor of about 15 [9]. The proposed KIRAMS-K120 superconducting cyclotron is composed of a 14.5 GHz electron cyclotron resonance (ECR) ion source, a vertical beam injection system, a 24 – 48 MHz high-frequency accelerating system, a low temperature superconducting (LTS) magnet system, a high voltage beam deflection system and a beam transport system.

This paper presents the magnet field design of the K120 superconducting cyclotron. The magnetic fields are excited by the LTS coils and the field distributions in the median plane of the magnet are mainly shaped by the sector geometries of a yoke.

We have decided the magnetic bending limit, K to 120 MeV for the first superconducting cyclotron in Korea. The charge to mass ratio, Z/A of the accelerable ions is 0.125 – 0.5. The range of the energy per nucleon is from 1.84 MeV/amu to 29 MeV/amu. The extraction radius has been set to 0.5 m considering the acceptable size and weight of the magnet. Two pairs of superconducting NbTi coils are used to regulate the magnetic field distribution according to the species and energies of the ions. The magnet pole is four sectored structure to make an azimuthally varying field (AVF).

We use analytic equations to design the basic parameters of the magnet like as the overall magnet size, the requiring Ampere-turns and the spiral angles [10]. The accurate magnetic fields are calculated by the 3-D magnetic field simulation program, Opera-3d TOSCA solver. The isochronous magnetic fields of the Carbon ions are used as the criteria of the magnet design. The Z/A of $^{12}C^{2+}$, $^{12}C^{4+}$ and $^{12}C^{6+}$ is 0.17, 0.33 and 0.5, respectively. The isochronous field of $^{12}C^{4+}$ is used to design of the sector geometry due to the fixed sector structure. The other two isochronous fields are used to design the operating range of the superconducting coils.

2. MAGNET STRUCTURE & PARAMETERS

2.1. The Superconducting Magnet Structure

The magnet of the KIRAMS-K120 superconducting cyclotron is pillbox type and consists of the iron yoke, the superconducting system and the trim coil system (Fig. 1). The magnet pole consists of four spiral sectors. The sectors are fourfold axisymmetric. The sectors shape the magnetic field distributions and determine the beam focusing properties. In the case of a superconducting cyclotron, generally the average magnetic field is higher than that of a conventional one. However, the standard deviation of the azimuthal magnetic field is little changed because of the magnetic saturation of an iron. As the average magnetic field increases, the beam stability of an AVF magnet decreases. The spiraled sector has been introduced to compensate the beam stability.

The superconducting system has four NbTi coil windings and cryo-cooling system. The inner two coils (α-coil) and the outer two coils (β-coil) are connected serial and have independent power supplies.

The trim coils are wound on the hill with a constant distance. The conductor of the trim coils is made of copper and is hollowed for water cooling. The trim coils are used

* Corresponding author: genuinei@kirams.re.kr

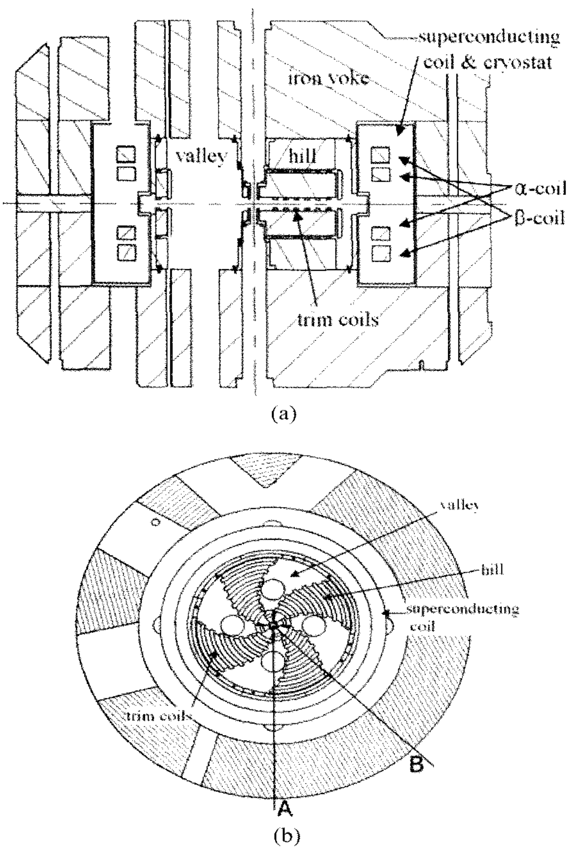

Fig. 1. KIRAMS-K120 superconducting magnet structure: (a) Horizontal cross-section view and (b) vertical cross-section view. The left half side (cut A) is valley section and the right half side (cut B) is hill section.

for fine tuning of the magnetic field by the superconducting coils.

2.2. The Operating range of the KIRAMS-K120

The operating range of the KIRAMS-K120 cyclotron is determined by the magnetic bending limit, extraction radius and RF frequency (Fig. 2). The magnetic bending limit is 120 MeV and the extraction radius is 0.5 m. The range of the RF frequency is from 24 MHz to 48 MHz with 2nd and 4th harmonic modes. The *T/A* is 1.84 MeV/amu – 29 MeV/amu at the extraction radius. The left and right oblique boundary in Fig. 2 is the magnetic bending limits of 115 MeV – 120 MeV. The *Z/A* of the lower-bound markers is 0.125 and that of the upper-bound markers is 0.5. The magnetic field at the center and extraction radius is 3.02T – 3.15 T and 3.09 T – 3.17 T, respectively (Fig. 3). The main parameters of the KIRAMS-K120 superconducting cyclotron are listed in Table I.

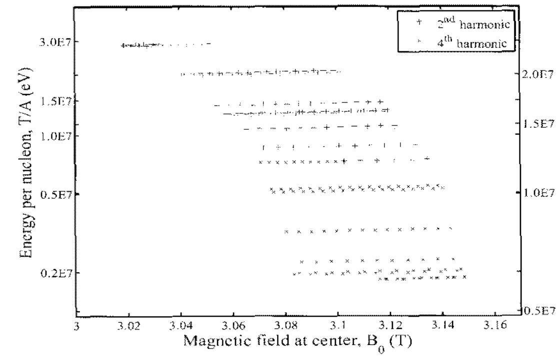

Fig. 2. Operating diagram of the KIRAMS-K120 cyclotron.

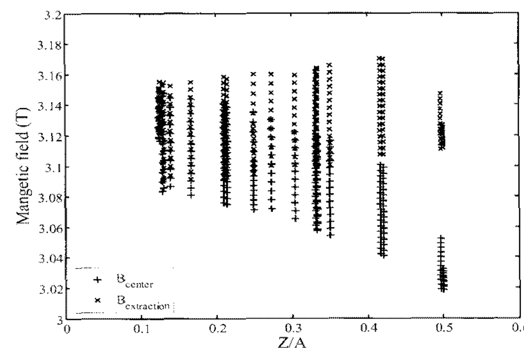

Fig. 3. Magnetic field range of the KIRAMS-K120 cyclotron.

TABLE I
SPECIFICATIONS OF KIRAMS-K120 SUPERCONDUCTING CYCLOTRON.

Parameters	Values
Bending limit (MeV)	120
Particle accelerated	$0.125 \leq Z/A \leq 0.5$
Extraction energy (MeV/amu)	1.84 – 29
Extraction radius (m)	0.5
Hill gap (m)	0.08
Harmonic mode	2, 4
RF frequency (MHz)	24 – 48
Magnetic field at center (T)	3.02 – 3.15
Magnetic field at extraction (T)	3.09 – 3.17

3. MAGNET FIELD DESIGN

3.1. Initial Design Parameters

A fourfold symmetric sector has been chosen to produce the azimuthally varying field. It is necessary to simplify the design criteria because of the wide operating range. We have chosen the Carbon ions the design objectives (Fig. 4).

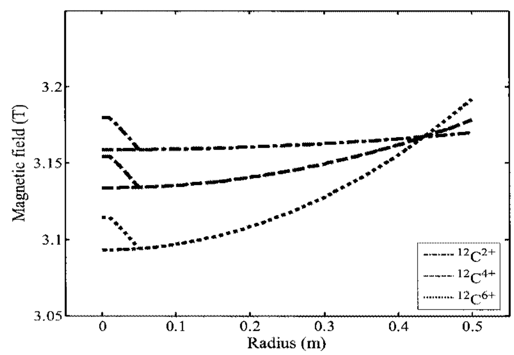

Fig. 4. The isochronous magnetic field of the Carbon 2^+, 4^+ and 6^+ ions.

Because there is no sector structure in the central region of the magnet, the decreasing field with the radius is required. The central magnetic field in Fig. 4 is calculated by Eq. (1).

$$B(r) = B_1\left(\frac{r_1}{r}\right)^n \quad (1)$$

$$n \equiv -\frac{dB/B}{dr/r} \quad (2)$$

where, the n is a field index. The field index has been approximated linearly by: $n = 0 - 0.01$ at $r = 0 - 0.05$ m. r_1 is 0.05 m and the B_1 is the magnetic field at r_1.

The initial magnet geometry is calculated by analytic equations. The magnetic field, B in the median plain can be expressed by Eq. (5) in cylindrical coordinate.

$$B(r,\theta) = B_{iso}(r)(1 + f(r)\sin N\theta) \quad (3)$$

where, B_{iso} is the isochronous magnetic field, f is the flutter amplitude by hill-valley structure, and N is the number of sectors. The $B_h(r)$ at hill center and $B_v(r)$ at valley center are approximated as Eq. (4) to calculate the hill width and spiral angle. The B_h and B_v are obtained by summation of isochronous field and quadratic function.

$$\begin{aligned} B_h(r) &= B_{iso}(r) - \frac{B_{peak}}{r_{peak}}\left(r - r_{peak}\right)^2 + B_{peak} \\ B_v(r) &= B_{iso}(r) + \frac{B_{peak}}{r_{peak}}\left(r - r_{peak}\right)^2 + B_{peak} \end{aligned} \quad (4)$$

where, B_{peak} indicates the maximum or minimum field at r_{peak} those are experienced values. The hill geometry is profiled by Bezier curve function with four control points. The spiral angle is determined by Archimedean spiral in conditions of beam focusing and geometrical limits.

Equation (5) expresses the radial and axial beam frequencies with the radius. These equations are used to calculate the beam stabilities.

$$\begin{aligned} \nu_r^2(r) &= 1 - n(r) + \frac{3N^2}{(N^2-1)(N^2-4)}F(r)(1 + \tan^2\xi(r)) \\ \nu_z^2(r) &= n(r) + \frac{N^2}{(N^2-1)}F(r)(1 + 2\tan^2\xi(r)) \end{aligned} \quad (5)$$

where, ν_r is the radial beam frequency, ν_z is the axial beam frequency, F is the flutter function and ξ is the spiral angle.

3.2. Accurate Magnet Design

The accurate design of the magnet is carried out using 3-D numerical simulation and beam dynamic calculation. An OPERA-3d TOSCA solver is used for the 3-D magnetic field simulation [11]. A GENSPEO program is used for the calculations of the beam stability, phase error and equilibrium orbit [12].

Firstly, the magnet model is drawn by OPERA-3d modeller based on the geometry of the analytic solution. Because the structure of the magnet pole is rotational around the z-axis and is symmetric with respect to the median plane, 1/8 model is used to save the simulation time (Fig. 5). Secondly, the nonlinear magneto-static problem is solved by the finite element method. Thirdly, the characteristics of the magnetic field are calculated by the GENSPEO. The second and third steps are iterative. The magnet model is rebuilt and simulated and the field is analyzed based on criteria. The main criteria are the isochronous field, beam stability and structural limits.

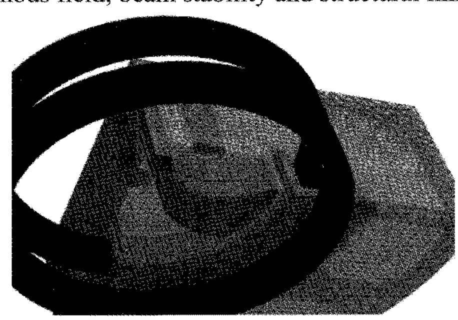

Fig. 5. 1/8 3-D numerical model of the KIRAMS-K120 magnet.

The main design parameters of the 3-D simulations are the superconducting coil and sector dimensions; hill angle, spiral angle and hill gap. The dimensions of the superconducting coils are optimized at the early stage of the sector design because the magnetic field distribution is changed by the coil dimensions. To make the three different field curves in Fig. 4, at least two pairs of coils are required. Three cases of coil structures are possible (Fig. 6). To find the optimal coil dimension, magnetic fields for the three test points of current densities are considered. Because there are two pairs of coils and three calculation points, nine combinations are simulated for each split case. We use 2-D interpolation method to find the optimal superconducting coil dimension and current density.

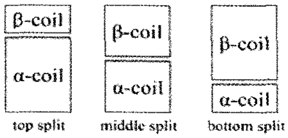

Fig. 6. Three different splits of superconducting coils.

4. RESULTS

The dimension of the superconducting coil has been designed to minimize the current variation according to the ions. The β-coil to α-coil ratio is 1.21 (Fig. 7). The current density of the α-coil is operated from 3998 A/cm^2 to 6629 A/cm^2 and that of the β-coil is operated from 3749 A/cm^2 to 6629 A/cm^2 with respect to the Carbon ions (Table II).

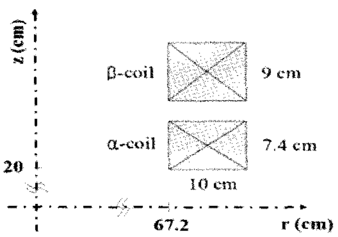

Fig. 7. The designed dimension of the superconducting coils.

TABLE II
OPERATING CURRENT DENSITY OF THE KIRAMS-K120 MAGNET.

	J_α (A/cm^2)	J_β (A/cm^2)
$^{12}C^{2+}$	3998	6418
$^{12}C^{4+}$	4995	5362
$^{12}C^{6+}$	6629	3749

The isochronous field for the $^{12}C^{4+}$ has been achieved by four spiral sectors. The maximum field is 3.84 T at the hill and the minimum field is 2.55 T at the valley (Fig. 8). The angular width and spiral angle at the extraction radius is 44.5° and 41.1°, respectively (Table III).

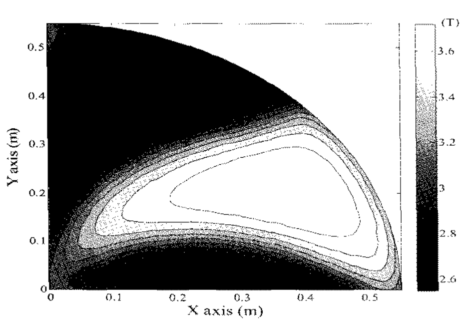

Fig. 8. A quarter field distribution of the median plane for the $^{12}C^{4+}$ ion.

TABLE III
MAIN PARAMETERS OF THE SECTOR.

Radius (m)	Hill angle (deg)	Spiral angle (deg)
0.05	42.0	5.0
0.1	41.6	9.9
0.15	42.5	14.7
0.2	42.5	19.2
0.25	42.0	23.6
0.3	41.5	27.6
0.35	41.2	31.4
0.4	41.1	34.9
0.45	42.0	38.1
0.5	44.5	41.1
0.55	48.0	43.8
0.6	50.0	46.3

The magnetic field of the $^{12}C^{4+}$ has been designed within the error of 0.1% (Fig. 9). The fields of the $^{12}C^{2+}$ and $^{12}C^{6+}$ have been obtained by the operating current densities in Table II. The field error of the $^{12}C^{2+}$ and $^{12}C^{6+}$ is 0.03% and 0.24%, respectively. Assumed the RF dee voltage 100 kV, the orbit revolutions of the Carbon ions are 50, 102 and 420. The integrated energies and phase errors have been plotted from the designed field and RF dee voltage (Fig. 10). The beam stabilities of the fields are reasonable. All the beam paths are in resonance free region or pass fast the resonance lines during the acceleration (Fig. 11).

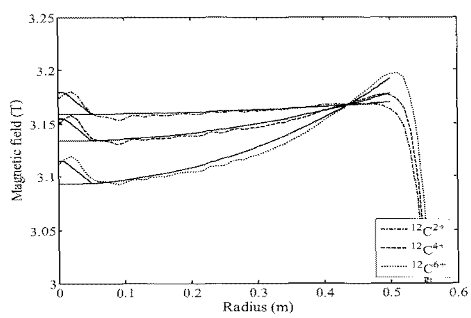

Fig. 9. The designed average magnetic fields comparison with isochronous fields (solid lines) of the Carbon ions.

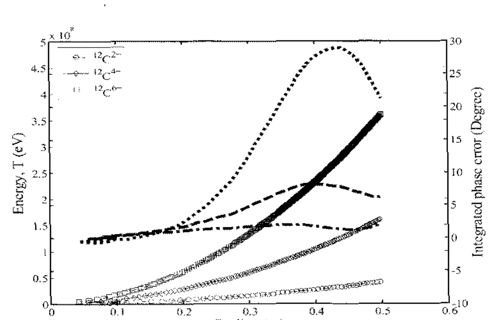

Fig. 10. The integrated energies (left y-axis) and the phase errors (right y-axis) of the Carbon ions. The markers represent the orbit radii.

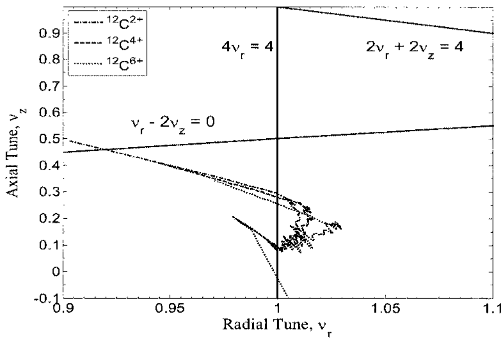

Fig. 11. Beam operating paths of the Carbon ions with important resonance conditions.

The overall dimensions of the KIRAMS-K120 magnet are diameter of 2.82 m and height of 2.01 m. The thickness of the side yoke plate is 0.425 m and the maximum thickness is 0.585 at the central region of the top and bottom yoke plate. The sector diameter is 1.1 m with the hill and valley gaps of 0.08 m and 0.64 m, respectively. The hill gap has been set by considering the space of the other systems; trim coil, RF structures and vacuum chamber. The valley gap has been determined by the space of the LTS system. The hill is divided into two pieces. The trim coils are wound on a piece of the hill near the median plane. The estimated overall weight of the magnet is 75 tons.

5. CONCLUSIONS

We have designed the magnetic field of the K120 superconducting cyclotron. The Carbon ions were used as criteria of the magnet design. We used analytic method to design the basic parameters of the magnet. The detailed magnetic field was simulated by the Opera-3d TOSCA solver and the field was analyzed by the GENSPEO. Spiral sector was designed for the isochronous and stable magnetic field. Two pairs of LTS coils were studied for the variable ion acceleration. The field errors will be reduced by employing the trim coils.

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