Design Study of a Superconducting Magnet for a FFAG accelerator

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Abstract. A superconducting magnet for the Fixed Field Alternating Gradient (FFAG) accelerator has been proposed. The static magnetic field is required to be proportional to the k-th power of the orbit radius where k is the geometrical field index of the accelerator. The left/right asymmetric coil with elliptical aperture is introduced to maximize the horizontal aperture with a compact magnet design. The 3D coil configuration is designed so that the design requirement can be fulfilled by means of integral magnetic field. The 3D magnetic field is generated so that the integral field along the beam trajectory may meet the beam optics requirement in the FFAG accelerator. The closed orbits can be also obtained at each energy by the beam tracking.

INTRODUCTION

The Fixed Field Alternating Gradient (FFAG) accelerator has lately received much attention for several applications [1]. In some cases, especially for medical applications, compactness of the accelerator is important, so it is useful to consider applying a superconducting magnet. The static magnetic field required for the FFAG accelerator provides an ideal application for superconducting magnet technology, because problems associated with time varying magnetic field such as AC loss can be neglected [2]. The superconducting magnet is possible to realize high magnetic field, so that the accelerator can reach a higher beam energy with a given accelerator size, or the accelerator can be smaller for a given beam energy. The FFAG accelerator magnet is required to have a non linear magnetic field that increases with the k-th power of the orbit radius, where the k is the geometrical field index in the accelerator. The left/right asymmetric coil structure is introduced for an effective magnetic design to generate the FFAG field. The 3D configuration of the coil is designed to obtain an integral field along the beam trajectory that fulfills the requirements of the accelerator design. The design study for an R&D magnet is reported in this paper.

MAGNETIC FIELD DESIGN FOR THE FFAG MAGNET

The FFAG accelerator has two major features. The “fixed field” implies that the magnetic field is constant in time. Hence, the FFAG accelerator is capable of accomplishing more rapid repetition than a conventional synchrotron. The “alternating gradient” means that the beam is strongly focused in the transverse direction. In addition, the phase stability condition is realized in the case of the FFAG synchrotron. Therefore the FFAG has unique advantages compared with cyclotrons and synchrotrons [1].

The magnetic field required for the FFAG magnet is given as follows:

$$B\,(x) = B_0\left(\frac{R_0 + x}{R_0}\right)^k \qquad (1)$$

where x is the distance from the center of the FFAG magnet , R_0 is the distance between the accelerator center and the magnet center, B_0 is the reference field at x=0, and k is the geometrical field index. The schematic view of the FFAG magnet in the vertical section is illustrated in Fig. 1.

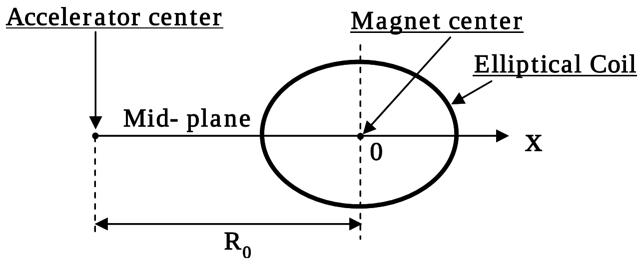


FIGURE 1. Schematic view of the FFAG accelerator in the vertical section.

The magnetic field given by (1) is expanded into the multipole field combination as follows:

$$B(x) = B_0\left(1 + r_0\frac{k}{R_0}\frac{x}{r_0} + r_0^2\frac{k(k-1)}{2!\,R_0^2}\left(\frac{x}{r_0}\right)^2 + \cdots\right) \quad (2)$$

where r_0 is the reference radius in the magnet.
The normal multipole field combination is given by

$$B(x) = B_0\left(b_1 + b_2\frac{x}{r_0} + b_3\left(\frac{x}{r_0}\right)^2 + \cdots\right) \quad (3)$$

Using (2) and (3), the normal multipole field components are given by

$$b_1 = 1 \;,\; b_2 = r_0\frac{k}{R_0} \;,\; b_3 = r_0^2\frac{k(k-1)}{2!R_0^2} \;,\; b_4 = \cdots \;, \quad (4)$$

When a pure mutipole field is produced with the superconducting coil, the current distribution is the cos(nθ) distribution given by

$$I(\theta) = I_0\cos(n\theta) \quad (5)$$

where θ is the azimuthal angle, I_0 is the magnet current, and n is an integer [3]. Fig. 2 shows a schematic view of the cos(nθ) current distributions to generate the magnetic field given by (1). The current distributions can be realized with multilayer coil each of which produces a pure multipole field. However, the magnetic forces on the coil are difficult and complex to be supported. Furthermore, the current distribution is not efficient because there are some parts where currents overlap and cancel. It is therefore convenient to combine the coils to give the current distribution shown in Fig. 3 (a) which is a left-right asymmetric distribution. Additionally, the current distribution is arranged on an ellipse so as to have a large horizontal aperture with a compact coil design. Fig. 3 (b) shows the combined current distribution on the ellipse.

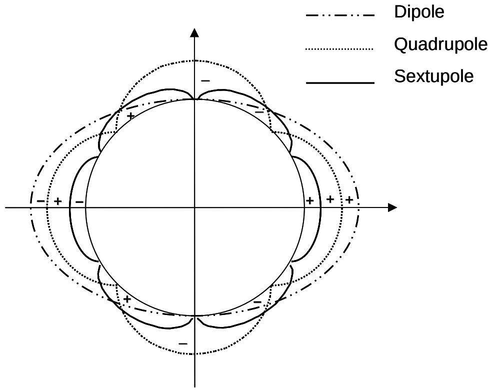
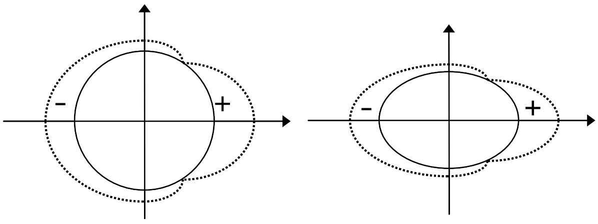


FIGURE 2. Each ideal current distribution for the normal multipole field component.



(a) (b)

FIGURE 3. Schematic view of the current distribution to realize combined multipole fields with (a) circular coil bore and (b) elliptical coil bore.

2D COIL CONFIGURATION

The coil is designed to meet the design requirement of an FFAG accelerator for medical applications. The parameters of the accelerator are listed in TABLE Ⅰ. Fig. 4 illustrates the 2D cross section of the coil. The line currents with the same current are arranged on the ellipse by adjusting the distance between the line currents to realize the current distribution as shown in Fig. 3(b). The "Local k value" applied as a parameter for the field on the mid-plane to evaluate the magnetic field is as follows [1]:

$$k_{local} = \frac{dB}{dx}\frac{R_0 + x}{B} \tag{6}$$

TABLE 1. Parameter of the FFAG accelerator**.**

Extraction energy	~200 MeV
Average beam current	~ Several 100 μA
Numbers of sector	12
Type of the magnet	Radial sector type
F/D ratio	2.8
Major axis of the beam pipe	0.8 m
Minor axis of the beam pipe	0.6 m
Field index, k	10
Ro	5 m
Excursion	0.4 m
Turn number	120
Bo	1.0 T

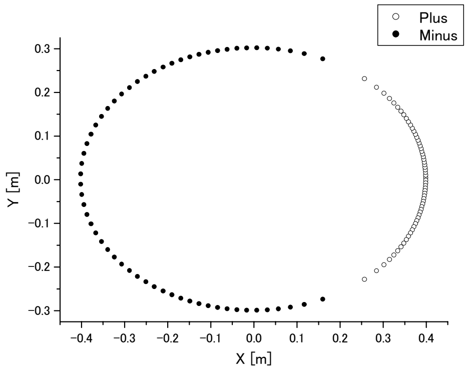


FIGURE 4. 2D cross section of the elliptic coil.

The conductor position of the coil is optimized to generate the required magnetic field when the coil is designed. Fig. 5 shows the local k value which was calculated with the cross section as shown in Fig. 4. The 2D conductor position was optimized using a computer program that we have developed. The calculation result satisfies the design requirement well in the range of the excursion.

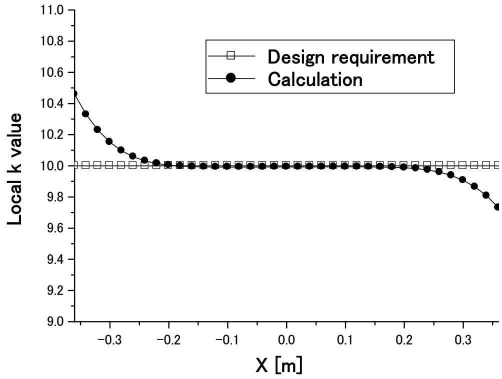
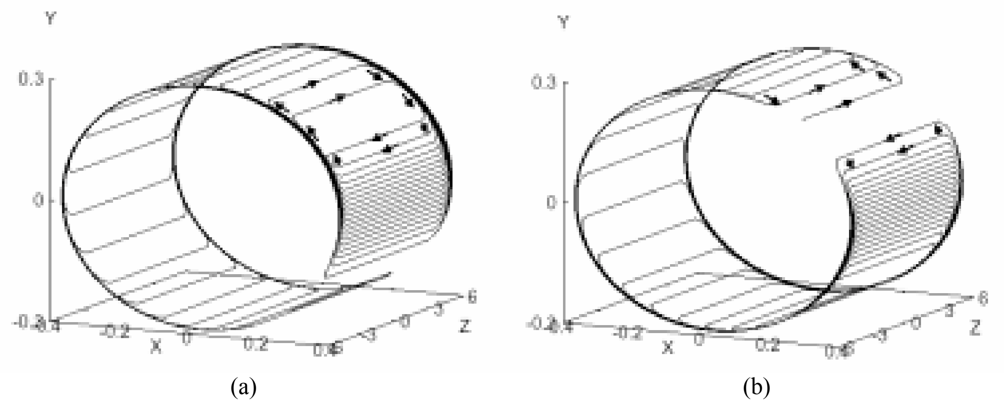


FIGURE 5. Local k value obtained by 2D calculation.

3D COIL CONFIGURATION

The coil end has greatly influence on the magnetic field distribution. Because the number of turns is large, the ratio of the physical length of the coil end to that of the straight section is large.

Consequently, it is difficult to design the 3D coil configuration so as to fulfill the design requirement locally at each radius. The 3D coil is therefore designed to meet the design requirement by means of the integral magnetic field along the beam trajectory. It is proposed to build the coil using the so-called "Single winding" pattern. The pattern has a characteristic that the difference of the straight length of the coil at the same position in each layer can be minimized when the number of the coil layers is even. Fig. 6 (a) illustrates the coil layer that is wound from the upper pole to the bottom pole. The next coil layer is wound from the bottom pole to the upper pole as shown in Fig. 6 (b), and it can be seen that the end currents cancel in many parts when the number of the turn is even.



(a) (b)

FIGURE 6. Single winding coil with continuous winding from/to top to/from bottom half coil. (a) The odd (1,3,5th . . .) layer and (b) the even (2,4,6th . . .) layer. A arrow shows the direction of the current.

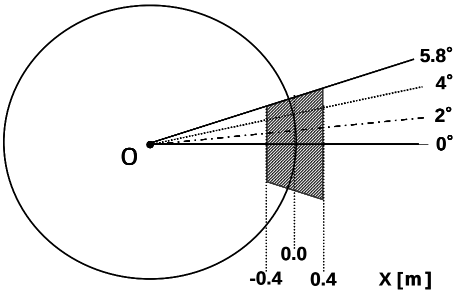


FIGURE 7. Schematic view of the FFAG accelerator in the top view.

Fig. 7 illustrates the schematic view of calculated area. The point O is the center of the accelerator, the circle is the beam trajectory in Fig. 7. The shaded area shows the coil which is trapezoidal to simulate the sector type magnet. Fig. 8 shows the local k+1 value by using BL, which is the integral vertical magnetic field B along the orbit L at each radius. The local k value should be replaced by the local k+1 in the design requirement because of the difference in the magnetic length due to the trapezoidal shape coil. As shown in Fig. 8, the local k+1 value nearly reaches the design requirement. It would be therefore possible to fulfill the design requirement for the integrated vertical magnetic field along the trajectory.

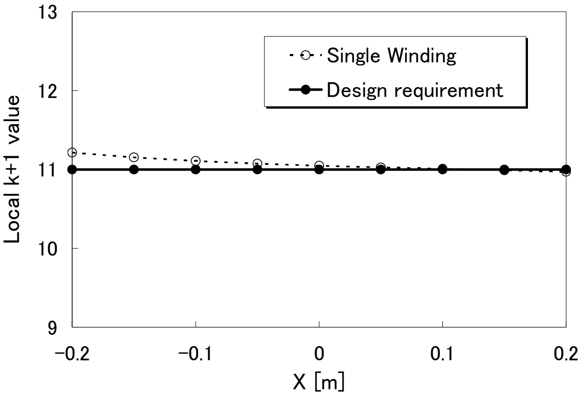
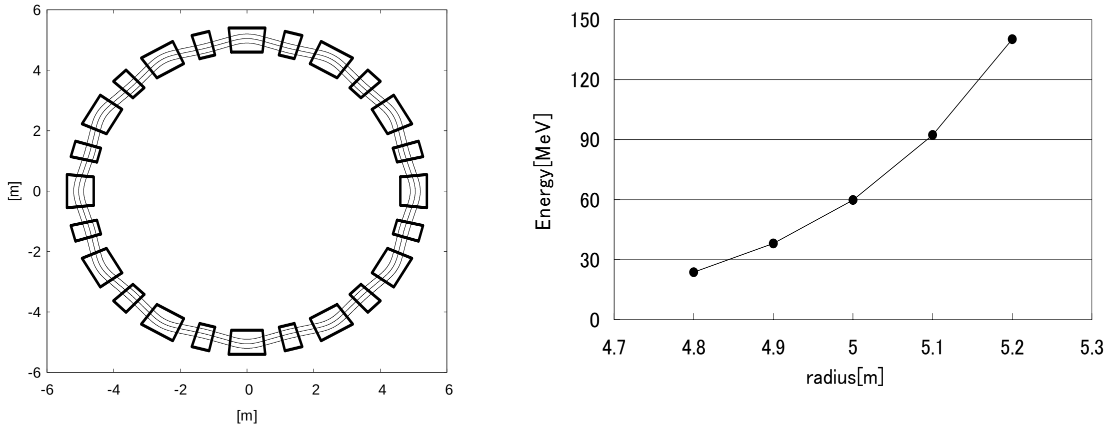


FIGURE 8. Local k+1 value obtained by BL at each radius.

TRACKING

The tracking a particle in the FFAG accelerator was performed with the magnetic field which almost fulfills the design requirement as shown in Fig. 8. The layout of the FFAG accelerator with some closed orbits is illustrated in Fig. 9(a). The beam energy can be achieved up to about 150 MeV as shown in Fig. 9(b). Therefore particles can be transported at each energy by means of the practical integral magnetic field that almost meets the design requirement. The vertical and horizontal tunes, which were also obtained in terms of the tracking simulation, are shown in Fig.10. As the beam energy increase, the tunes are across the resonance lines. Consequently the beam would be disappeared during acceleration. The redesign of the coil is therefore essential so as not to cross the resonance lines.



(a) (b)

FIGURE 9. (a) Layout of a FFAG accelerator with some closed orbits. (b) Beam energy at each radius of closed orbits. The position x=0 is the center of the FFAG magnet aperture.

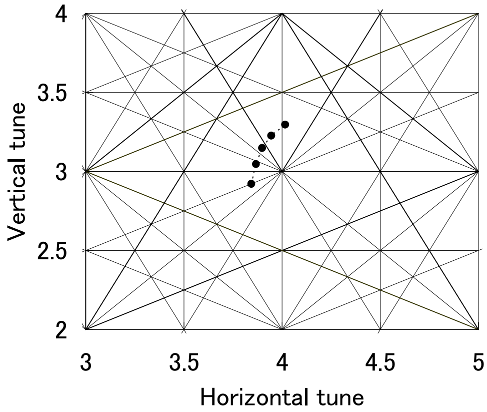


FIGURE 10. Tune diagram obtained by the beam tracking.

CONCLUSION

A superconducting magnet design for a FFAG is proposed. The cross section of the coil is optimized with a computer program that we have developed. The 3D coil configuration is designed to fulfill the design requirement by means of the integral field. The magnetic field was calculated and evaluated in 2D and 3D. The particle tracking was also performed. Particles can be transported at each energy in the field for which the local k+1 meets the design requirement.

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