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Evaluation of Asymmetric Quadrupoles for a Non-Scaling Fixed Field Alternating Gradient Accelerator

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A non-scaling fixed field alternating gradient (NS-FFAG) accelerator was constructed, which employs conventional quadrupoles. The possible demerit is the beam instability caused by the variable focusing strength when the orbit radius of the beam changes. To overcome this instability, it was suggested that the asymmetric quadrupole has different current flows in each coil. The magnetic field of the asymmetric quadrupole was found to be more similar to the magnetic field required for the FFAG accelerator than the constructed NS-FFAG accelerator. In this study, a simulation of the beam dynamics was carried out to evaluate the improvement to the beam stability for the NS-FFAG accelerator using the SIMION program. The beam dynamics simulation was conducted with the 'hard edge' model; it ignored the fringe field at the end of the magnet. The magnetic field map of the suggested magnet was created using the SIMION program. The lattices for the simulation combined the suggested magnets. The magnets were evaluated for beam stability in the lattices through the SIMION program.

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I. INTRODUCTION

Recently, fixed field alternating gradient (FFAG) accelerators have attracted some attention, with merits such as their modest size and capability of accelerating beams with high energy and high current. The magnetic field of the accelerator is constant when the energy of the particle beam increases. The trajectories of the particles in the accelerator have spiral shapes, just like a cyclotron. The FFAG accelerator comes in two types - the scaling accelerator and the non-scaling fixed field alternating gradient (NS-FFAG) accelerator. The scaling FFAG accelerator has a constant field index whereas the NS-FFAG accelerator has a non-constant field index. The particle beam has a constant betatron tune in the magnetic field with a constant field index [1]. The first constructed NS-FFAG accelerator (EMMA) consists of defocusing-focusing (D-F) lattices with quadrupoles [2]. To get the bending and focusing force in one quadrupole, each quadrupole should slide horizontally [3]. The sliding quadrupole has a weakness for beam stability due to the linear magnetic field map and the position of the beam center. The asymmetric quadrupoles make the non-linear magnetic field map and the position of the beam center located at the center of the magnet. The asymmetric magnet can lead to an extraction with a more stable beam than with a linear magnetic field. This study evaluates the stability of the beam in asymmetric quadrupoles using SIMION [4].

II. MAGNET

The magnets in the scaling FFAG accelerator have alternating gradients; therefore, the beam is strongly focused in the transverse and vertical direction. The magnet requires a magnetic field as follows.

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

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, and k is field index [5]. The magnetic field given by Eq. (1) is expanded and simplified in the multipole expansion as follows.

$$B(x) = B_0(b_0 + b_1 x + b_2 x^2 + \cdots), \tag{2}$$

where b_0, b_1, b_2 are the dipole, quadrupole and sextupole multipole components. The constructed NS-FFAG accelerator is composed of quadrupoles. It has a magnetic field with only b_0, b_1 multipole components. The magnetic field is different from that in Eq. (1) as it leads to

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Table 1. Multipole components for the scaling FFAG magnet, conventional defocusing magnet, and asymmetric defocusing magnet.

	Required parameters of magnetic field for scaling FFAG	Conventional defocusing quadrupole	Asymmetric defocusing magnet	unit
b_0	−0.1114	−0.1114	−0.1114	T
b_1	4.843	4.843	4.8429	T/m
b_2	−100.4	0	−31.261	$\mathrm{T/m^2}$

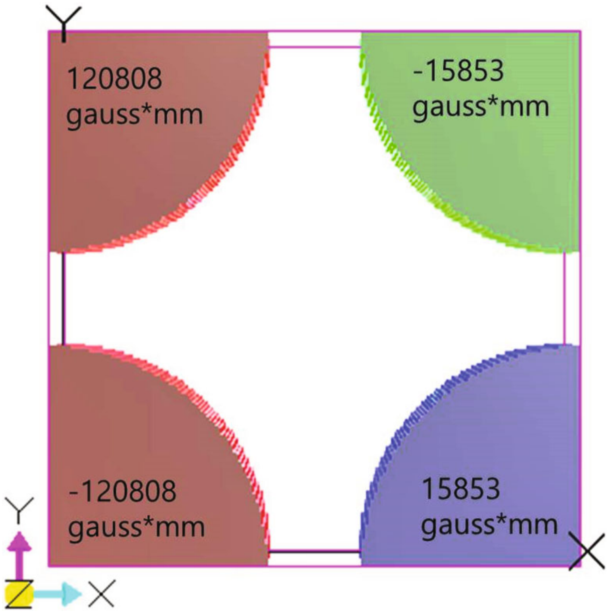

Fig. 1. (Color online) Magnetic potential of each coil (pole) for the asymmetric defocusing magnet.

the variation of the field index in the transverse direction. We have proposed the asymmetric magnet has a non-linear magnetic field with a sextupole component. This non-linear magnetic field has a variation of the field index less than the linear magnetic field.

1. Asymmetric defocusing magnet

The asymmetric magnet originates from the error in the excitation current for quadrupoles [6]. Each coil of a conventional quadrupole has the same current flow, whereas each coil of an asymmetric magnet has different current flows. In the SIMION program, we cannot have a set current, but can have a magnetic potential for each coil.

In Fig. 1, the four sectors indicate the poles of the asymmetric defocusing magnet where the numbers represent the intensity of the magnetic potential. In the asymmetric defocusing magnet, the required region has a non-linear magnetic field distribution in the radial direction of the vertical magnetic field, as shown in Fig. 2. The calculated polynomial expression indicates the multipole components as shown in Fig. 2. Multipole components for the scaling FFAG magnet, conventional defocusing magnet, and asymmetric defocusing magnet are shown in Table 1. The sextupole component of the conventional defocusing quadrupole is zero; however, the scaling

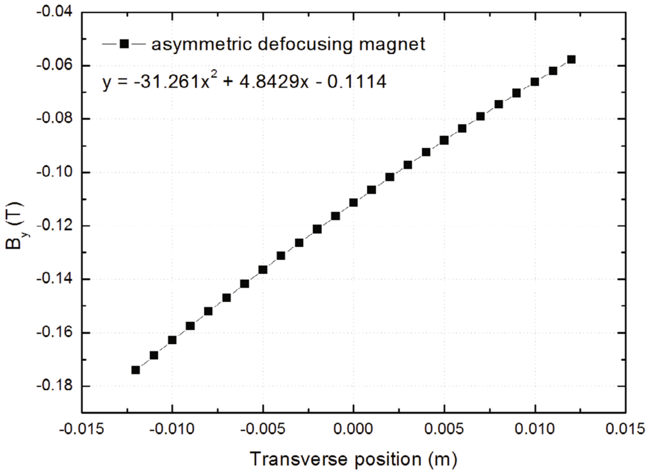

Fig. 2. Transverse field map of the asymmetric defocusing magnet.

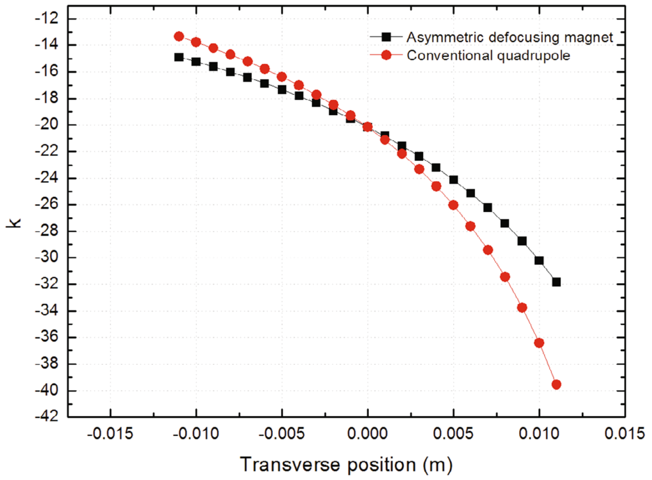

Fig. 3. (Color online) Variation of the field indexes for the asymmetric defocusing magnet and conventional quadrupole.

Table 2. Multipole components for the scaling FFAG magnet, conventional focusing magnet, and asymmetric focusing magnet.

	Required parameters of magnetic field for scaling FFAG	Conventional focusing quadrupole	Asymmetric focusing magnet	unit
b_0	0.0308	0.0308	0.0308	T
b_1	−6.487	−6.487	−6.4869	T/m
b_2	759	0	15.886	T/m^2

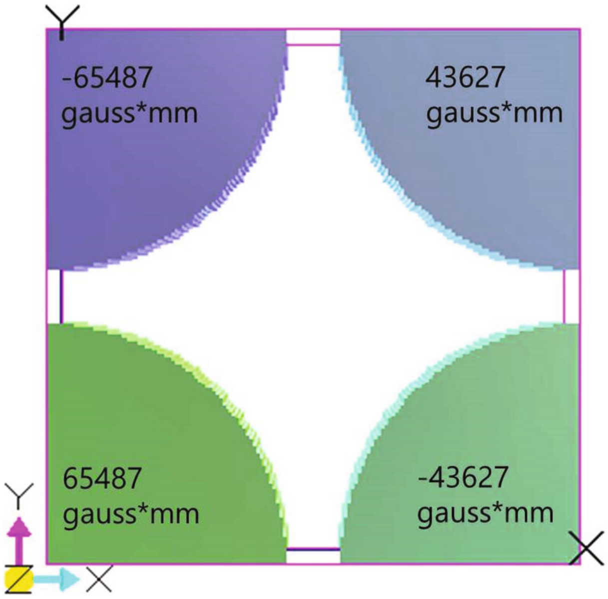

Fig. 4. (Color online) Magnetic potential of each pole for the asymmetric focusing magnet.

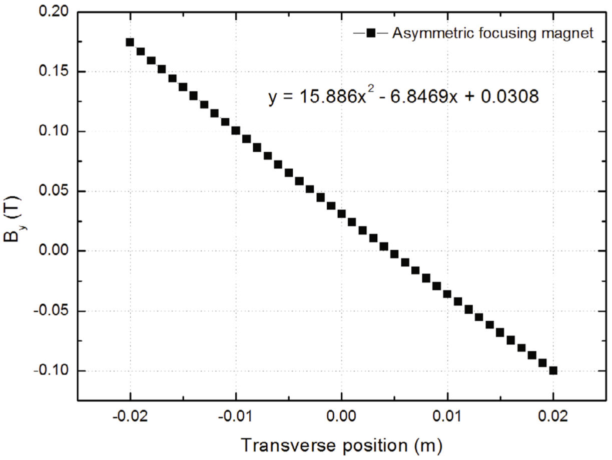

Fig. 5. Asymmetric focusing magnet transverse field map.

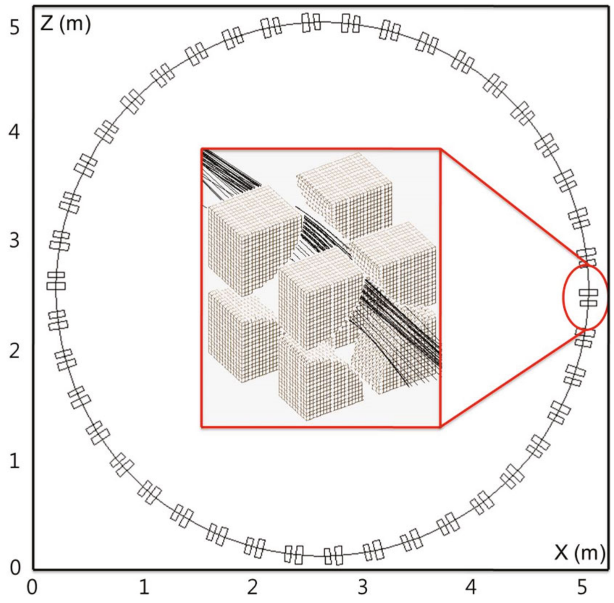

Fig. 6. (Color online) Ring with 42 D-F lattices of asymmetric magnets in SIMION.

FFAG magnet requires a field strength of −100.2 T/m^2. The sextupole component of the asymmetric defocusing magnet has a strength of −31.261 T/m^2. The asymmetric defocusing magnet is similar to the scaling FFAG magnet field with the sextupole component. The field indexes of the asymmetric defocusing magnet and conventional quadrupole were calculated for comparison, as shown in Fig. 3. The field index k is already mentioned and represented as follows.

$$k = \frac{dB}{dx}\frac{R_0 + x}{B}, \tag{3}$$

where R_0 is the distance from the accelerator center to the magnet center [5]. The differences between the minimum and maximum are 16.94 and 26.24, respectively. The field index for the scaling FFAG accelerator must be constant. The smaller field index variation implies that the magnetic field for the asymmetric defocusing magnet is more similar to the scaling FFAG accelerator than the conventional quadrupole.

2. Asymmetric focusing magnet

The conventional quadrupole of the constructed NS-FFAG accelerator can slide in the transverse direction,

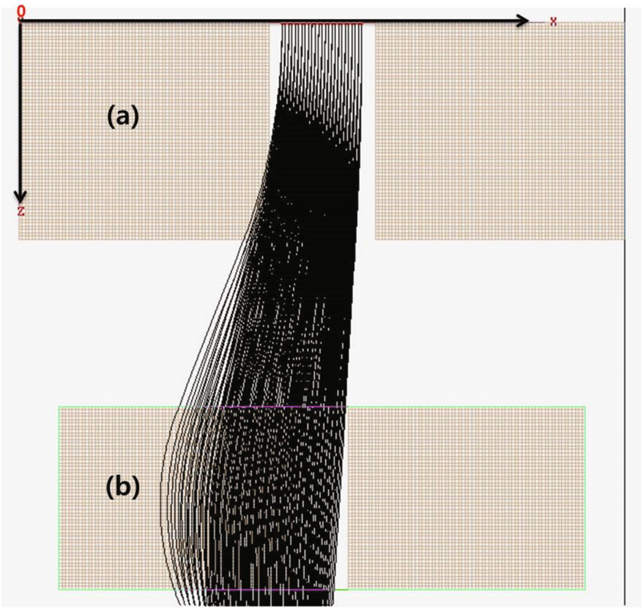

Fig. 7. (Color online) Initial condition of SIMION simulation where (a) is an asymmetric defocusing magnet and (b) is an asymmetric focusing magnet.

the displacement of which can distort the magnetic field. The asymmetric focusing magnet was suggested to prevent this distortion as the asymmetric current flows can achieve the dipole component without the displacement. In Fig. 4, the asymmetric focusing magnet model with pole shape and magnetic potential intensity in the SIMION program is shown. The sectors indicate the poles and the numbers indicate the magnetic potential intensity. The magnetic field of the asymmetric field map has dipole and quadrupole components which are the same as the scaling FFAG at the required parameters at the center of the magnet, as shown in Fig. 5.

Multipole components for the scaling FFAG magnet, conventional focusing magnet, and asymmetric focusing magnet are shown in Table 2. The dipole and quadrupole components of the asymmetric focusing magnet are 0.0308 T and −6.4869 T/m at the magnet center, respectively, which are similar to the conventional quadrupole values.

III. SIMULATION

For verification, we simulate the model of the asymmetric magnet for the NS-FFAG accelerator. This model was the same for that used for the constructed EMMA except for the magnets. The magnets of the model were changed from the conventional quadrupole to the asymmetric magnet and followed the hard edge model in which the fringe field is zero. The radius of the new model is 2.367 m and is composed of 42 D-F lattices as shown in Fig. 6 [2].

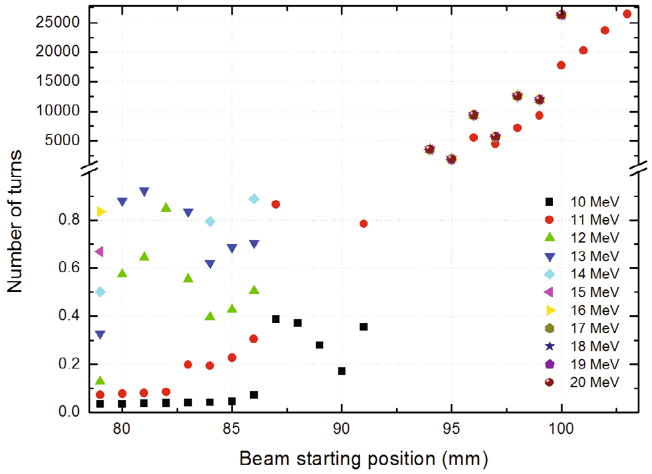

Fig. 8. (Color online) Number of turns for all energies.

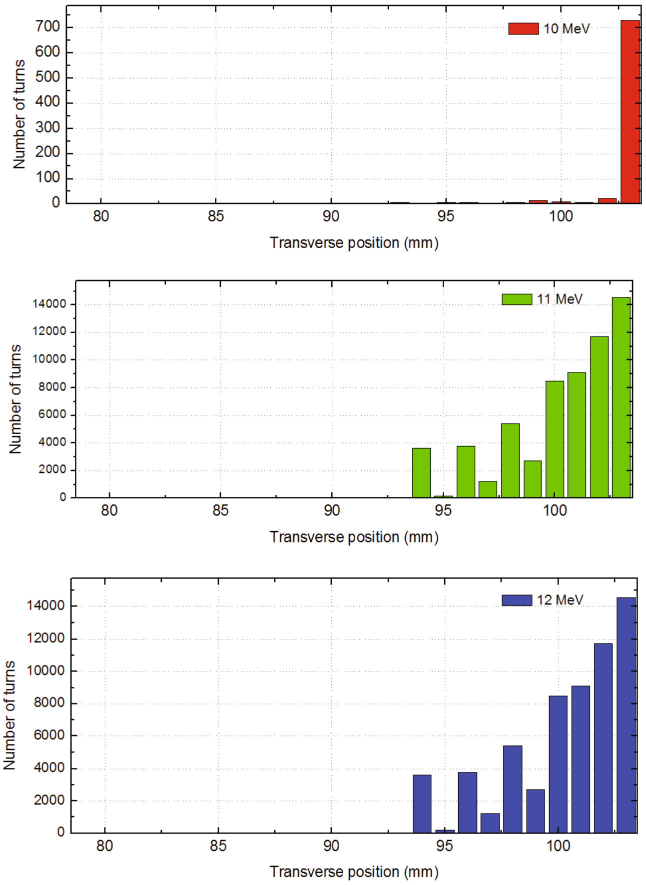

Fig. 9. (Color online) Number of Turns for 10, 11, and 12 MeV.

The initial condition of the beam simulation is shown in Fig. 7 where (a) is the asymmetric defocusing magnet and (b) is the asymmetric focusing magnet. The electrons traveled individually and there were 10 electrons in the 10 - 20 MeV range. The simulation process was carried out from the point source at various positions with ranges from 79 to 103 mm.

IV. RESULT

The number of turns for the electron beam at the 10 to 20 MeV energy range is shown in Fig. 8. The starting position and turn number of the electron beam is represented by the x- and y-axes, respectively. The 10 to 12 MeV electron beams were the dominant energy compared to the other energies. In the case of the 10 to 12 MeV electron beams, the number of turns in the ring structure with various starting positions is shown in Fig. 9.

The 10 MeV electron beam rotated 728 times at the 103 mm position. The 11 MeV electron beam rotated 25732 times, and the 12 MeV rotated 14565 times. The number of turns indicates that the asymmetric magnet is suitable for use in a ring type accelerator.

V. CONCLUSION

The first operated EMMA consists of conventional-type quadrupole magnets. The FFAG accelerator required a proper magnetic field, which had a sextupole component, unlike the conventional-type quadrupole magnet, while the magnetic field of the asymmetric-type magnet had a sextupole component. The conventional quadrupole in the NS-FFAG accelerator must slide to get the bending and focusing force in one quadrupole. Due to this sliding, the displacement allowed for the beam stability deterioration. The asymmetric magnet can generate a magnetic field for the FFAG accelerator without displacement. We composed the magnet designated for the magnetic potential to apply the NS-FFAG with a proper magnetic field by using the SIMION program to determine the suitability of the asymmetric magnet. The field index variation of the asymmetric defocusing magnet was less than that of the conventional-type magnet. The asymmetric focusing magnet generated the proper magnetic field for the NS-FFAG accelerator. We simulated the beam trajectories with the proposed magnet by using the SIMION program. The simulation result showed that the electron beam rotated over the 700 times with an energy range of 10 to 12 MeV. Therefore, the proposed magnet has the available components for a ring type accelerator.

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