THE STUDY OF HELIUM ION FFAG ACCELERATOR*

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Abstract

A helium ion Fixed-Field Alternating Gradient (FFAG) accelerator with periodic focusing structure was designed aiming at providing helium ion beam with a high beam current and peak 36 MeV energy at a lower cost for the study of the impact of helium embitterment on fusion reactor envelope material. A scaling FFAG accelerator with eight super-periods and a triplet focusing lattice-DFD combination is adopted for helium ion FFAG accelerator. In this paper, the magnetic lattice is optimized by analytical and numerical techniques. The large-aperture magnets are designed using a 3D magnetic field simulation code OPERA-TOSCA. Induction acceleration cavity without wake field will be used for helium ion FFAG accelerator. Some results of lattice design, magnet design and preliminary longitudinal tracking study are presented in the paper.

INTRODUCTION

Fixed-field alternating gradient (FFAG) accelerator has the advantages of rapid cycling and strong focusing than the conventional synchrotron and cyclotron. On account of the constant field, the repetition frequency of FFAG accelerator, which is only restricted by frequency tuning rate of acceleration cavity, can be as high as 1 kHz. In addition, the restriction for space charge effect maybe be alleviated by a large physical aperture of vacuum chamber providing multi-orbits for particles with different energy. Thus FFAG accelerator has the capability of accelerating low and medium energy, high average current and pulsed ion and electron beams, which can be used in Accelerator Driven Sub-critical Reactor (ADSR), nuclear physics, spallation neutron source, etc. In material science, helium embrittlement [1] directly influencing the macroscopic and microscopic characteristics of the fusion reactor blanket materials is a very serious problem to cause damages, which is one of key researches in the field of nuclear science and technology.

In the paper, a compact scaling FFAG accelerator with eight super-periods and triplet combination focusing lattice is designed to provide helium ion beam with a high average current and peak 36 MeV energy for the study of helium embitterment. Then, the large-aperture magnets are designed by means of a 3D magnetic field simulation software OPERA-TOSCA. In the end part of the paper, induction acceleration is used instead of radio frequency acceleration generally adopted for FFAG accelerator up to now.

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BEAM OPTICS DESIGN

On our design, scaling FFAG type originally proposed in 1950s [2] is used. Compared with non-scaling FFAG type, scaling FFAG type has the advantages of constant field index, zero chromaticity, geometrically similar orbits for different energy and large orbit excursion, but with the disadvantages of quite complicated closed orbit. It is difficult to optimize the closed orbit of scaling FFAG accelerator, because the ideal orbit for particles even with same energy is not on the constant dipole field and focusing strength. For preliminary calculation, the linear model with constant curvature and constant focusing strength gives a good approximation. Compared with spiral section magnet with edge focusing for vertical direction in addition to the focusing in horizontal direction from the magnet body, radial section magnet provides strong focusing for both direction coming from

Table1: Helium Ion FFAG Accelerator Main Parameters

Parameters	**Design goal**
Energy / MeV	2 ~ 36
Super-periods	8
Field Index	4.44
orbit radius / m	1.64 ~ 2.14
Ring circumference / m	11.42 ~ 14.51
Long straight / m	0.48 ~ 0.62
Short straight / m	0.08
F/2 Bending angle / deg	10.44
D Bending angle / deg	3.20
Magnetic field for F / T	0.37~ 1.2
Curvature for F / m	0.55 ~ 0.72
Magnetic field for D / T	−0.34 ~ −1.12
Curvature for D / m	−0.59 ~ −0.77
Opening angle / deg	F/2 : 31.3 D : −8.8
Betatron tunes	In : 3.44/1.16 Fin : 3.25/1.12
Injection	Multi-Turn Injection
Average output current:	μA ~ mA
Revolution period /ns	1163.6 ~ 350.9
Repetition Rate / Hz	500
Aperture / mm	680(H)×60(V)

magnet body, and has the advantages of good optical properties and small edge field effect. While the existent of the alternating bending fields results in larger circumference, lower momentum compaction makes for smaller apertures. So, triplet focusing lattice-DFD is used for helium ion FFAG accelerator.

According to the relation between penetration depth of helium ions in blanket materials and helium ion energy, helium ion FFAG accelerator is designed to have the peak extraction energy of 36 MeV, orbit excursion 0.5 m, repetition frequency 500 Hz, and average output current $\mu A \sim mA$. Table 1 gives some main parameters of helium ion FFAG accelerator. In this design, tune shift caused by different long drift for each energy particles is also away from the first order and second order resonance lines.

MAGNET DESIGN

Magnetic field for scaling radial sector DFD in median plane increases with radius r^k with k=4.44, and field gradient is generated and optimized by adjusting slant pole and coil current of main iron. H type with the aperture 680 mm for horizontal direction and 60 mm for vertical direction is used for helium ion FFAG accelerator. The radial sector DFD can be carefully designed by means of Poisson Superfish program and three-dimensional magnet simulation code OPERA-TOSCA, figure 1 gives structure diagram without coils for eight super-periods.

Figure 1: Magnet structure diagram without coils for eight super-periods.

In order to guarantee the bending angle of particles meeting theoretical value in our design, magnetic field in the actual magnet design is slightly higher than the theoretical value in linear model with constant bending filed, concurrently keeping relative change of field index within 3.2%. Figure 2 shows the relation for field index and relative change of field index in median plane versus radius, and figure 3 shows magnetic field in radial direction for different argument. However, as magnetic dispersion of the field to field disturbance, which might not be serious for main magnets, the complicated fringe effect, maybe mitigated by magnet shimming, is a rather serious problem, which is well and obviously shown in figure 3 with a few red lines displaying the change of magnetic field versus radial in the magnet edge. The extending distance of magnetic field for different geometrical radius is almost the same, so there's a reasonable proportion between the ratio for extending distance to magnetic gap and geometrical radius.

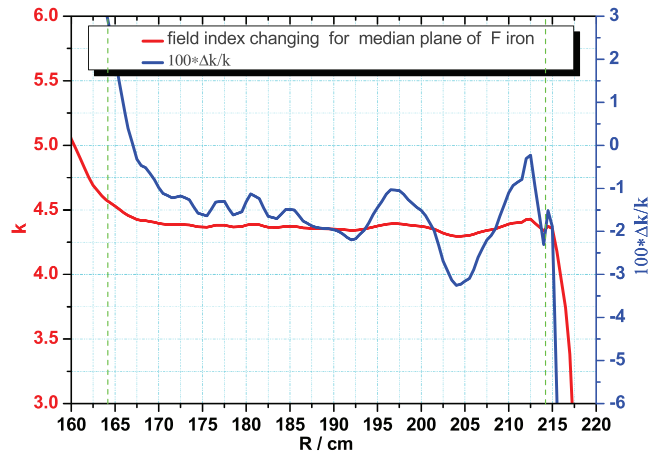

Figure 2: Field index and relative change of field index in median plane.

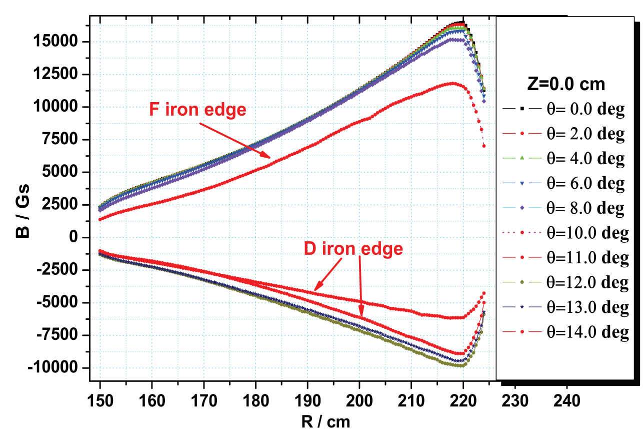

Figure 3: Magnetic field in radial direction for different argument.

LONGITUDINAL MOTION STUDY

Particles in FFAG accelerator gain high energy by just adjusting the frequency of accelerate cavity, unlike traditional alternating gradient accelerator providing particles with high energy by synchronously adjusting magnetic field of bending iron and frequency of radio frequency cavity. So far radio frequency (RF) acceleration with variable frequency and fixed frequency had been being adopted for FFAG accelerator. In order to obtain a high average current, induction acceleration, proposed by Ken Takayama and Junichi Kishiro in 2000 aiming at improving the intensity of high-energy particle beam and perfecting the performance of acceleration [3], will be chosen instead of conventional RF acceleration. Induction acceleration has the advantages of no wake field and avoiding the potential breakdown of acceleration field, and therefore transient current can be as high as 10 kA.

Not only do the modulator driving induction acceleration for helium ion FFAG accelerator need high output power, but also there is the necessary resonance relationship between pulse output period of modulator and revolution period of particles. Equation 1 shows the relation between revolution period of particles and acceleration number.

$$T_n = \frac{A_1\left\{\sqrt{(E_{in}+n\cdot\Delta E)\left[(E_{in}+n\cdot\Delta E)+2\varepsilon_0\right]}\right\}^{0.18384}+A_2}{\sqrt{1-\left[\varepsilon_0/(\varepsilon_0+E_{in}+n\cdot\Delta E)\right]^2}} \quad (1)$$

where, ε_0 is rest mass of helium ion, A_1, A_2 is the constant concerned with lattice, A_1=13.9841, A_2=4.26962. In order to reduce repetition frequency of the modulator output pulse, one acceleration for particles per twice circles is adopted, namely, $T_M=2T_n$, where, T_M is pulse output period of modulator.

Synchrony particles are discussed above. In fact, it is possible for asynchronous particles to break away from output pulse area for acceleration due to the presence of voltage drop and energy dispersion. For example, under certain circumstance that there is asynchronous particles for energy gain per a revolution 1% less than synchrony particles in 40 keV flat-topped wave voltage, when synchrony particles with 36 MeV is extracted, asynchronous particles is 1.6 microsecond behind synchrony particles, which can be so much larger than synchrony particle revolution period of extraction energy 36 MeV. Consequently, taking some constrained measures is prerequisite to guarantee particles always in output pulse area for acceleration. In consideration of solid-state modulator whose output pulse model can be adjustable, three adjusted-waveforms with the feature of energy compensation, displayed in figure 4, are taken into account for induction acceleration of helium ion FFAG accelerator.

The three adjusted-waveforms and corresponding longitudinal energy acceptance preliminary obtained by longitudinal simulation are shown in figure 4 respectively. Figure 4 obviously illustrates that the longitudinal energy acceptance of inclining upwards waveform is smaller than that of head-trail restraint waveform, and the extracted bunch of double platform waveform is extremely compressed compared with that of head-trail restraint waveform, which will cause severe space charge effect and lead to beam loss. Consequently, head-trail restraint waveform shows a great advantage of simultaneously gathering acceleration and longitudinal focusing.

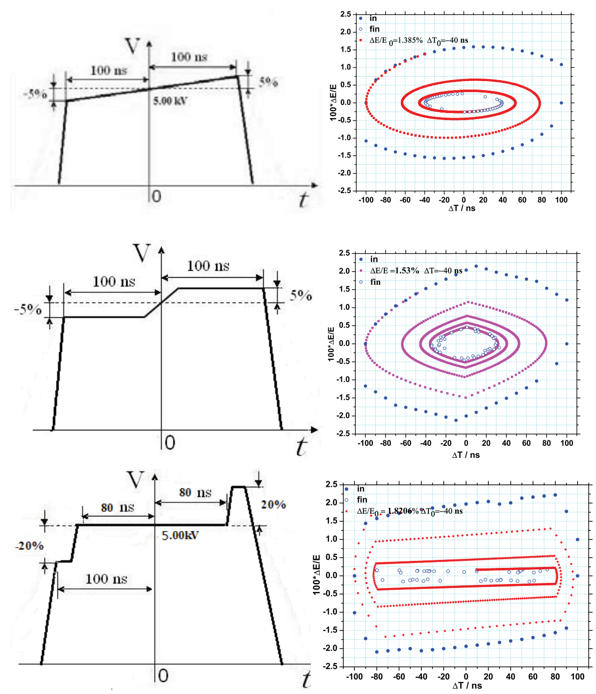

Figure 4：Three adjusted-waveforms for acceleration and longitudinal energy acceptance respectively corresponding to three waveforms: (1) top: inclining upwards waveform; (2) middle: double platform waveform; (3) below: head-trail restraint waveform.

SUMMARY

Linear model gives a good approximation for initiate lattice design of FFAG accelerator. Triplet radial section DFD demonstrates good optical properties, but more jobs are needed to study fringe effect and field disturbance caused by large magnet aperture. The head-trail restraint waveform not only accelerates particles but also focus particles in longitudinal direction, nevertheless, how to get this waveform remains a critical problem.

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