150-MeV FIXED FIELD ALTERNATING GRADIENT ACCELERATOR AND RETURN-YOKE FREE MAGNET

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Abstract

150 MeV Fixed Field Alternating Gradient(FFAG) Accelerator is now under construction at KEK. 150 MeV FFAG is regarded as a prototype machine for the practical accelerator. A distinguished features of this machine is Return-Yoke Free magnet. In order to overcome the peculiar disadvantage of FFAG, that is a lack of the space for the beam injection and extraction, we innovated the new type of magnet. The magnets was fabricated, and tested to be measured the profile of magnetic field. We are also developing the beam extraction system in high repetition rate around a KHz. The switching power supply with high repetition rate for the kicker magnet is designed and fabricated. Present status of the construction of 150 MeV FFAG accerelator will be presented.

1 INTRODUCTION

The world first proton FFAG synchrotron (PoP FFAG)was successfully commissioned in March 2000. Measured parameters of the PoP FFAG such as betatron tunes and synchrotron tune agreed with the design values very well. FFAG demonstrate the very rapid acceleration, where the proton beam was accelerated from 50keV to 500keV within 1msec. According to these results, it was found that the design procedure applied to the PoP FFAG, was appropriate. Under this success, the design of 150MeV FFAG synchrotron has been started.

150 MeV FFAG is the prototype accelerater to investigate the possibilities of various application; the high power proton machine, the proton therapy, the accelerator as the reactor driver and so on. It is necessary for a practical machine to have a large current. A remarkable feature of the FFAG accelerator is the possibility of very rapid machine cycle compared to conventional synchrotron because of the static magnetic field. We intend to operate this FFAG in high repetition rate and achieve the large current. The establishment of the beam extraction in such rapid cycle acceleration is important, which is also a main issue of this project.

Anyhow, one of the difficulties of the FFAG accelerator design was to make a space for beam injection and extraction. In order to overcome this difficulty, a new type of magnet, so called ”Return-Yoke Free” magnet, has been invented. The detail of Return-Yoke Free magnet will be discribed in the follwing section.

Figure 1 shows a schematic layout of the 150MeV FFAG synchrotron, which will be placed at the East Counter Hall of KEK.

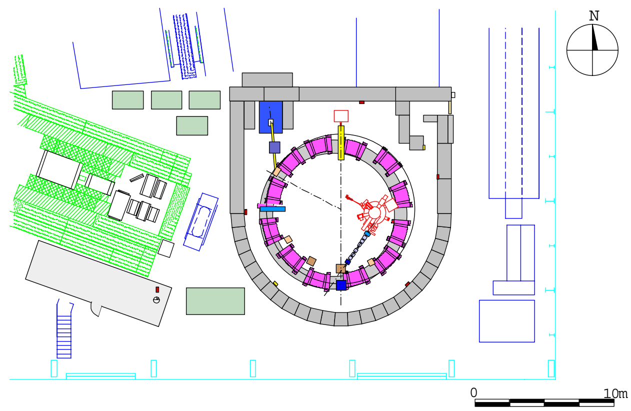

Figure 1: Layout of 150MeV FFAG synchrotron

Table 1 summarizes the main parameters of this machine. The injector is a 12MeV H^- cyclotron system. The cycrotron itself and their power supply are also fabricated. A positive hydrogen beam is injected into the FFAG ring by the injection system, which consists of a septum magnet, a septum electrode and two sets of the bump magnet. The beam is accerarated up to 150 MeV by the RF system with the high permeability magnetic alloy. The repetition rate of the machine is 250Hz at the first stage, in future can be increased up to 1kHz by adding another RF system. The beam is extracted with a rapid cycling kicker magnet and septum manget.

Table 1: Main Parameters of 150MeV FFAG synchrotron

Type of Magnet	Triplet Radial (DFD)
Num. of Sector	12
k-value	7.6
Beam Energy (MeV)	12→150 (proton)
Average Radius (m)	4.47→5.20
Betatron Tune	Hor. 3.69∼3.80 Ver. 1.14∼1.30
Maximum Field (T) (on orbit)	Focus 1.63 Defocus 0.78
Repetition (Hz)	250

The beam emittance at the beam extraction is assumed to be 50πmm·mrad in the current design. To extract the beam with the fast extraction, one kicker magnet and one septum magnet are to be installed in the adjacent straight sections in the ring. Considering the beam size at the extraction, to obtain a sufficient orbit separation at the septum magnet, more than 500 gauss of field strength is required for the kicker magnet and the field strength more than 2kgauss is needed for the septum magnet. The switching power supply for the kicker magnet had been fabricated, another instruments is now under construction.

The oparation current of 150 MeV FFAG is limitted by the amount of the concrete shield we have. The radiation limit just outside of the shield block shuould be less than 20$\mu Sv/h$, so that the maximum current is 40nA (2.5x10^{11} proton per second). Actually, it is possible to give larger current without the radiation limit.

Anyhow, three dimmensional spot scannning technique is an ideal irradiation method for the cancer therapy, where the cancer tissue is scanned with the well-regurated and pulsed beam. FFAG can give the well-regurated beam. Furthermore, it is possible to operate the FFAG accelerator in high repetition rate, so that the large beam current make the irradiation time shorter. After the accomplishment of the 150 MeV FFAG operation in high repetition rate, we aim to develop such type of irradiation sysytem in this project.

2 DESIGN OF MAIN MAGNET

2.1 "Return-Yoke Free" Magnet

Radial sector type of the FFAG acceleratorhas been originally proposed by Ohkawa in 1953. Figure 2(a) and (b) show schematically the equilibrium orbits of original radial sector FFAG accelerator and the triplet sector FFAG accelerator, which is applied to the 150MeV FFAG synchrotron as well as the PoP FFAG. In the case of FFAG accelerator, mean field index k (k-value) tends to be large considerably. However, with the type of the triplet magnet, the fringing field between focusing and defocusing fields can be easily cancelled.

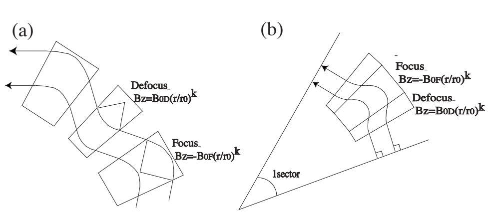

Figure 2: Lattice of Radial Sector Type FFAG (a) Original Radial Sector (b) Triplet Radial Sector

Figure 3 shows two type of triplet sector magnet. The type (a) is the ordinary triplet sector magnet which has been used for the PoP FFAG, and (b) is the "Return-Yoke Free" magnet which has been newly developed for the 150MeV FFAG. Even the type (b) magnet has no return yoke on the side of the forcus sector, it also realizes same field as of the ordinary magnet. In the case of Return-Yoke Free magnet, as is shown in the Figure 3, the magnet flux is excited mainly with the coils of the normal bending part and makes a return loop going through the gap of adjusent reverse bendding parts. There are four "shunt yokes" at the corner of the magnet not only support upper and lower poles, but also adjust the magnetic flux. Furthermore, the small coils can be attached on the poles of normal bending magnet, which play the role of knobs for fine filed tunings. The "Return-Yoke Free" magnet makes it possible to install the injection, extraction system and so on in the forcus magnet region.

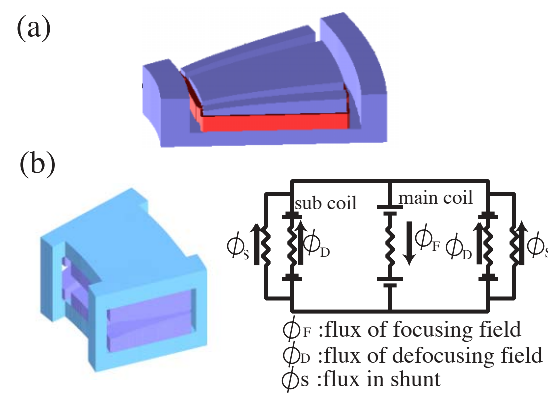

Figure 3: Triplet FFAG Magnet (a) Ordinary Structure, (b) "Return-Yoke Free".

2.2 Measurements of the magnetic field

We have already fabricated the magnets and tested to be measured the magnetic field. Figure 4 shows the result of the field measurements. Left side figure shows the profile on the medium plane of the magnet, where the coloerd lines correspond to the magnetic field as the function of x posision in the magnet. X direction is discribed in the right side of the figure. Discrepancy between any two magnets is less than 0.3%, so that all of the magnets are identical.

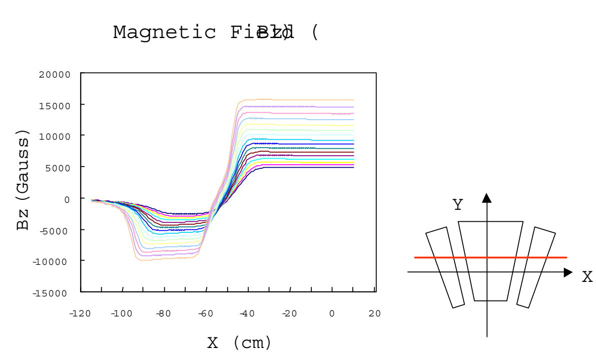

Figure 4: A typical Result of the magnetic field.

Figure 5 shows the photograph of the Return-Yoke Free Magnet for 150 MeV FFAG accerelator.

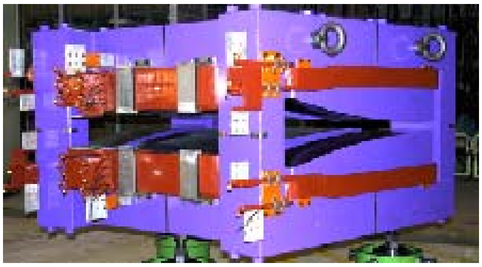

Figure 5: "Return-Yoke Free" Magnet for 150MeV FFAG accelerator.

2.3 Magnet Design

The 150MeV FFAG synchrotron must be designed to satisfy the zero chromaticity condition, where betatron tunes do not depend on momentum. At the first step to design the machine, we carefully determined the basic parameters of the machine with linealized model. The field index k, number of cell, average radius, ratio of focusing to defocusing magnetic field (FD ratio), angle of magnet-pole and so on are searched with the follwing two constraints. One is to keep the betatron oscillations stable, and another is to keep the orbit excursion as small as possible. The final desegin of the lattice function is shown in the Figure 6.

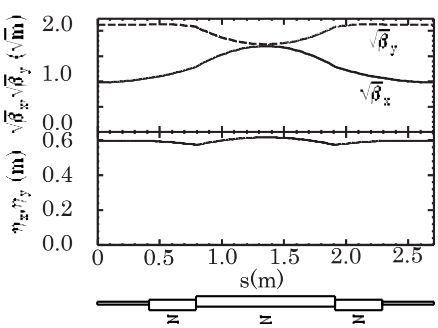

Figure 6: Lattice Function of Linearized Model

Seconderly, the detail designe of the magnet, which satisfied such basic parameters and the zero-chromaticity condition, was carried out. The 3-dimensional magnetic field is calculated with the calculation code, TOSCA. The equation of the ideal case, $\mathrm{halfgap} = \mathrm{h_0(r_0/r)^k}$, is regarded as the initial value of the pole shape, and we carefully optimized the pole shape with checking the betatron tune given by the tracking simulation. Finally, the designe shown in the Figure 7 was given. In the left side of Figure 8 shows the BL integration of the final designe. The both plots of the forcusing and deforcusing sector gives the value (k+1) as the indexes of the BL integration. In the right side of Figure 8 shows the FD ratio with this designed magnet. FD ratio is almost constant over the area where the beam is accelereted, and this leads to the zero-chromaticity condition.

Figure 9 shows the calculated result of the tune shift with

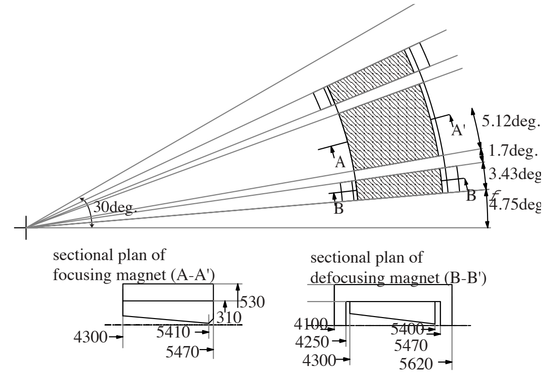

Figure 7: Pole Shape of the Magnet(unit=mm)

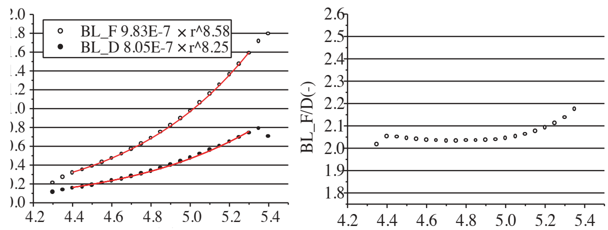

Figure 8: BL Integration and FD Ratio in a Radius

the final designe, where the betatron tunes do not cross the resonance lines up to third order during the acceleration.

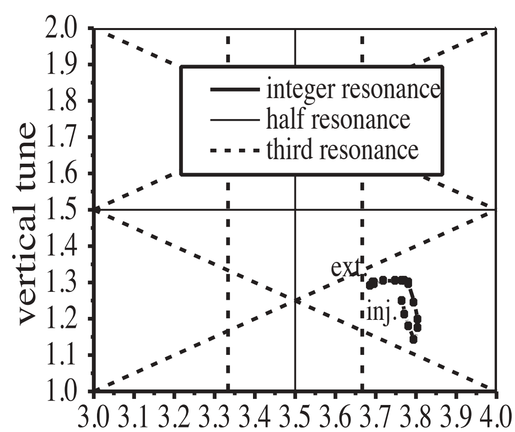

Figure 9: Tune Shift during Acceleration

3 SUMMARY

According to the design of 150MeV FFAG synchrotron, 150 MeV FFAG is now under construction. The "Return-Yoke Free" magnets have been fabricated satisfactorily. The injector cyclotron, the power supply for extraction kicker magnet are also completed. The development of any other instruments, beam diagnostics porgress favorably. Construction will be finished within this year. After getting the permission as the radioactive instrument by the government, we will start the commissioning.