A 150MeV FFAG SYNCHROTRON WITH "RETURN-YOKE FREE" MAGNET

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Abstract

The 150MeV proton FFAG (Fixed Field Alternating Gradient) synchrotron is under construction at KEK to investigate the possibilities of various applications such as proton beam therapy after the success of the POP FFAG synchrotron. One of distinguished features of this machine compared with the PoP FFAG is to use a new type of magnet, "Return-Yoke Free" magnet. Because there is no return-yoke in the median plane in this magnet, the beam injection and extraction become easier.

1 INTRODUCTION

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

One of the difficulties of the FFAG accelerator design is to keep a long straight section 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.

Figure 1 shows a schematic layout of the 150MeV FFAG synchrotron, which will be placed at the East Counter Hall of KEK. Table 1 summarizes the main parameters of this machine. The injector is a 12MeV H^- cyclotron. A negative hydrogen beam is injected into the FFAG ring using charge exchange injection scheme.

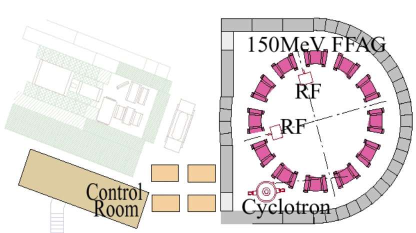

Figure 1: Layout of 150MeV FFAG synchrotron

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. The repetition rate of the machine is 250Hz at the first stage and can be increased up to 1kHz in future. The beam is extracted with a rapid cycling kicker magnet.

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

2 DESIGN OF MAIN MAGNET

2.1 *Triplet Lattice*

Radial sector type of the FFAG accelerator[1, 2] has 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 similar to the PoP FFAG. In the FFAG accelerator, mean field index k (k-value) is large considerably.

The triplet type of the magnet has many advantages. The fringing field between focusing and defocusing fields can be easily cancelled. Long straight sections which gives sufficient space for installing the injection and extraction devices, and the beam diagnostics instruments, can be obtained.

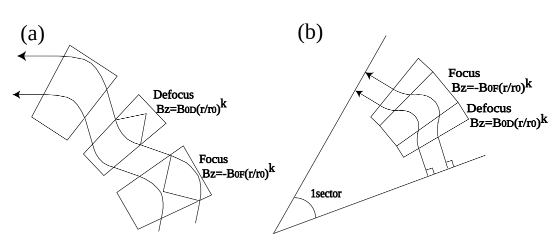

Figure 2: Lattice of Radial Sector Type FFAG (a) Original Radial Sector (b) Triplet Radial Sector

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2.2 "Return-Yoke Free" Magnet

Figure 3(a) and (b) show an ordinary triplet sector magnet, which has been used for the PoP FFAG, and "Return-Yoke Free" magnet, which has been newly developed for the 150MeV FFAG, respectively.

In order to realize a triplet focusing structure, a normal bending magnet and reversed field magnets on both sides are combined together without having return-yoke as shown in Figure 3(b). The magnet flux excited mainly with the coils attached on the poles of normal bending magnet, makes a loop which goes through the gap of a normal bend and returns from the gap of a reversed bend. Total flux of the normal bend must be larger than the one of reversed bend so that the orbits can close around the machine. There are four "shunt yokes" at the corner of the magnet not only support upper and lower poles, but also adjust the magnetic flux. And the small coils attached on the poles of normal bending magnet, play the role of knobs for fine filed tunings.

The "Return-Yoke Free" magnet makes it possible to inject or extract the beam even from a magnet region. Another practical side benefit is the weight reduction because of no solid block as a return yoke.

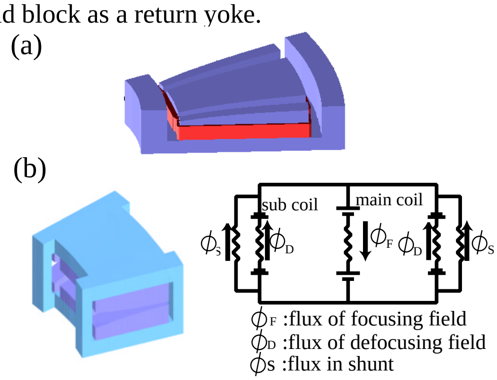


Figure 3: Triplet FFAG Magnet (a) Ordinary Structure, (b) "Return-Yoke Free"

The small "Return-Yoke Free" magnet was developed and constructed to verify these features. Figure 4 shows the field measurement of the small R&D magnet. The results showed the good agreement with the results of 3-dimensional field calculation.

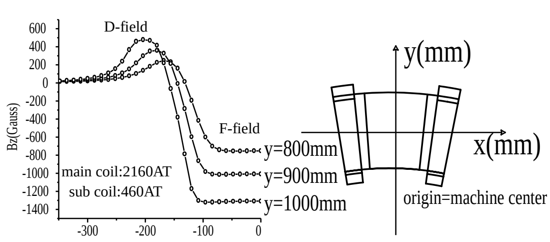


Figure 4: Typical Field Measurement Results of R&D Magnet

2.3 Magnet Design

In order to design the machine, basic parameters has been determined with the linearized model. The field index k, which is the most important parameter, has been carefully optimised under two constraints. The first constraint is to keep the betatron oscillations stable. The second one is to keep the orbit excursion as small as possible. Other parameters, number of cell, average radius, ratio of focusing and defocusing field intensity (FD ratio), angle of magnet-pole are also determined with the linearized model. Figure 5 shows the lattice function calculated with the linearized model.

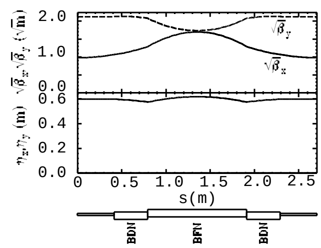


Figure 5: Lattice Function of Linearized Model

The design of the main magnet was carried out with 3-dimensional field calculation by a code TOSCA and the tracking simulation, based on the basic parameters.

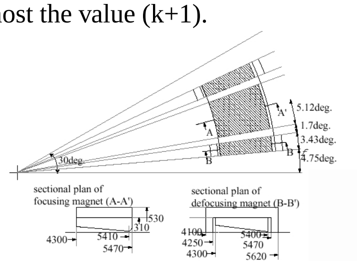
The 150MeV FFAG synchrotron is designed as a scaled machine, so that betatron tunes should not depend on momentum. However, under the effects of the fringing field and the field saturation, it is difficult to make the field which satisfies the zero chromaticity condition.

If the fringing field and the field saturation effect can be ignored, the required field would be realized with the pole shape shown by the equation, $\mathrm{halfgap} = \mathrm{h_0(r_0/r)^k}$. This equation is the start point of the design of the pole shape.

The pole shape is then optimized through the following steps so that the BL integration can follow the function of the (k+1) power of the radius.

1. to change the pole shape index of focusing and defocusing magnet respectively in order to tune the central part of the field
2. to adopt the tangent line at the inside part of the pole in order to compensate the fringing field due to the large gap
3. to attach a shim at the end of the focusing pole in order to prevent from the field saturation analogous to logowsky's curve
4. to widen slightly the outside part of the gap of the defocusing magnets with the curve shown by the eq. (D3) in Figure 6 in order to reduce the defocusing field intensity as the residual field saturation at the pole of the focusing magnet

Figure 6 shows the plan of the designed magnet and the equations of the pole shape. Figure 7 shows the BL integration and the FD ratio with this designed magnet. The indexes of the BL integration of focusing and defocusing field are almost the value (k+1).



$$
\begin{aligned}
halfgap &= -0.156 \times (r - 4475) + 90.079 \\
&\qquad (4300 < r < 4475)(\mathrm{F1}) \\
halfgap &= 21 \left(\frac{5400}{r}\right)^{7.75} \\
&\qquad (4475 < r < 5410)(\mathrm{F2}) \\
halfgap &= -0.156 \times (r - 4475) + 90.079 \\
&\qquad (4300 < r < 4500)(\mathrm{D1}) \\
halfgap &= 20 \left(\frac{5400}{r}\right)^{9.32} \\
&\qquad (4500 < r < 4900)(\mathrm{D2}) \\
halfgap &= 39.9 \left(\frac{4900}{r}\right)^{11.555} + 9.57 \\
&\qquad (r = 4900 < r < 5400)(\mathrm{D3})
\end{aligned}
$$

Figure 6: Pole Shape of the Magnet(unit=mm)

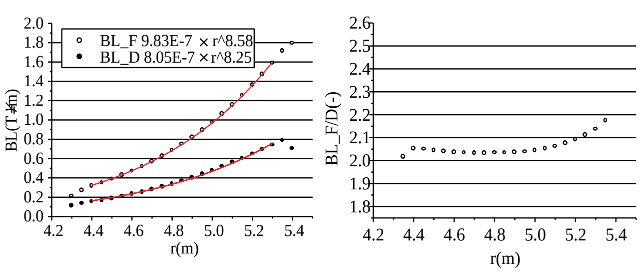


Figure 7: BL Integration and FD Ratio in a Radius

Figure 8 shows the tune shift, which is calculated with the tracking simulation, during the acceleration. In general, it is desirable that the betatron tunes should not cross the resonance lines up to third order. This constraint is satisfied.

Figure 9 is the picture of "Return-Yoke Free" Magnet for 150MeV FFAG.

3 BEAM EXTRACTION

As mentioned in the previous section, the fast beam extraction is to be employed in 150MeV FFAG. 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.

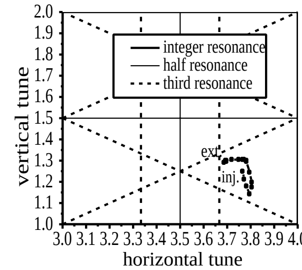


Figure 8: Tune Shift during Acceleration

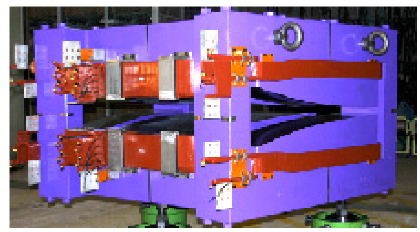


Figure 9: "Return-Yoke Free" Magnet for 150MeV FFAG synchrtron

Figure 10 shows a typical extraction orbit. 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. As shown in Figure 9, beam is ejected from the F-pole of the sector magnet. Thus, the invention of the "Return-Yoke Free" magnet makes the extraction system very simple.

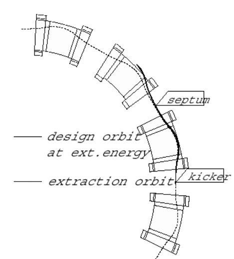


Figure 10: Beam Extraction Scheme

4 SUMMARY

The design of 150MeV FFAG synchrotron has been completed, and the beam extraction scheme with triplet "Return-Yoke Free" magnet is established. This machine is expected to be the prototype for many application of the future FFAG accelerator.

5 REFERENCES

[1] T.Adachi et al., Proc. of EPAC2000 p581-583

[2] T.Ohkawa, Proc. of annual meeting of JPS(1953)

[3] K. R. Symon et al., Phys. Rev 103(1956)1837