BEAM INJECTION AND EXTRACTION IN 150MeV FFAG

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Abstract

The 150MeV FFAG is a prototype FFAG synchrotron for practical applications. The fast extraction of proton beam from a FFAG ring is the first trial in the world, and the demonstration is a milestone for a practical FFAG accelerator.

In the paper, the overview of the beam injection and extraction schemes in the 150MeV FFAG is to be presented

1 INTRODUCTION

After the successful commissioning of the PoP FFAG, which is the world first proton FFAG synchrotron, a new project which aims to construct a FFAG synchrotron called 150MeV FFAG was started.

The 150MeV FFAG is a prototype FFAG synchrotron for practical applications, such as beam therapy[1]. Thus, the beam extraction is a indispensable function for it, and it is the first trial of proton beam extraction from a high energy FFAG accelerator. Therefore, the demonstration would prove the potential of FFAG accelerator for a practical use accelerator. The important parameters of 150MeV FFAG in the beam injection and extraction are summarized in Table 1.

In the followings, the overview of the beam injection and extraction schemes in the 150MeV FFAG is to be presented.

Table 1: Main parameters of 150MeV FFAG for beam injection(inj)) and extraction(ext)

(1)Momentum	137MeV/c(inj),550MeV/c(ext)
(2)Horizontal tune	$\sim$ 3.8
(3)Revolution period	$\sim$650ns(inj),220ns(ext)
(4)Number of cell	12
(5)length of drift space	$\sim$ 60cm

2 BEAM EXTRACTION FROM 150MEV FFAG

The important characteristics of FFAG accelerator is fast acceleration and high repetition rate. To match the characteristics, In 150MeV FFAG, the fast beam extraction with kicker and septum magnets is to be employed. In such a scheme, the crucial problem is the orbit separation at the septum magnets, since the beam loss at the septum conductor is a dominant source of the beam loss in the fast extraction.

If the kick angle at septum(θ_{kick}) and the phase advance between the kicker and the septum(ϕ) are given, the orbit separation at septum magnet(x_{obt}) is expressed in the following equation.

$$\Delta x_{obt} = \theta_{kick}\sqrt{\beta_{kicker} \cdot \beta_{septum}}\sin\phi \qquad (1)$$

where $\beta_{kicker} and\ \beta_{septum}$ mean beta functions at the kicker and the septum magnet, respectively.

2.1 Orbit separation at septum magnet

In the design of the extraction scheme, the first point is to find out the optimum location for septum and kicker.

For the study, single-particle tracking simulation using Runge-Kutta method, which was used in the design of the 150MeV FFAG itself[4], was carried out.

The kick given by the kicker magnet is converted to the orbit separation at the septum magnet in the fast extraction. In the simulation, the kicker is installed at θ(azimuthal position)$= 30°$.

Thus, from equation 1, the optimum phase advance is $(1/2 + n) \times \pi$. From the criterion, Considering the horizontal tune of 150MeV FFAG,$\sim$3.8, the drift spaces at $\theta = 150°$ and $\theta = 240°$ are preferable for the location of the septum magnet.

According to eq. 1, the phase advance directly affects the orbit separation at the septum. Thus, the stability of betatron tune must be checked. In radial sector FFAG accelerators, horizontal betatron tunes, can be varied by changing the relative field strength of the F-pole and that of the D-pole(F-D ratio). According to the tracking simulations, the horizontal tune shift within the range of plausible F-D ratio is less than 0.02[2]. From eq. 1, the shift of the extracted beam position at the septum is less than 0.01mm for such a phase shift.

Figure 1 shows the orbit separation at the septum magnet in the case of kicker field of 900gauss. In the study, the gap hight of the kicker and the septum magnet is assumed to be 20mm, which is wide enough for the extracted beam of 10πmm·mrad[1]. The orbit separation at the septum magnet is about 13mm in maximum. Assuming the maximum current density in a holo conductor as 60A/mm^2, the achievable field strength of the septum magnet is about 4kgauss.

2.2 Extraction orbit

From Figure 1, the drift spaces at 150° and 240° are adopted as the candidate for the location of the septum magnet. Among them, the drift space at 150° was employed to suppress the potential orbit shift caused by the

[1]The vertical beam size is expected to be $\sim$12mm

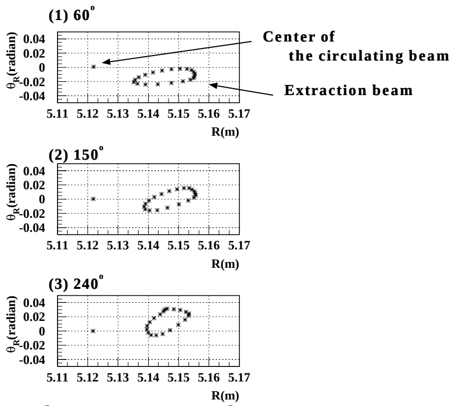

Figure 1: Orbit separation at the extraction septum

error field. As the orbit length gets longer, and, in result, the phase advance gets larger, plausible discrepancy between the designed phase advance and the real one would get larger.

Figure 2 shows a typical extraction orbit. The extraction emittance is 100πmm·mrad. The field strength of the kicker magnet and the septum magnet are 900gauss and 3kgauss, respectively.

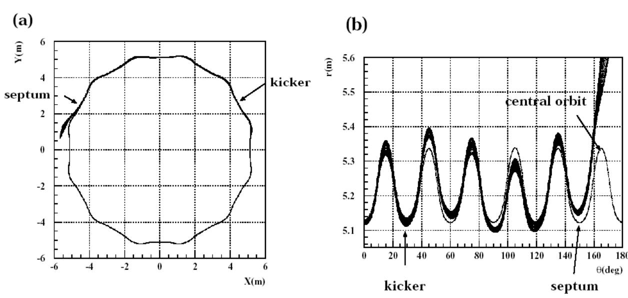

Figure 2: Typical extraction orbit of 150MeV FFAG (a)real space projection (b)r-θ space projection

From the above result, it is shown the beam with 100πmm·mrad. is surely extracted. In the extraction, the following things should be noted for the future development of FFAG accelerator.

The beam orbit of a radial sector FFAG tends to approach to the edge of the magnet at the center of the F-pole. Thus, the extracted beam also tends to go out from the edge of the F-pole. Therefore, the lack of free space for the beam extraction was a problem in a radial sector FFAG. However, the yoke-free type magnet, which was proposed in the development of the 150MeV FFAG, gives free space in the region and solves the problem[1].

Though the free space problem was solved by employing the yoke-free type magnet, the beam extraction in the radial sector FFAG has another potential problem. Due to the orbit characteristics, the beam tends to traverse the edge of the magnet with a small angle. It gives the strong edge “de”-focusing. In result, the horizontal beam size gets larger. For the problem, an correction pole attached to the extraction point or correction focusing element installed at the extraction point would be helpful. It was found that the correction pole also change the field distribution of the main field. As a result, it will break the symmetry of the field distribution of the ring. Thus, for the realization of the idea, further careful study is required.

At present, a realistic solution would be the latter one and we employed it.

3 BEAM INJECTION INTO 150MEV FFAG

In the beam injection to 150MeV FFAG, two schemes were proposed. One is the charge exchange injection with H^- beam using a charge stripping foil. The other is the phase space painting injection with H^+ beam using septa and bumps.

The former scheme can provide a high intensity beam with a relatively small beam size. However the limited applicable energy and particle would be problems. In addition, in the case of the 150MeV FFAG,at present, there is no available H^- ion source which matches with our operation scheme. For the latter scheme, the beam emittance inevitably gets larger to increase the beam intensity, but it has wide applications. Considering these points, the phase painting injection was employed in the 150MeV.

the beam extraction simulation shows that beam of 100πmm·mrad is surely extracted. Taking into account the adiabatic dumping, the injection scheme should be designed so that the beam with the emittance of 400πmm·mrad is surely injected.

3.1 Bump orbit

The optimum phase advance in the bump orbit is $n \times \pi$, where n is integer. Using a similar study done for the beam extraction orbit, two candidates were found. The relative azimuthal distances between the bumps are 90° and 150°. Among them, the former one was adopted to suppress the potential orbit shift caused by the error field.

3.2 Septa

The next problems is the configuration of the septa. Figure 3 shows the horizontal phase space of the injection beam(horizontal emittance : 50πmm·mrad.) and that of the circulating beam (horizontal emittance: 400πmm·mrad.) at the center of the drift space next of the bump magnet(@60°). The field strength of the bump magnet is set 300gauss. The bump field gives a orbit separation of about 3mm. It should be noted that the magnetic field of 300gauss is corresponding to electric field of 15kV/cm for a proton with kinetic energy of 10MeV. Thus, instead of the bump magnet, electrostatic bump is also plausible.

According to the tracking study, the beam must be bent almost 90˙ in a drift space where the beam injected from outside. Bending field of about 1 Tesla is required for such a case. To generate such a strong field with DC magnet, orbit separation of more than 3cm is needed. Due to the above reason, two septum are to be employed for the beam

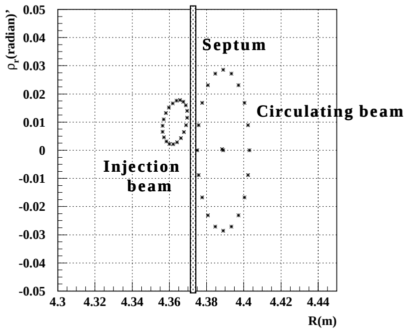

Figure 3: Horizontal phase space of injection beam and circulating beam at ES septum

injection. One is a electro static(ES) septum inserted in the drift space at 60° and the other is a septum magnet of 1 Tesla installed in the drift space at 90°. In an ES septum, the conductor separating the injection beam and circulating beam is grounded and it can be made vary thin, typically $\sim$ 0.1mm. Applicable electric field gradient is about 100kV/cm. The beading angle with a uniform electric field is given by eq.2, where θ, E, L, p and β mean bending angle,field gradient, length of the septum, beam momentum and velocity of the beam, respectively.

$$\tan\theta = \frac{EL}{p\beta} \qquad (2)$$

Figure 4 shows the electric field dependence of the ES septum in the orbit separation at the septum magnet. For a reference, the orbit separation in the case of the second candidate(see 3.1) was also plotted in the same figure. Even with a relatively low field, $\sim$ 35 kV/cm, sufficient orbit separation(¿3cm)can be obtained.

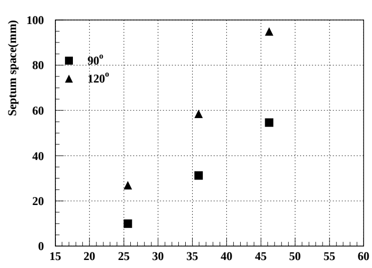

Figure 4: Electric field dependence of ES septum in the orbit separation at the injection septum magnet

3.3 *Injection Orbit*

The above discussion shows that sufficient orbit separation was obtained with the combination of the ES septum and the septum magnet of moderate parameters. Figure 5 shows a typical injection orbit. In the simulation, electric field of 35kV/cm was applied in the ES septum. For the septum magnet and the bump magnets, magnetic field of 1T and 300gauss were applied, respectively.

Figure 6 shows the horizontal phase space of injection beam(horizontal emittance: 50πmm·mrad.) and that of the circulating beam(horizontal emittance: 400πmm·mrad.) at the septum magnet.

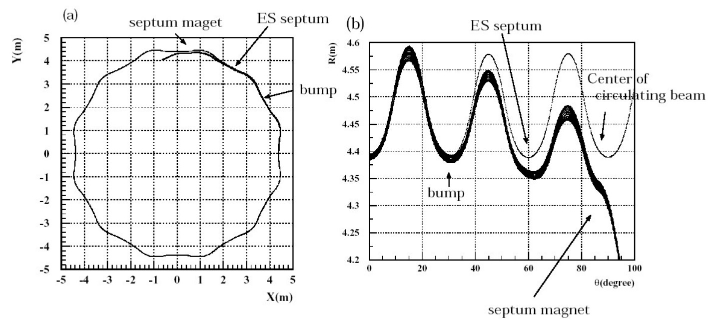

Figure 5: Typical extraction orbit of 150MeV FFAG (a)real space projection (b)r-θ space projection

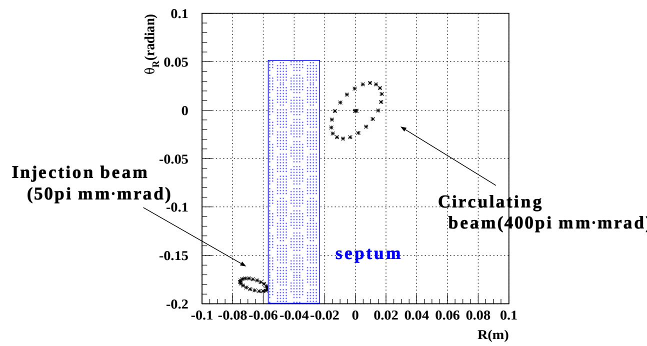

Figure 6: Horizontal phase space at the injection septum magnet

4 SUMMARY

In the 150MeV FFAG, the phase space painting with H^+ beam was employed for the beam injection. With a EM septum, septum and bump magnets, it is shown that beam with emittance of 400 πmm·mrad. was surely injected with moderate instrumental parameters. For the beam extraction, the fast extraction with kicker and septum magnet is to be employed. It was shown that a beam with emittance of 100πmm· mrad can be extracted. To realize the scheme, the hardware design is now going on.

5 REFERENCES

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