A FFAG DESIGN STUDY FOR AN ACCELERATOR-DRIVEN SYSTEM*

T.-Y. Lee†, H. S. Lee, H. S. Kang, Pohang Accelerator Lab, Pohang, Kyungbuk, 790-784 KOREA

Abstract

A 1 GeV, 10 MW FFAG accelerator is discussed as a candidate for the accelerator-driven sub-critical nuclear reactor system. Scaling and non-scaling schemes are explained and compared with each other along with radial and spiral-sector FFAG accelerators. Advantages and disadvantages of each scheme are considered. Particularly, the idea of semi-scaling scheme based on spiral-sector type FFAG is proposed.

INTRODUCTION

After the Fukushima nuclear reactor accident, the nuclear reactor safety issue has become very important in many countries. If nuclear power is to become one of the main energy sources of the future, this safety issue should be resolved along with the issue of nuclear waste whose lifetime can be as long as a few hundred thousand years. The key issue of the reactor safety is how to terminate the chain reaction in the reactor in an emergency.

In this regard, an old but valuable idea is to use the accelerator-driven sub-nuclear reactor (ADSR), a nuclear reactor that maintains chain reaction only with additional neutrons furnished from outside source. [1, 2, 3] ADSR uses neutrons from the spallation process that is activated by a proton accelerator. In an accident or an emergency, the accelerator stops immediately and because the neutron supply is terminated the chain reaction fails to be sustained. That is how ADSR is supposed to work. The reason this old and bright idea has not been realized is that current accelerators are not able to meet the requirements of this scheme. The requirements on the proton accelerator is determined by the output power goal and how low is the reactor is kept below the criticality $k = 1$. For safety reasons, $k = 0.98$ is preferred and under this condition we need 1 GeV, 10 MW (hence 10 mA current) proton accelerator to produce 700MW output. This is a huge challenge for accelerator scientists considering that the power of the 1 GeV proton linear accelerator of the Spallation Neutron Source (SNS) at Oakridge National Laboratory is only 1.5 MW.

The high power requirement eliminates the proton synchrotron from the candidates because it is unable to deliver such a high power. Synchrotron accelerates particles by varying the magnetic fields but you can achieve only a few Herz of acceleration cycles. Hence, synchrotrons can not deliver high current of protons. The proton linear accelerator can deliver 10 MW proton beam, however its construction costs is very high. Note that the SNS super conducting proton linear accelerator is 350 m long. That is why a Fixed-Field Alternating Gradient (FFAG) accelerator attracts much interests recently for the purpose of ADSR. A FFAG is a circular accelerator composed of separated magnets just like a synchrotron. However, the difference is that its magnetic field is fixed in time scale but varies in space while the synchrotron magnetic field is fixed in space but varies in time. Hence, FFAG accelerators can accelerate very fast and deliver high current proton beam in a relatively compact machine size.

This paper explains several types of FFAG accelerators, radial and spiral FFAG accelerators, and scaling and non-scaling FFAG accelerators. Then, this paper proposes a spiral semi-scaling FFAG accelerator as the best option for the ADSR scheme and explains why.

FFAG ACCELERATORS

Just like ADSR, the idea of FFAG accelerator was a old one but recently revived for the construction of a compact and high current proton accelerator. [4, 5, 6] In a circular accelerator, the basic relation is

$$B\rho = \frac{p}{e}, \tag{1}$$

where B is the bending magnet field, ρ is the radius of curvature, and p is the particle momentum. Hence, along with the acceleration (and, thus, the increase of momentum), the orbit radius is either increased as in a Cyclotron or kept constant if the bending magnetic field is increased accordingly as in a synchrotron. Because varying magnetic fields takes time, the acceleration of a synchrotron is rather slow and that is why a synchrotron is unable to deliver high current proton beams.

A FFAG accelerator is composed of several bending magnets just like a synchrotron but the magnetic field is fixed in time. Hence, the orbit radius increases along with the acceleration, however unlike the Cyclotron, the magnetic field varies spatially and this gives magnet gradient focusing to the beam and allows compact machine at the same time. Since no magnetic field varying is involved, FFAG acceleration can be as fast as a few kHz and deliver high current proton beam. This is the basic principle how a FFAG accelerator works. There are several different schemes and types of FFAG accelerators that uses this principle as will be briefly reviewed below.

Radial and Spiral FFAG Accelerators

In the radial-sector type FFAG, the magnetic field B varies only radially as

$$B = B_0 \left(\frac{r}{r_0}\right)^k, \tag{2}$$

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† tylee@postech.ac.kr

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where r is the distance from the machine center, r_0 is a reference value of r, and k is a constant. Since this magnetic field contains dB/dr component, it gives the beam gradient focusing. The defocusing is given by placing the above bending magnet reversed, which gives negative bending to the beam. The bends and negative bends constitutes the alternating gradient structure. A schematic figure is shown in Fig. 1. Obviously, the existence of negative bends make the FFAG ring circumference larger as can be seen in the relation,

$$N(\Theta_F - \Theta_D) = 2\pi, \tag{3}$$

where N is the number of sectors, Θ_F is the angle of the bending magnet, and Θ_D is the angle of the negative bending magnet.

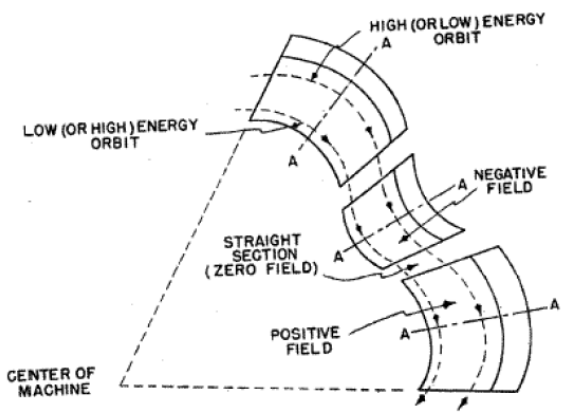

Figure 1: Schematic figure of a radial-sector FFAG [6]). As the beam is accelerated, the orbit moves to outside.

In a spiral-sector type FFAG, the magnetic field has both radial and angular dependence as in

$$B = B_0 \left(\frac{r}{r_0}\right)^k f\left(\theta - \tan\xi \ln\frac{r}{r_0}\right), \tag{4}$$

where θ is the azimuthal angle and ξ is the spiral angle and f is a function of them. Unlike the radial-sector type, it uses no negative bends and the defocusing is provided by the edge focusing. As a result, it is more compact than the radial-sector type but the focusing is rather weak. A spiral-type FFAG is shown in Fig. 2.

Scaling and Non-Scaling FFAG Schemes

In a circular accelerator, synchrotron or FFAG, resonances should be avoided in the acceleration process. A scaling FFAG keeps the betatron tunes unchanged, which means keeping the zero chromaticity. Equations of betatron motion in a scaling radial sector FFAG are given by [8]

$$\frac{d^2x}{d\theta^2} + \left(\frac{r^2}{\rho^2} + \frac{r}{\rho}k\right)x = 0, \tag{5}$$

$$\frac{d^2y}{d\theta^2} - \left(\frac{r}{\rho}k\right)y = 0, \tag{6}$$

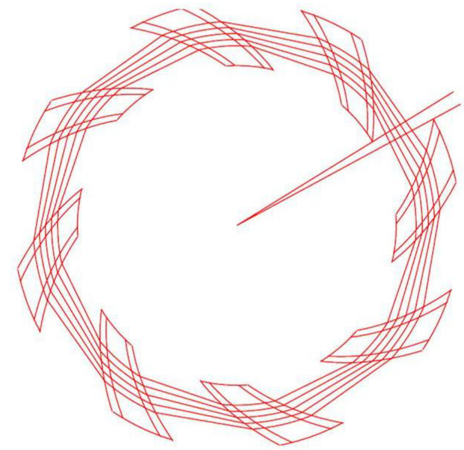

Figure 2: Spiral-sector FFAG and its orbits [7]. Again, the beam orbit moves outside, as it is accelerated.

where k is the field index defined by $k = (r/B)(dB/dr)$. Hence, if the betatron motion is to be independent of the momentum, both r/ρ and k should be independent of the momentum p:

$$\frac{d}{dp}\left(\frac{r}{\rho}\right) = 0, \tag{7}$$

$$\frac{d}{dp}(k) = 0. \tag{8}$$

It is easy to make k independent of p by choosing k constant, when the magnetic field has the form given in Eq. (2). If we further choose r/ρ independent of r, not only the betatron motion but the orbit scales (independent of the momentum) a and that is why it is called scaling FFAG. The orbit excursion is sometimes large and the magnets can be very big and heavy. The argument is equally applicable to the spiral sector FFAG and the two accelerators in the above two figures belong to scaling FFAG category.

However, the problem is that it is very difficult and tricky to choose r/ρ independent of p. That is why a non-scaling scheme has been invented. A non-scaling FFAG does not keep 0-chromaticity and allows the tunes come close to resonances. The non-scaling scheme uses the fact that it takes time for resonances to blow the beam and accelerates the beam fast enough to reach the final momentum before resonances kill the beam. Hence, it needs huge accelerating power, which is the main challenge of the non-scaling scheme. Since k can be any number in this scheme, it is customary to choose $k = 1$, which means a simple gradient magnet with no multipoles. With this choice, the lattice is composed of purely linear element and the dynamic aperture is huge. Furthermore, if a defocusing magnet is used as the main magnet, the orbit is compressed as in Fig. 3, unlike the scaling case.

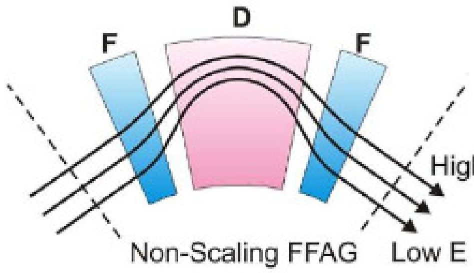

Figure 3: Orbits of a non-scaling FFAG are compressed within a short dimension [9].

SPIRAL SECTOR SEMI-SCALING FFAG FOR ADSR

Important criteria for choosing a adequate accelerator type for ADSR are as follows:

- One of the most important criteria to choose a right accelerator type for ADSR is economy. It costs huge to build a 1 GeV, 10 MW proton accelerator whatever type of accelerator it would be. Furthermore, a nuclear reactor may need another accelerator as a backup in case the primary accelerator stops. Hence, it is important to choose an accelerator based on economy consideration. That is why FFAG is considered here instead of linear accelerators, which uses proven technology.
- Another important criterion is the ease and simplicity of design, construction, and operation of the accelerators.
- The accelerator does not have to be a small emittance machine because the spallation target in the nuclear reactor is rather large.

The combination of the need for a compact machine and no need for small emittance gives the spiral sector FFAG as a candidate for the ADSR accelerator. Furthermore, This paper considers the scaling accelerator complicated in designing and tricker in operating. Hence, a scaling FFAG is not considered in this paper. However, if the non-scaling scheme is to work stably, it should give enough time of acceleration before resonances kill the beam. It is not a trivial matter to make sure that the non-scaling scheme will work successfully. Therefore, this paper proposes a semi-scaling scheme based on a spiral-sector FFAG accelerator. It still uses constant k and the orbit excursion exists. However, it ignores keeping r/ρ independent of p, which means that the betatron tunes can vary along the acceleration and the acceleration system should be powerful enough to survive the resonances. Hence, the orbit excursion per revolution is large and the orbit shape will be more or less that of fig. 2, although the orbit does not scale exactly along the acceleration. As can be seen from fig. 2, the particle motion is not exactly periodic because when the particle passed through 2π angle, it sees a bit different magnetic field that is spiraled out and this is particularly so when the orbit excursion per revolution is larger.

Resonances happen in the periodic motion. When the periodicity is broken slightly, the resonances are not perfect either, which may be reflected with longer growth time. Therefore, you obtain sufficiently long time to accelerate the beam before it is killed by resonances. The more RF power you have, the longer growth time you havw. You need a computer simulation to get more accurate information of your design.

CONCLUSION

Semi-scaling scheme based on a spiral-sector FFAG is proposed as a compact and efficient candidate for the accelerator of the ADSR scheme.

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