FFAG EXPERIENCE AND FUTURE PROSPECTS

Y. Mori*,
Research Reactor Institute, Kyoto University, Osaka, Japan

Abstract

The outline of the various FFAG accelerators that have been constructed and the operational experience with different machines are presented. Common issues are identified, and contrasting experiences highlighted. The capability of FFAGs to meet the requirements for applications such as ion therapy, accelerator-driven subcritical reactors(ADSR), and muon accelerators are followed by a description of the main objectives and challenges for future prospects.

INTRODUCTION

As the name stands for, the FFAG accelerator completes with a static magnetic field and strong (AG) focusing. To organize these two issues in beam dynamics during beam acceleration, the beam loss caused by betatron resonance crossing has to be overcome. There are two ways to prevail this problem; one is to realize a special beam optics keeping the operating betatron tunes constant, thus zero-chromatic optics. The other is to cross the betatron resonances as quick as possible to eliminate the practical beam losses during acceleration. The former type of FFAG calls ”Scaling” and the latter ”Non-scaling”.

The scaling FFAG where the betatron tunes are always constant during acceleration is free from the problems crossing betatron resonances. Eventually, it could have a fairly large momentum acceptance of more than +-100%. On the other hand,the non-scaling FFAG where all optical elements are essentially linear changes the betatron tunes during beam acceleration, Thus, fast resonance-crossing, that is, fast acceleration is essential in the non-scaling FFAG. The orbit excursion of non-scaling FFAG is rather small compared with that of scaling FFAG, therefore, small aperture magnets become available.

Fixed field alternating gradient (FFAG) accelerator has various advantages:

(1) Strong(AG) focusing in 3D space.

(2) Fast beam acceleration.

Strong focusing in 3D space means the transverse AG-focusing and the longitudinal phase focusing in rf acceleration. Static magnetic field gives the fast acceleration and also large repetition rate, which are useful for accelerating the short-lived particles such as muon, and also making an intense averaged beam current.

The idea of FFAG was brought by Okawa [1], Kerst and Symon [2], and Kolomensky [3], independently, in early 1950s. In MURA project of 1960s, a couple of electron models were developed, however, since then no practical FFAG accelerator had been for 50 years, and especially, the proton FFAG was not realized. In 2000, re-birth of FFAG has been brought with the world’s first proton FFAG (POP) which came out at KEK [4]. Since then, development of FFAGs has been implemented in many places [5], [6], [7], [8], [9] and many FFAGs have been constructed.

In this paper, I will summarize the experiences since 2000 till now and make some future prospects of FFAG accelerators.

BEAM OPTICS AND DYNAMICS

The betatron oscillation motion in horizontal and vertical directions can expressed in the following equation, respectively.

$$\frac{d^2x}{ds^2} + (\frac{1}{\rho^2} - K)x = 0. \qquad (1)$$

$$\frac{d^2z}{ds^2} + Kz = 0. \qquad (2)$$

Here, K is defined as a form with magnetic field gradient.

$$K = -\frac{1}{B\rho}\frac{\partial B_z}{\partial r}. \qquad (3)$$

In this section, the condition of zero chromaticity in betatron motions for FFAG are briefly summarized.

Circular case

Keeping the ”zero chromaticity” where the betatron tunes in transverse plane are constant for different beam momentum in the circular orbit ($s = r\theta$), the orbit similarity and constant geometrical field index must be satisfied.

$$\frac{d(r^2/\rho^2)}{dp} = 0. \qquad (4)$$

$$\frac{d(K\rho^2)}{dp} = 0. \qquad (5)$$

Originally, the concept of the FFAG was dedicated to the ring and the orbit excursion is developed horizontally. Recently, even in vertical direction, the zero chromaticity can be realized [10].

In case of the horizontal orbit excursion, the orbit similarity and constant geometrical field index required for satisfying the zero-chromaticity shown in the eqs.(3) and (4) lead the magnetic field configuration as shown in this formula.

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* mori@rri.kyoto-u.ac.jp

$$B(r,\theta) = B_0(\frac{r}{r_0})^k f(\theta - \zeta \ln \frac{r}{r_0}), \qquad (6)$$

where

$$\zeta = \tan \xi, \qquad (7)$$

and, ξ is a spiral angle. Leading from this magnetic field configuration in the cylindrical or circular orbit, there two types of beam optics allow to realize a zero-chromatic scaling FFAG:one is called the radial sector lattice and the other the spiral sector lattice. In the radial sector lattice, the AG focusing takes FODO with a negative bend gradient magnet. On the other hand, in the spiral sector lattice, the alternating focusing and defocusing can be realized with the edge effect. In case of the vertical orbit excursion, the zero-chromatic condition requires the following magnetic field configurations [10].

$$B = B_x + iB_y = \exp[k(y - ix)]. \qquad (8)$$

Straight case

In the ordinary circular scaling FFAG lattice assuming a azimuthal symmetry, there are some disadvantages; Large dispersion and orbit excursion require large horizontal apertures of the magnet the rf cavity, and the space of the magnet-free straight section is rather small for placing the injection/extraction devices and rf cavities. Having the long straight line keeping the scaling condition to satisfy the zero-chromaticity, these difficulties can be ovecome.

The equations describing the betatron motions in linear coordinates are expressed in eqs.(1). In order to satisfy the zero-chromaticity in this frame, the orbit curvature and the field index have to be constant. This leads the magnetic field configuration to be an exponential form shown as [11],

$$B_z = B_0 exp[(\frac{n}{\rho})x]. \qquad (9)$$

Using the scaling FFAG straight lattice, we could realize a dispersion suppressor and also matching insertion with the curved scaling FFAG lattice. For the dispersion suppressor, successive π-cells in the horizontal plane can suppress the dispersion.

In order to match the straight line with the circular ring FFAG lattice, the the 1st order (linear) matching condition expressed in eq. (6) has to be satisified between the straight and ring.

$$\frac{k+1}{r_m} = \frac{n}{\rho} \qquad (10)$$

Using a newly discovered scaling FFAG straight line, the design of scaling FFAG becomes more flexible and capable for various applications and the scaling FFAG opens a new advanced stage.

Acceleration

In rf acceleration, we also had an advancement in the scaling FFAG design. The beam acceleration in the scaling FFAG has some varieties because the momentum compaction is always strictly constant for different beam energies and has no higher orders. This situation takes either variable frequency of fixed frequency rf in beam acceleration. For the variable frequency rf acceleration, a broad-band rf cavity using magnetic alloys becomes feasible, which has actually been used for the world first proton FFAG (PoP-FFAG) at KEK. And, for the fixed frequency rf acceleration, the stationary bucket acceleration scheme can be useful for the relativistic high energy particle such as muon and electron.

For the fixed frequency rf acceleration, there was also a new advancement. In the strong focusing machine, the rf acceleration theory tells us that two rf buckets below and above the transition energy are interfered with some conditions, which was analyzed by Symon and Sessler in 1960s [12], and a serpentine acceleration path between two buckets is existed. The serpentine acceleration path was devoted to accelerate the relativistic particle in the non-scaling FFAG [13].

$$H = 2\pi m_0 c^2 [\frac{(\gamma_s^2 - 1)^\lambda}{2\gamma_s} \frac{(\gamma^2 - 1)^{-\lambda+1}}{(1-\lambda)} + \gamma] + \frac{eV_{rf} f_0}{h} \cos\phi, \qquad (11)$$

where

$$\lambda = \frac{k}{2(k+1)}. \qquad (12)$$

In the scaling FFAG, Hamiltonian describing the longitudinal particle motion can be analytically derived [14] as presented in eq. (11), and it shows a serpentine path accelerating either non-relativistic or relativistic particles exists. Thus, either lepton or hadron scaling FFAGs could use the scheme of serpentine acceleration.

PAST AND FUTURE

Numbers of FFAG accelerators have been either constructed or under development in the world last decade since the POP proton FFAG was developed in Japan. We summarize

Lepton FFAG

Muon phase rotation ring with FFAG optics to reduce the energy spread of muon beam called PRISM (Phase rotation Ring for Intense Slow Muons) has been developed at Osaka University for the experiment with μ-e conversion rare events where the lower limit of branching ratio should be less than 10^{-18} [15]. Before constructing full model, they have carried out the demonstration test of phase rotation for such large momentum spreading beam with α-particles [16]. Although the number of rf cavity is just one (in real experiment, five-six rf cavities are needed), still they have clarified the phase rotation in principle, and the experimental results show a good agreement with the results predicted by the beam simulation.

The world first non-scaling FFAG electron model of muon accelerator for future neutrino factory has been successfully developed recently in UK [13]. One of the unique features of this machine is beam acceleration using fixed frequency rf described above. The neutrino factory(NuFact) which devotes the lepton flavor international collaboration experiment with high energy neutrino beams is based on the muon accelerator complex with non-scaling FFAG [17]. As an injector of non-scaling FFAG, RLA is a candidate in the present design of NuFact . However, the RLA is a cost-driving accelerator, thus the scaling FFAG using stationary bucket or harmonic-number jump acceleration is also under consideration [18].

In industrial applications, two Japanese companies have developed the FFAGs so far. NHV Co. has recently developed an electron FFAG as a prototype for various applications such as sterilization, bonding polymers, etc. The beam energy is about 500keV and average beam current is about 20mA [19]. They have already completed the development and the performance is just they expected. Based on the success of the proto-type, in NHV Co., they have also started the development of a 10MeV electron FFAG using advanced scaling FFAG concept. In Mitsubishi Electric Co., a very compact electron accelerator based on the complex of FFAG and Betatron has been developed [20]. The specifications are shown in this table. The maximum beam energy is about 6MeV and the repetition rate is 1kHz. The average beam current of 200 μ A is expected. They have already demonstrated the operation of the machine and the performance was just as they expected.

Hadron FFAGs

After the success of the world first proton FFAG (POP), a higher energy proton FFAG was developed at KEK in 2004. The maximum energy of this machine was 150MeV. A very high repetition of 100Hz in operation has been demonstrated. This machine was moved to Kyusyu University in 2007 and is being to use as a multi-purpose machine for various application fields including the education of students, especially as a tool to accelerate the secondary particles such as isomers with their large beam emittance [21].

In Kyoto University, Research Reactor Institute(KURRI), the basic study of ADSR(Accelerator Driven Sub-critical Reactor has been carried out, combining FFAG proton accelerator and KUCA reactor. The 150MeV proton FFAG was installed at the newly constructed building called "Innovation Research Laboratory".

The 150MeV proton FFAG, which is composed of Injector, Booster and Main Ring, and they are all FFAG rings. The beam is transported from the FFAG to KUCA through the long beam transport line.

March in 2009, the first beam from the FFAG was successfully injected into the KUCA reactor and we have started the ADSR experimental studies [22]. Since the FFAG operates with 30Hz, prompt neutrons are created in every 33msec, then, the delayed neutrons amplified by nuclear fission reactions came out depending on the reactor sub-criticality.

The sub-criticality and their dynamical behaviors were measured and analyzed with PNM and Feynman-alfa methods, respectively. Both methods were very useful for detecting the sub-criticality of the ADSR system during operation. In 2010, another memorial ADSR experiment was carried out, which was the first ADSR experiment with thorium loaded core. A couple of upgradings on the machine performance are under development. The beam intensity has been successfully increased almost 100 times with charge-exchanged H^- ion beam injection [23].

Applications of the FFAG accelerators for medical use have been proposed in two different fields: hadron beam therapy and boron neutrino capture therapy. The FFAG accelerators are seen as good candidates for hadron therapy applications, with various potential advantages such as conformal spot scanning treatment with high repetition pulsed mode operation compared to cyclotrons or pulsed synchrotrons.

In France, the RACCAM project [24] has been initiated, which aims at producing a preliminary design study of a variable energy proton installation, based on a variable energy, 5 to15MeV H^- injector cyclotron followed by a spiral lattice FFAG ring with 70 to 180MeV extraction energy. Preliminary studies have lead to a project of a prototype proton therapy accelerator in the Antoine Lacassagne proton therapy clinic. In UK, the PAMELA project [25] for designing a hadron therapy accelerator has been funded to invoke the achievements of the non-scaling FFAG accelerator, EMMA.

A new type of compact neutron source called FFAG-ERIT(Emittance Recovery Internal Target) has been developed boron neutrino capture therapy at KURRI [26]. Neutrons are generated at the Be target placed internally into the proton FFAG storage ring. To suppress the emittance growth caused by Rutherford scatterings, ionization cooling with energy recovering is adopted. The FFAG-ERIT ring has worked nicely as expected. Neutron yield was measured with irradiation method and it was about more than 10^{13}n/sec [27], [28].

As described above, the unique features of FFAG compared with the ordinary accelerators are (1) Strong beam focusing in 3D space and (2) Fast beam acceleration. These features are obviously suitable for high intensity beam and also for very short lived particle accelerators. Moreover, especially in the scaling (zero chromatic) FFAG, the momentum acceptance is fairly large and it would be very useful for the secondary particle beam acceleration. Actually, these features are only to be provided by linac, not by ordinary ring accelerators such as cyclotron or synchrotron and practical fields in the application are the high intensity proton accelerator for ADSR and muon accelerator for Neutrino Factory/Muon collider. Recent studies on FFAGs, especially on the advancements of scaling FFAG, provides

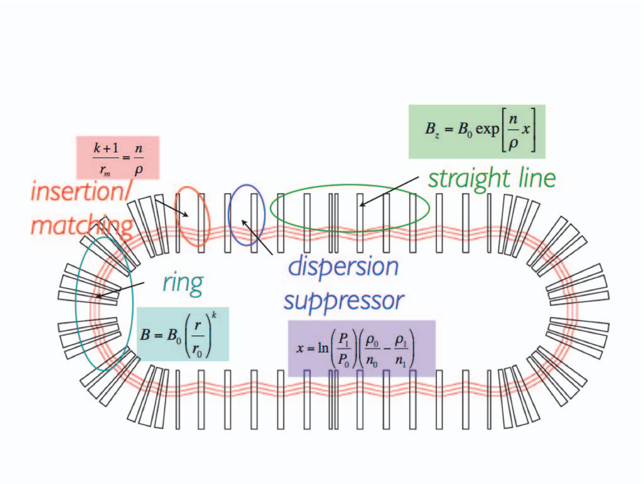

Figure 1: Schematic layout of advanced scaling (zero chromatic) FFAG [9].

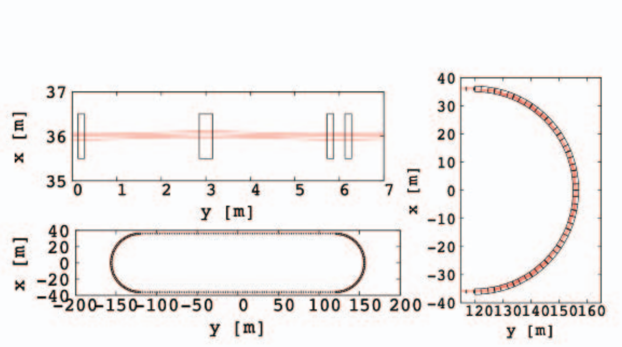

Figure 2: Design of a racetrack scaling FFAG for 3.8GeV/c muon decay ring [29].

very large capabilities for the applications in these fields. Advancements on the beam optics and dynamics are based on deep studies on zero chromaticity and flexible designs in 3D phase space become possible at the moment. In Fig. 1, a schematic layout of the advanced scaling FFAG racetrack ring is presented [9]. In beam acceleration, fixed frequency rf acceleration such as serpentine path, stationary bucket and harmonic-number jump accelerations become feasible, which allows very fast acceleration. Moreover, various rf gymnastics such as stacking, coalescing and multi-bunch acceleration can also be realized, which are very difficult for the linac. For example, one beam specification requested of the proton beam for ADSR and pulsed SNS is its time structure. The pulsed SNS requires a short pulse ($<0.5\mu$sec) and relatively low repetition proton beam. On the other hand, the beam time structure for the ADSR is rather modest and a relatively higher repetition rate (>100Hz) is favorable to avoid thermal shock on the target. The types of accelerator which could satisfy both these requirements simultaneously are a proton linear accelerator (LINAC)/proton storage ring(PSR) complex, or a fixed field alternating gradient(FFAG) accelerator. Neither a cyclotron or synchrotron can be used. A LINAC/PSR complex is a straightforward solution but very expensive. In muon acceleration, the FFAG accelerator is useful because of its capabilities of strong beam focusing and very fast acceleration. Muon accelerator and muon-decay storage ring should be the most useful applications of FFAGs. Figure 2 shows an example of muon-decay ring with advanced scaling FFAG [29].

SUMMARY

The various experiences of FFAG accelerators in the different projects after the FFAG accelerator was rebirth in 2000 with the development of the world first proton FFAG (POP) are summarized. Future prospects based on the recent advancements of FFAGs such as zero-chromatic straight line, dispersion suppressing and serpentine acceleration are also described.

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REFERENCES

[1] T. Ohkawa, Workshop at annual meeting of JPS, 1953.

[2] K.R. Symon, D.W. Kerst et al., Phys. Rev 103(1956)1837.

[3] A.A. Kolomenski, "Theory of Circular Accelerators", 1966, p.340.

[4] Y. Mori et al., Proc. of 12th Symp. on Accelerator Science and Technology(1999), Wako, Japan.
Aiba et al., Proc. of EPAC2000(2000), Vienna, Austria, pp.581-583.

[5] D. Trbojevic, Proc. of Int. Workshop on FFAG Accelerators(FFAG04), KEK, Tsukuba(2004)pp9-10.

[6] A. Ruggiero, Proc. of Int. Workshop on FFAG Accelerators(FFAG04), KEK, Tsukuba(2004)pp53-61.

[7] S. Berg, Proc. of Int. Workshop on FFAG Accelerators(FFAG04), KEK, Tsukuba(2004)pp1-9.

[8] C. Johnstone et al., J. Modern Physics A, 26(2011)1690.

[9] Y.Mori, J. Modern Physics A, 26(2011)1744.

[10] S. Brooks, Proc. of IPAC'11, 2011.

[11] J.B. Lagrange et al., Proc. of PAC'09(2009), Vancouver, Canada.

[12] K.R. Symon, A.M. Sessler, Proc. Int. Conf. High Energy Acc. (1956), p.44.

[13] S. Machida et al., Nature Physics,8(2012)243.

[14] E. Yamakawa et al., Proc. of FFAG09(2009), FNAL, Chicago, USA.

[15] LOI (The PRISM Project) for Nuclear and Particle Physics Experiments at the J-PARC(2003).

[16] A. Sato et al.,Proc. of EPAC2004(2004), Edingburgh, Scotland, pp.2508-2510.

[17] Neutrino Factory Design Group, IDS-NF, 2011.

[18] T. Planche et al., Proc. of PAC'09(2009), Vancouver, Canada.

[19] T. Baba et al., Proc. of EPAC08(2008), Genoa, Italy, pp.3371-3373.

[20] H. Tanaka et al., Proc. of Cyclotorons 2004 (2004), Tokyo, Japan.

[21] Y .Yonemura et al., Proc. of EPAC08(2008), Genoa, Italy, pp.3523-3525.

[22] C.H. Pyeon et al., Journal. of Nucl. Scie. and Tech., Vol.46 No.12, pp.1091-1093(2009).

[23] T. Uesugi et al., Proc. of EPAC08(2008), Genoa, Italy, pp.1013-1015.
Y. Ishi et al., Proc. of IPAC'10(2010), Kyoto, Japan, pp.1327-1329.

[24] S. Antoine et al., Nucl. Instr. Meth., A602(3)(2009)pp.293-305.

[25] T. Yokoi, Inter. Journal of Modern Physics A, 26(2011)1887.

[26] Y. Mori, Nucl. Instr. Meth., PRS, A563(2006) 591-595.

[27] K. Okabe et al., Proc. of IPAC'10(2010), Kyoto, Japan, PP3897-3899.

[28] Y. Mori, Proc. of PAC'09(2009), Vancouver, Canada.

[29] JB. Lagrange and Y. Mori; INTERNAL REPORT, acc-kurri-0508-02-2012, KURRI, 2012.