DEVELOPMENT OF FFAG ACCELERATORS IN JAPAN

Y.Mori, K.Okabe*
Kyoto University, Research Reactor Institute, *Fukui University, Dept. Engineering.

Abstract

Recent development of FFAG accelerators and their applications in Japan are described.

INTRODUCTION

The scaling type of FFAG accelerator has unique features compared with other types of accelerator. The features of the scaling type of FFAG accelerator can be summarized by the following distinctive characteristics: (1)Strong focusing: The FFAG accelerator has strong focusing characteristics in the beam optics in all directions: Alternating gradient (AG) focusing in the transverse direction and phase focusing with rf acceleration in the longitudinal direction. (2)Moving orbit: The magnetic field in the FFAG accelerator is static; therefore, the beam orbits move during acceleration. This is like a cyclotron but not as pronounced because the magnetic field gradient is fairly large. (3)Zero chromaticity: Because of the strong focusing behaviour as described above, a betatron resonance is a harmful problem in the beam optics. To avoid resonance crossing which leads to beam loss, the betatron tunes should remain constant during acceleration.

Various advantages exist in FFAG accelerators compared with other accelerators such as cyclotron and synchrotron. Since the magnetic field is static, there is no need to synchronize the RF pattern with the magnetic field. This results in a high repetition rate for the beam acceleration with a modest number of particles in the ring. Thus, high average beam current becomes available because space charge and collective effects are below threshold. Very large acceptances for horizontal and longitudinal directions are also possible for the FFAG. A typical value of the horizontal acceptance is 10,000 π mm.mrad and the momentum acceptance becomes some tens of percent.

High beam current allows a new type of proton or electron driver. Fast acceleration and large acceptance may open the door for acceleration of short-lived particles such as muons, unstable nuclei, etc. A neutrino factory based on a muon accelerator and storage ring has been seriously discussed recently, and the FFAG accelerator is conceived as a most promising way for muon acceleration up to several tens of GeV.

The idea of the FFAG accelerator was originally conceived by Ohkawa in 1953 [1]. The first electron model of an FFAG was developed by Kerst, Cole and Symon in the MURA accelerator project in the late 1950s and several electron models were constructed in the early 1960s [2]. However, since then no proton and practical FFAG accelerator has been built until recently, mainly because of technical difficulties.

One of the technical problems was its complicated magnetic field configuration. The magnetic field is totally nonlinear to meet the optical constraints such as zero chromaticity adequately. The magnet design must, therefore, be accomplished with 3D magnetic field calculation. This problem has been overcome by 3D field simulation codes such as TOSCA-OPERA with recent fast computers.

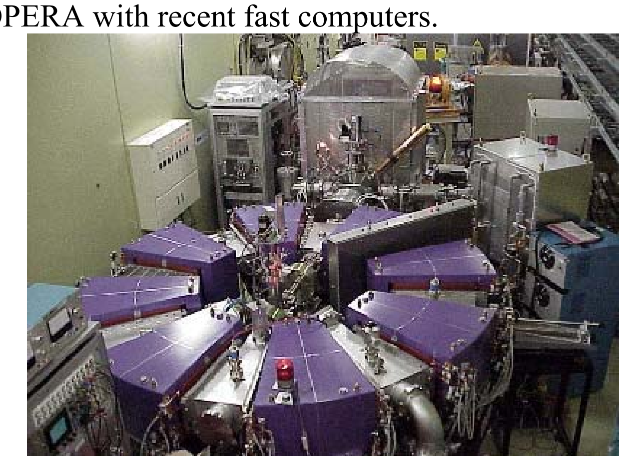


Figure. 1: POP-FFAG accelerator.

The other difficulty was rf acceleration. In the electron models at the MURA project, the beam acceleration was mostly with induction and/or a fixed frequency system. In order to accelerate heavy particles such as protons, a variable frequency rf system is essential. Moreover, since room for the rf acceleration system in the ring of an FFAG accelerator is normally limited because of its compactness and high super-periodicity, a rather high rf field gradient is necessary. These requirements are difficult for an ordinary tuned rf cavity like a ferrite-loaded cavity, which is commonly used in a proton synchrotron. For a proton FFAG accelerator, a broad band and high gradient rf cavity is required. A new type of rf cavity developed at KEK in Japan [3] made it possible to overcome this problem. This type of rf cavity uses a high permeability magnetic alloy (MA) such as FINEMET. The rf characteristics and performance of MA have proved suitable for use in rf cavities in a FFAG proton accelerator.

In 1999, the world's first proton FFAG accelerator was demonstrated at KEK [4, 5]. Named POP-FFAG, it is shown in Figure 1. The POP-FFAG accelerates protons from 50 keV to 500 keV within 1 msec. Following this success, it has been recognized that FFAG accelerators have advantages in rapid acceleration with large momentum acceptance, which are needed both for muon accelerators and for high power proton drivers. Since then, intensive studies and discussions have been undertaken and various novel ideas have emerged. Research and development of FFAG accelerators for many applications are also in progress at many institutes.

SCALING FFAGS

In scaling FFAG accelerators like POP-FFAG, each beam orbit for different beam momenta has similarity in shape (curvature), and zero chromaticity in the beam optics is realized. Thus, the betatron tunes for both horizontal and vertical directions are constant during beam acceleration avoiding any problems from resonance crossing. In cylindrical coordinates, it can be shown analytically that the configuration of the magnetic field at the median plane can be expressed by the following equation [6]:

$$B(r,\theta) = B_0\left(\frac{r}{r_0}\right)^k f\left(\theta - \varsigma \ln\frac{r}{r_0}\right) \tag{1}$$

where $\zeta=\tan\xi$, and ξ is a spiral angle of the magnet in the azimuth plane. Accordingly, two schemes for beam focusing are invoked by this magnetic field configuration: one is radial sector focusing and the other spiral sector focusing. Radial sector focusing uses a combination of positive and negative bending magnets to create strong beam focusing with a FODO lattice configuration. In spiral sector focusing, edge focusing is used efficiently. For the POP-FFAG, a radial focusing DFD lattice was adopted. In order to design the beam optics for the POP-FFAG, we applied a linearised model [7] as the first step, which was verified by particle tracking for the hard edge magnet configuration.

One of the difficulties of designing the optics in the real FFAG machine is how to treat the effect of the fringing field of each magnet. In the FFAG accelerator, either for radial sector or spiral sector designs, the beam focusing includes the edge focusing in its structure. Therefore, careful consideration and designing for the effects of the fringing fields become very important and in practice 3D field calculations and beam tracking simulations are essential, although they are the most time consuming part of the design. Various 3D field simulation codes are available; we have been using TOSCA-OPERA.

The scaling type of FFAG accelerator has a large acceptance both in transverse and longitudinal directions. In the transverse direction, especially in the horizontal direction, the physical aperture must be large because the beam orbit should move as a function of the beam momentum. Nonlinear magnetic field components are inevitable in the scaling type of FFAG accelerator having zero chromaticity and the dynamic aperture is reduced by the nonlinear fields. If the phase advance of the betatron oscillation for each cell in both the horizontal and vertical directions is chosen to be less than 90 degrees, the effects on the dynamic aperture caused by sextupole and octupole fields can be eliminated. The horizontal dynamic aperture estimated by beam tracking for the POP-FFAG was more than 5,000 π mm.mrad.

In order to realize a scaling type of proton FFAG accelerator, various technical difficulties have to be overcome. Especially for heavy particles such as protons, a broad band and high gradient rf acceleration system working at relatively low rf frequency is necessary.

This type of rf system is very difficult to realize with an ordinary rf acceleration system using ferrite. A new type of rf cavity using high permeability magnetic alloys (MA cavity) has been developed to solve these problems. increased by making core cut if necessary.

The high permeability magnetic alloys, in general, have a large saturation field and the permeability is very large even at high field, compared with ferrite. Therefore, a high μQ value is realized although the Q value itself is relatively small. The μQf stays constant even at large rf field.

Figure. 2: Kyoto University FFAG

To achieve zero chromaticity, the magnets used in FFAG accelerators should be gradient magnets to satisfy the magnetic field configuration as described above. Several ways to realize such a type of magnet have been proposed: (1)Tapered gap, (2)Flat gap with surface coils and (3) Cos(theta)-like magnet.

In triplet focusing structures, such as DFD in a radial sector FFAG accelerator, the return yoke of the centre magnet can be eliminated because the field directions for F and D magnets are opposite to each other. This type of magnet is called a “Return Yoke-Free Magnet”, and has been used for the 150-MeV FFAG accelerator developed at KEK, described below. The magnet of the FFAG accelerator is DC, so a superconducting magnet seems to be interesting. To make a proper field gradient, a multilayer coil with single winding technique can be applied. The multilayer coil type of superconducting magnet was also developed at KEK [8].

Beam dynamics of resonance crossing have been studied on the POP-FFAG accelerator [9]. Crossing $3Q_x = 7$ has been examined (the super-periodicity is eight), and the islands in phase space move outward in this case. Then some particles are trapped by the islands and carried away to large amplitude.

We confirmed experimentally that (non-structural) third order resonances could be crossed without beam loss. It is clear that the crossing speed alone is not enough to describe resonance crossing. Not only should the crossing speed be fast enough but the resonance width should be sufficiently narrow to avoid a deterioration of beam emittance due to resonance crossing.

DEVELOPMENT OF A 150MEV FFAG ACCELERATOR

A 150 MeV proton FFAG accelerator, which is expected to be a prototype FFAG accelerator for various applications such as proton therapy and an accelerator-driven reactor, has been developed at KEK [10-15]. The machine was designed in 2000, assembled and finally commissioned in March 2003. The similarly designed 150MeV FFAG accelerator has been also constructed at Kyoto University for ADS experiment. Figure 2 shows a picture of the 150 MeV FFAG at Kyoto University.

From the machine development point of view, beam extraction and rapid cycling operation were important subjects to explore in order to judge the potential of an FFAG for various applications. The experimental results for these topics are described in the following sections.

An FFAG has an ability to generate a high repetition pulse beam as long as the rf voltage allows since its guiding fields are constant in time. That increases the average current in general. Particularly for medical applications, a pulsed beam of time structure with several hundred Hz is desirable for cancer therapy treatment using a spot scanning technique.

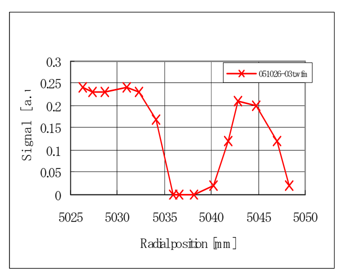
The rf cavity to achieve high repetition, say 100 Hz, was however still a big challenge; high field gradient and rapid frequency variability and large horizontal aperture to accommodate beam orbits have to be fulfilled. A possible solution is the so-called MA (Magnetic Alloy) cavity, which works in the MHz band and has a low Q-value. After many tests and improvement, we finally established an rf system which can provide ~6 kV (~35 kV/m) rf continuously [16].

Beam extraction has been performed for the first time at the 150 MeV FFAG. The extraction scheme is the fast extraction commonly used in synchrotrons. A kicker magnet and a septum magnet should work at 100 Hz as well. We use an air-cored magnet as a kicker. The required kicker strength is about 500~600 Gauss with length of 0.6 m. The maximum voltage and current of the kicker power supply are 70 kV and 2000 A, respectively. The switching part is a MOSFET (Metal Oxide Semiconductor Field-effect Transistor) array. The extraction septum magnet is a pulsed magnet with a fringing field suppression plate whose thickness is less than 3 mm. The field of the septum magnet is about 4-5 kGauss with a length of 0.5 m. High extraction efficiency with these devices was expected.

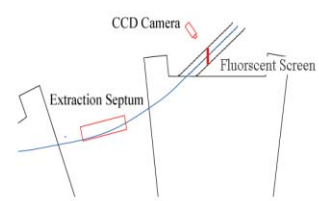
The experimental results at beam extraction with 100 Hz operation are shown in Fig. 3. We compared beam currents in the ring and at the extraction line. The extraction efficiency was measured as more than 90%.

One of the critical beam dynamics issues was resonance crossing. It was identified at an early stage of the beam commissioning. While the principle of a scaling FFAG gives a zero chromaticity condition, betatron tunes would not be exactly constant over the momentum from injection to extraction due to fringe fields and field saturation effects. The design horizontal tune was above the resonance of $3Q_x=11$ but it turned out to be slightly below the resonance in practice. Consequently, the horizontal tune has to cross the third order resonance during acceleration.

In the crossing of $3Q_x=11$ in the 150 MeV FFAG, the islands in phase space are initially located at a very large amplitude. They come close and penetrate the beam as the resonance is crossed, and finally disappear after crossing. When the crossing is fast compared to the particle motion in phase space, the islands disappear without deteriorating the beam emittance. When the crossing speed is relatively slow, the particles can reach large amplitude and be lost at the injection septum since the tune

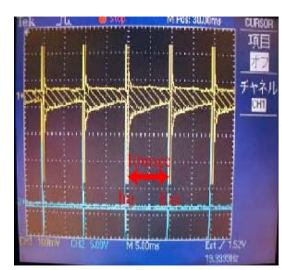


(a) measured beam



(b) setup of screen monitor and camera

(c) beam on screen



(d) beam signal of 100 Hz

Figure 3: Results of the beam extraction

crosses resonance at a beam energy slightly above that at injection.

EMITTANCE RECOVERY INTERNAL TARGET (ERIT) WITH FFAG

As one of the secondary particle sources, an accelerator-based intense thermal or epithermal neutron source has been strongly requested recently. Only the intense source for such neutrons which has used so far is a nuclear reactor. The expected neutron yield from the accelerator-based neutron source should be about 10^{13}-10^{14} n/cm^2/sec, which could be effectively comparable with that from a 5-10MW class nuclear reactor such as Kyoto University research reactor (KUR). In the ordinary accelerator-based neutron sources, ^{7}Li(p,n)^{7}Be or ^{9}Be(p,n)^{9}B reactions with low energy (~10MeV) protons have been commonly used. The ordinary accelerator-based neutron sources use a cyclotron or proton linac. The accelerated protons are extracted from the accelerators and hit a thick Li or beryllium target placed outside of the accelerators. To obtain such a high neutron yield, the extracted proton beam current should be more than 100mA.

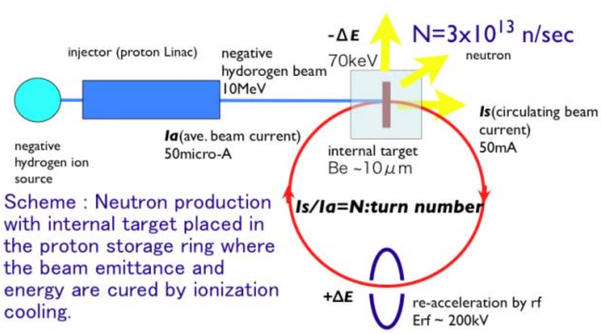
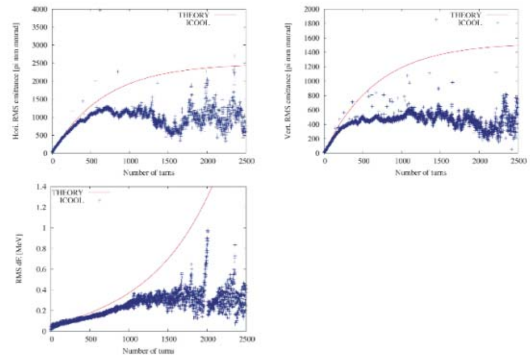
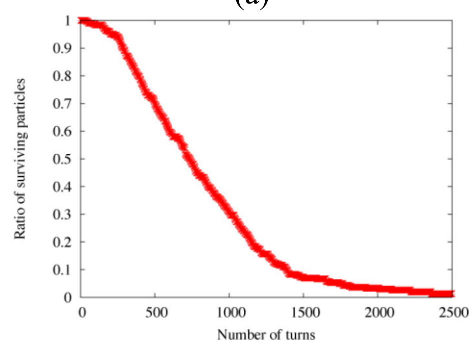


Figure 4: Schematic layout of ERIT.

As for BNCT medical applications, an accelerator-based intense thermal or epithermal neutron source has been strongly requested recently. A scaling type of FFAG accelerator with ERIT (energy/emittance recovery internal target) concept has been proposed for this purpose and is now under construction.[17,18] Figure 4 shows a schematic diagram of ERIT.



(a)



(b)

Figure 5: Transverse and longitudinal emittance growth in ERIT.

The circulating current of the beam inside of a strong focusing ring accelerator such as FFAG accelerator is fairly large because the same beam bunch orbits the ring many times with large revolution frequency. For example in case of neutron production, when 1×10^{11} protons at 10MeV orbit inside of a ring of circumference 10m, the circulating beam current in the ring reaches 70mA. The number 1×10^{11} protons per bunch is relatively modest for such strong focusing proton accelerators of this energy. If a neutron production internal target such as beryllium thin foil is inserted into the ring and the beam hits the target efficiently, the neutron yield should become comparable with that from a nuclear reactor.

In this scheme, however, the incident proton beam will be lost from the ring very quick because the beam energy of the incident protons is lost to ionization of the target atoms turn by turn, and also because the beam emittance in transverse and longitudinal directions are blown up by multiple scatterings with the target electrons. These deleterious effects, however, can be cured by ionization cooling.[19,20,21] The transverse emittance reaches equilibrium because of ionization cooling which is invoked in this energy recovery internal target scheme. For a 11MeV proton beam with 5μm beryllium target, the transverse emittance reaches to be about 2500mm.mrad(rms) after 2,500 turns as shown in Fig. 5-(a). In reality, the beam life is limited by the vertical acceptance of the beam. The beam simulations have been carried out with ICOOL and the results are also shown in Fig. 5-(a). The figure 5-(b) presents the particle survival as a function of turn number. It can be seen from this figure, the average number of turns for beam survival is about 900 turns.

On the other hand, since there is no cooling effect expected in the longitudinal direction, a large energy spread is inevitable. For example, after 1,000turns using the same beryllium target described above, the energy spread of the 10MeV proton beam can be about 10%.

In order to circulate such a large transverse and longitudinal emittance beam in the ring, the FFAG accelerator seems to be one of the most suitable accelerators. The FFAG has very large acceptance, especially in momentum space, compared with other types of the ring accelerators, because zero chromaticity in the beam focusing is fulfilled. Moreover, the FFAG is the ring that has the functions both of acceleration and storage, which can be an ideal for the internal target type of secondary particle source and it may be applied for generating not only for neutrons but for other particles such as pions, although the ionization cooling efficiency is small.

SUMMARY

Recent progress of FFAG accelerators are very impressing. Quite few scaling type of FFAG accelerators have been built and commissioned for various applications. One of the interesting applications is an intense secondary particle source with an ERIT (emittance recovery internal target) scheme. An intense neutron source with ERIT for BNCT is under development in Japan.

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