Developments of FFAG Accelerator

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Abstract. Development of the FFAG accelerators in the various places are reviewed.

1. INTRODUCTION

The FFAG(Fixed Field Alternating Gradient) accelerator has unique features compared with other types of accelerator and they could be summarized with the following distinctive aspects;

(1) Strong focusing: The FFAG accelerator have strong focusing characteristics in the manner of beam optics for 3-D directions: Alternating gradient (AG) focusing in the transverse direction and phase focusing with rf acceleration in the longitudinal direction.

(2) Moving orbit: The magnetic filed in FFAG accelerator is static, therefore, the beam orbits are moving during acceleration. This is more like cyclotron but not much as it because the magnetic field gradient is fairly large.

(3) Zero chromaticity: Because of the strong focusing behavior in the beam optics as described above, resonance crossing, which could birng beam losses, is a harmful problem from the beam optics point of view. To avoid resonance crossing, the betatron tunes should be kept constant during acceleration.

Various advantages compared with other accelerators such as cyclotron and synchrotron exist in the FFAG accelerators . Since the magnetic field is static, the beam acceleration could be allowed only by RF pattern. There is no need to synchronize a RF pattern with magnetic field. This results a high repetition rate of beam acceleration with modest number of particles in the ring. High average beam current, therefore, can be available because space charge and collective effects become below threshold.

Very large acceptance for horizontal and longitudinal directions are also possible for FFAG. Typical value of the horizontal acceptance is 10,000mm.mrad and the momentum acceptance becomes more than several 10%.

High beam current and large acceptance allow a new type of proton or electron driver. Fast acceleration and large acceptance can also open a window for acceleration of short-lived particles such as muon, unstable nuclei, etc. Recently, neutrino factory, in paticular, based on muon accelerator and storage ring has been seriously discussed. It is conceived that FFAG accelerator should be a possible candidate to accelerate muons efficiently up to several 10GeV.

The idea of FFAG accelerator was originally brought by Ohkawa in 1953. The first electron model of FFAG accelerator was built by Kerst, Cole and Symon at MURA in late 50s and following that. several electron models were constructed. However, since then, no practical FFAG accelerator has ever been built until recently. In paticular, proton FFAG has been never developed because of several severe technical problems.

One of the difficulties to make a proton FFAG accelerator in reality was its complicated magnetic field configuration. In the ordinary FFAG accelerator (scaling type), the betatron tunes should be kept constant during the beam acceleration to avoid the resonance crossing which may cause beam losses. The magnetic field, therefore, should be designed properly including nonlinear field components to keep the betatron tunes constant, which is so called “zero chromaticity”. This could be overcome, now a days, by 3-D field simulation codes such as TOSCA with recent fast computers.

The other difficulty was rf acceleration. In the electron models at MURA, the beam acceleration was carried out by mostly induction and/or fixed frequency rf system because they accelerated electrons. In order to accelerate heavy practices such as proton, variable frequency rf system is necessary. In addition, the room for rf system in the ring is normally limited because of its compactness and high super-periodicity. Thus, rather large field gradient in the rf cavity is necessary. It is difficult for an ordinary tuned rf cavity like a ferrite-loaded cavity, which has been commonly used in proton synchrotron, to satisfy these conditions. For a proton FFAG accelerator, broad band and high gradient rf cavity is

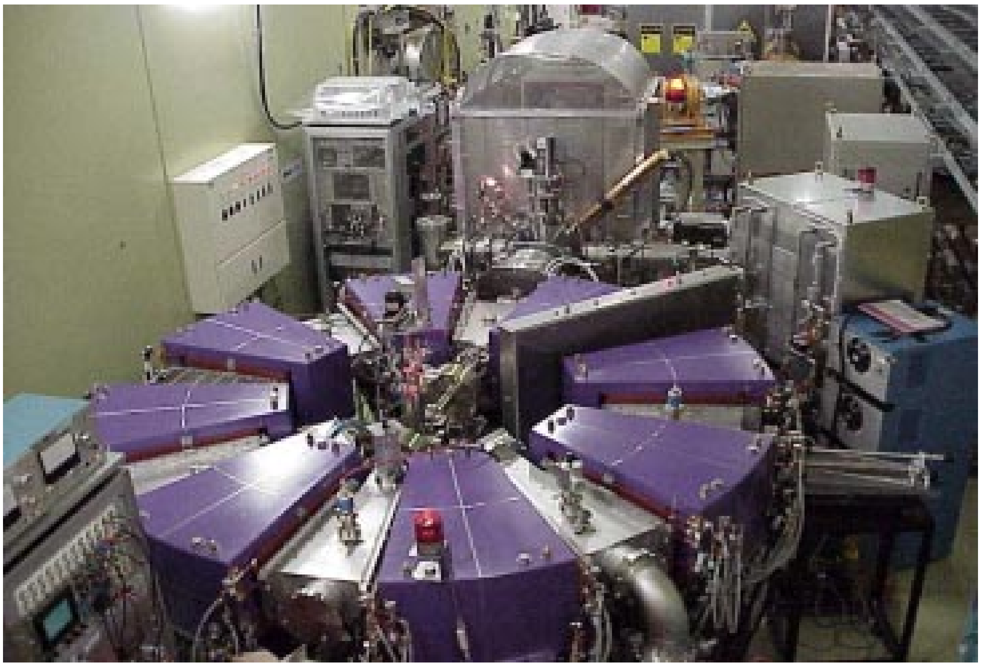


Fig. 1 PoP FFAG accelerator.

requested.

A newly developed rf cavity has 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 been just suitable for an rf cavity of FFAG proton accelerator.

In 2000, the world first proton FFAG accelerator has been demonstrated at KEK. We name it POP-FFAG. Figure 1 shows a picture of POP-FFAG. The POP-FFAG accelerates proton from 50keV to 500 keV within 1msec.

2. SCALING FFAG

Until recently, the FFAG accelerator means an accelerator having a static magnetic field with zero chromatic beam optics. Thus, the magnetic field has to be non linear. However, if very large acceleration is possible, the constraints of zero chromaticity may be broken, which means a linear lattice configuration, because the betatron resonances even linear resonances could be passed safely. Thus, now a days, the FFAG accelerator which satisfy the zero chromatic beam optics is called :Scaling" and the other "Non-scaling".

The scaling FFAG is based on zero chromatic beam optics using non-linear field. In the transverse direction, the beam behavior is affected by non-linear field. On the other hand, since the momentum compaction factor of the scaling type of FFAG does not depend on the beam momentum, the longitudinal beam motion becomes quite linear at high energy. On the other hand, in the non-scaling FFAG, linear magnetic field in transverse beam optics is exploited. The betatron resonance crossing, therefore, is inevitable. Moreover, the longitudinal beam dynamics becomes strongly nonlinear.

The design procedure of the scaling type of FFAG which has been undertaken at KEK is shown below.

The transverse beam behaviors of the scaling type of FFAG accelerator are characterized with zero chromatic optics. In the ring accelerator, the transverse beam motions are described by the betatron equations derived by Kerst.

$$\begin{aligned} x'' + g_x x &= 0 \\ z'' + g_z z &= 0 \end{aligned},$$

where

$$
\begin{aligned}
g_x &= \frac{K^2}{K_0^2}(1-k), \\
g_z &= \frac{K^2}{K_0^2}k.
\end{aligned}
\qquad .
$$

Here, k is a magnetic field index looking from the machine center and it is sometimes called “geometrical field index”, and K is local curvature of the beam orbit.

In the betatron equations, obviously, the following two conditions must be fulfilled to accomplish zero chromatic optics.

$$
\begin{aligned}
&\frac{\partial}{\partial p}\left(\frac{K}{K_0}\right)_{\theta = const} = 0, \\
&\frac{\partial k}{\partial p} = 0.
\end{aligned}
\qquad .
$$

The following magnetic field configuration in the cylindrical coordinate can satisfy the above zero-chromatic condition.

$$
B(r,\theta) = B_i\left(\frac{r_i}{r}\right)F\left(\theta - \varsigma \ln\frac{r}{r_i}\right).
$$

Here, z = tan x, and is a spiral angle of the magnet in azimuthal plane. According from the magnetic field configuration, the two types of the transverse focusing in the FFAG accelerator have been conceived; One is radial focusing and the other spiral focusing. The one which Ohkawa has proposed in 1953 was radial focusing. The radial focusing uses negative bend magnets to make a strong focusing FODO lattice configuration. In the spiral focusing, the edge focusing is invoked efficiently.

Design Procedure

The magnetic field of the scaling type of FFAG accelerator is totally nonlinear as shown in eq.(4). The exact beam optics parameters, therefore, can be obtained with beam tracking simulation. As the first step of the optics design in the

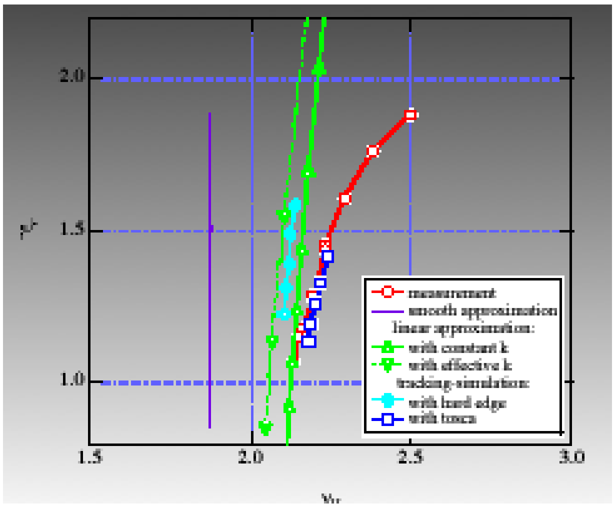


Fig.2 linear, hard edge, tracking

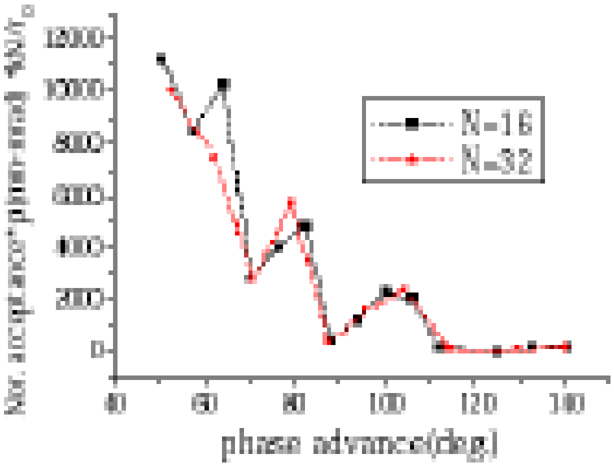


Fig.3 Dynamic apertures

Fig. 4 MA core for rf cavity.

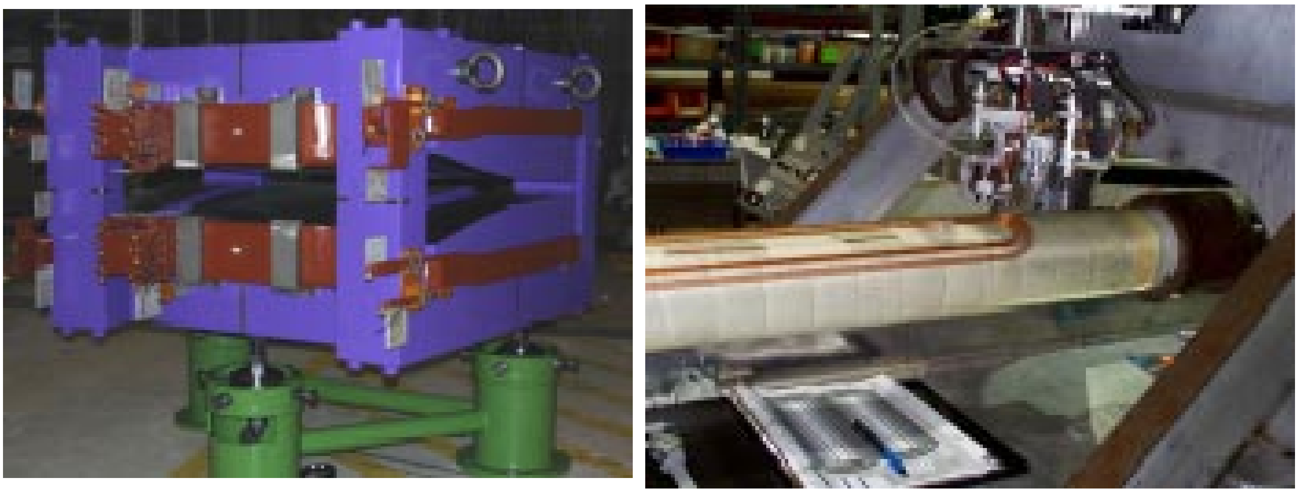
FFAG accelerators, we set a linearized model in which the magnets are all treated as combined function type. The orbit curvature in the magnet is constant and the field index around this orbit can be expressed with a circumference factor, h=r/r, where r is a mean radius of the orbit measured from the machine center. In the case of the radial focusing sector with DFD triplet configuration, the linearized parameters can be defined in ref.1. The similar modeling can also be done for a spiral focusing sector type of the FFAG accelerator. [1]

The green colored triangles in Fig. 2 show the calculated betatron tunes with a linearized model of the POP-FFAG for the different F/D ratio. The particle tracking results for the hard edge magnets where the magnetic field configurations are just as shown in eq. 5 are also shown in this figure as cobalt blue colored rectangular. The difference between the linearized model and the beam tracking with hard edge magnets are relatively small. Thus, the linearized model seems to work as the first step of optics design for the FFAG accelerator.

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, the beam focusing includes natively the edge focusing in its structure. Therefore, the careful consideration and designing for the effects of the fringing fields becomes very important and practically, 3D field calculations and beam tracking simulations are essential although they are most time consuming part in the design works. Various 3D field simulation codes are available in these days but we have been using a TOSCA-OPERA so far.

The results with the 3D field calculation with TOSCA-OPERA for the POP-FFAG are shown in Fig. 2 with blue colored open squares. The difference from the no-fringe hard edge model is obvious. Also, the measured betatron tunes in the POP-FFAG are shown in the figure with red colored open circles. The agreement between the measurement and design based on 3D field simulation is very impressive.

One of the features of FFAG accelerator is its large acceptance both in transverse and longitudinal directions. Since the FFAG accelerator includes as its nature very different momentum orbits in the same ring, the longitudinal acceptance becomes very large. In the transverse direction, especially in horizontal direction, the physical aperture must be large because the beam orbit should move as a function of the beam momentum. The nonlinear magnetic field components are inevitable in the scaling type of the FFAG accelerator to have zero chromaticity and the dynamic aperture should be suffered by the nonlinear fields. The lattice configuration in the FFAG accelerator is very symmetric, which means that the lattice should consist of the same cells placed periodically and the superpreodicity becomes very large. If the phase advance of the betatron oscillation for each cell in both horizontal and vertical direction is chosen less than 90 degree, the



(a)Yoke-free (b)Super conducting

Fig. 5-a,b Types of Magnets.

effects to the dynamic aperture caused by sectupole and octapole fields can be eliminated.

In Fig. 3, the dynamic apertures estimated by beam tracking are shown as a function of the phase advance per cell. As can be seen from this figure, the dynamic aperture becomes very large for the phase advance of less than 90 degree.

Hardwares

In order to realize a scaling type of the FFAG accelerators such as POP-FFAG, efforts for the hardware developments had to be done to overcome the various technical difficulties. Here, the developments of a broadband and high gradient rf cavity and various types of the magnets which could satisfy the field configurations in the scaling type of FFAG accelerator.

A. Broad band and high gradient rf cavity

The rf acceleration, especially for heavy particles such as proton, a broad band and high gradient rf acceleration system working at relatively low rf frequency is necessary. The requirements of the rf cavity for heavy particle acceleration are summarized as follows.

1)Broad band: The frequency sweep of a factor is needed.
2)High gradient: The high field gradient makes it fast acceleration possible.
3)Large aperture: The large aperture, especially in horizontal, can accommodate orbit excursion.
4)Large longitudinal acceptance: The frequency of a few MHz provides to have large longitudinal acceptance.

This type of the rf system is very difficult to realize with an ordinary rf acceleration system with ferrite loaded rf cavity used in proton synchrotron. The new type of rf cavity using the high permeability magnetic alloys (MA cavity) has been developed to solve these problems.

Characteristics of magnetic alloy are summarized as follows.

1) Large permeability: ~2000 at 5MHz
2) High Curie temperature: ~570 deg.
3) Thin tape : ~18micron
4) Small Q value : ~0.6. The Q value can be increased with cutting core if necessary.

The high permeability magnetic alloys, in general, has a large saturation field and the permeability is very large even at high field compared with ferrite. Therefore, the high mQ value is realized although Q value itself is relatively small. The mQf stays constant even at large rf field. Figure 4 shows a MA core for the FFAG proton accelerator under development at KEK.

B. Gradient magnet

To make zero chromaticity, the magnet used in FFAG accelerators should be a gradient magnet. There have been proposed several ways to realized such type of magnet.

1) Tapered gap (Fig. 5-a): The magnet pole shape has a configuration of large gap in side and small gap outside.
2) Flat gap with surface coils : The gradient magnetic field can be generated by trim coils on the flat gap of the magnet.
3)Cos (theta) like magnet

In the triplet focusing structures such as DFD of the radial sector FFAG accelerator, the return yoke of the center magnet can be eliminated because the field directions for F and D magnets are opposite each other. This type of the magnet is called " Return Yoke Free Magnet", which has been used for the FFAG under development at KEK.

The magnet of the FFAG accelerator is DC, therefore, the superconducting magnet seems to be interesting. To make proper field gradient, multilayer coil with single winding technique can be applied. The multilayer coil type of super conducting magnet is under development at KEK as shown in Fig.5-b.

3. R&D ACTIVITIES IN JAPAN

Three new projects with FFAG accelerators are going on in Japan; (1) Proton FFAG accelerator at KEK, (2) FFAG accelerator for accelerator driven system(ADS) at Kyoto Univ., and (3) Muon phase rotation with FFAG ring at Osaka Univ. I will describe briefly about these projects in this paper. There have been also proposed other future projects such as hadron beam therapy, electron source for sterilization, neutron source for BNCT and muon accelerator for neutrino factory.

Proton FFAG Accelerator at KEK

After the success of the PoP-FFAG which is the world first proton FFAG accelerator, a proton FFAG accelerator whose maximum energy is 150MeV has been developed at KEK. This proton FFAG accelerator aims to be a prototype for various applications such as proton beam therapy.

The schematic layout of the proton FFAG accelerator is shown in Fig. 6. The average radius of the FFAG accelerator

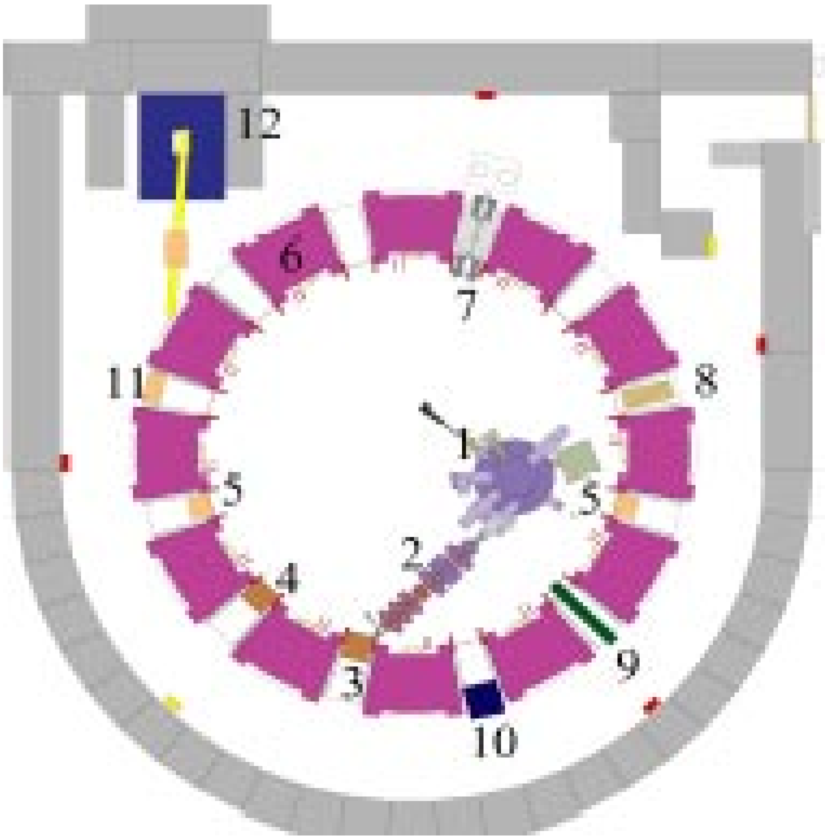


FIg. 6 Proton FFAG accelerator developed at KEK.

is about 4.5m. The maximum attainable energy in this ring is about 150MeV where the injected beam energy should be 12MeV. A compact cyclotron is used as an injector. The basic parameters of the FFAG accelerator are shown in Table 1.

Table 1 Main parameters of the proton FFAG accelerator.

# of secotrs	12
Field index	7.5
Energy	12-150MeV
Repetition rate	125(250)Hz
Clossed orbit radius	4.4-5.3m
Betatron tunes	
Hor.	2.7
Ver.	1.2
rf frequency	1.5-4.6MHz

The construction of the FFAG accelerator was completed in April of 2003 except the beam transport for extraction. Figure 7 shows a picture of the FFAG accelerator, and the magnet and the rf cavity used in this accelerator are also shown in Fig. 7.

The first one turn of the beam around the ring at injection energy was observed in April 3rd of 2003 after the completion of the accelerator construction. It took, however, a couple of months to achieve a multi-turn of the beam in the ring because a closed orbit at beam injection was rather distorted (the reasons are described later) than expected. The electric septum for beam injection had to be relocated at the quite different position from the designed value in order to obtain a multi-turn of the beam.

After the success of the multi-turn of the beam in the ring, the betatron tunes were measured and the results were compared with the designed ones. Figure 8 shows the measured and the designed betatron tunes both for horizontal and vertical directions as a function of the strength of F/D ratio. As can be clearly seen from this figure, the difference

Fig. 7 Picture of the proton FFAG accelerator.

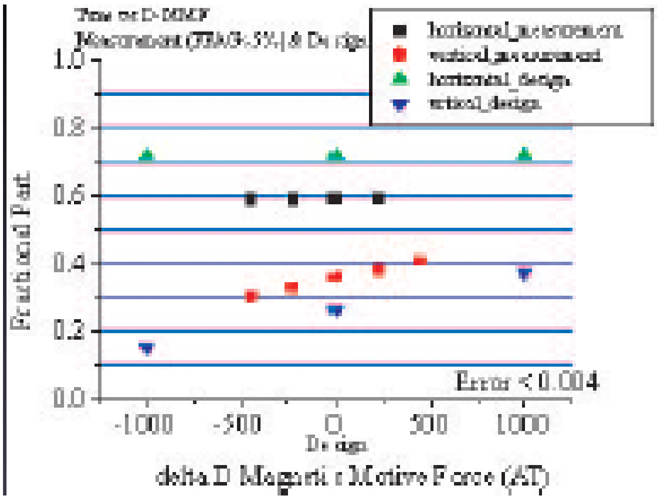


FIg. 8 Betatron tunes

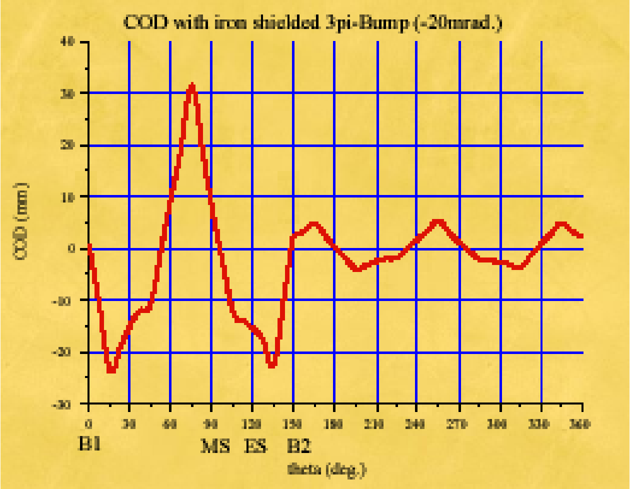


Fig. 9 COD caused by bump magnets at injection.

between the designed and the measured ones, especially for the horizontal direction, was obvious. It was found that the large closed orbit distortion caused by the magnetic insertions placed at the straight sections such as bumpers and rf cavity induced the observed tune shift.

The unexpected closed orbit distortion(COD) was found during the optimization of beam injection. The large COD was observed when the injection bump magnets and/or the MA rf cavity were installed in the ring. Since the length of the straight section in this ring is relatively short (~50cm) to make a ring compact, fairly large stray magnetic field of about 500G exists there. Once a magnetic devices such as the bump magnets made of ferrite are placed in the straight section, the magnetic field there can be eliminated and, thus, the COD occurs. Figure 9 shows a calculated COD when the two injection bump magnets are installed in the ring. At the positions of the injection magnetic septum and electric septum, the estimated CODs were about +9mm and -16mm, respectively. The measured CODs showed good agreement with them.

The rf cavity was another COD error source. Magnetic alloy (MA) cores were loaded into the rf cavity which brought the broad band and high gradient performance. The stray magnetic field affected the rf characteristics of the MA cores.

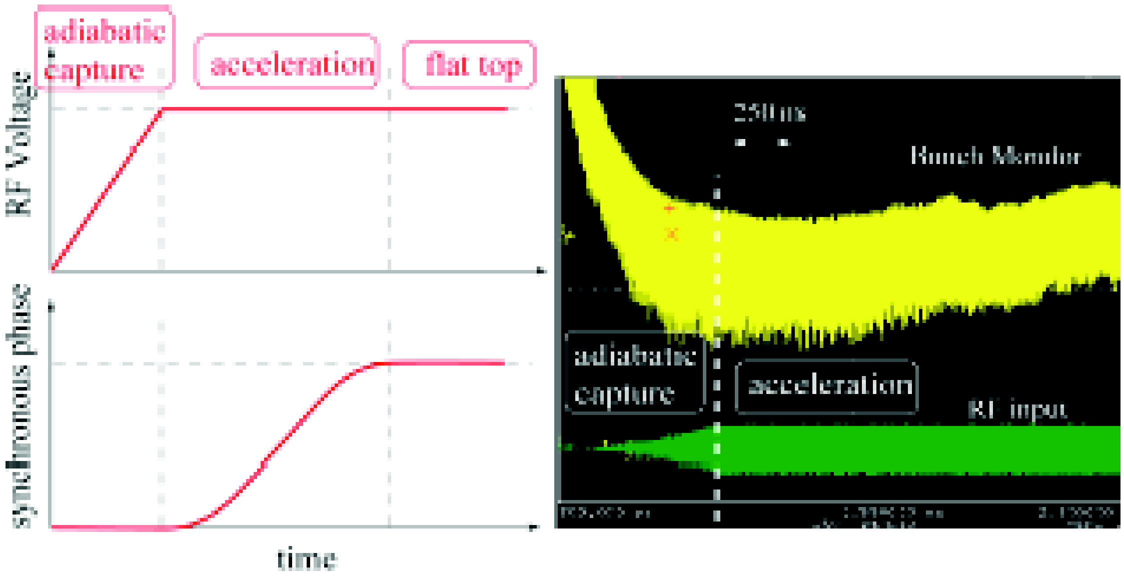


Fig. 10 First beam acceleration.

Magnetic shields, therefore, had to be attached to the rf cavity in order to avoid the deteriorate effects from the stray magnetic field. They changed the magnetic field configuration at the straight section where the rf cavity was placed and caused the COD.

These CODs affected not only the beam orbit configurations but the strength of the betatron resonances. The ring was designed to keep a high symmetry where the super periodicity was 12. The CODs, however, could break the symmetry if they are not small enough to induce the various non-structure betatron resonances. The operational betatron tunes in this ring move about 0.15 for both horizontal and vertical directions from injection to extraction. Therefore, the beam crosses some non-structure resonances during acceleration and could be lost. To overcome these problems, the corrections of the CODs were essential and important.

In order to correct the COD caused by the injection bump magnets, we have tried two ways; one was to make a correction dipole field inside of the bump magnet by putting small pieces of the permanent magnets and the other to fabricate the air-core bump magnets. The COD caused by the bump magnets were well corrected by both methods , which was the case for the correction permanent magnets. The error field caused by the rf cavity was corrected by a pair of dipole magnets located at the both side of the rf gap.

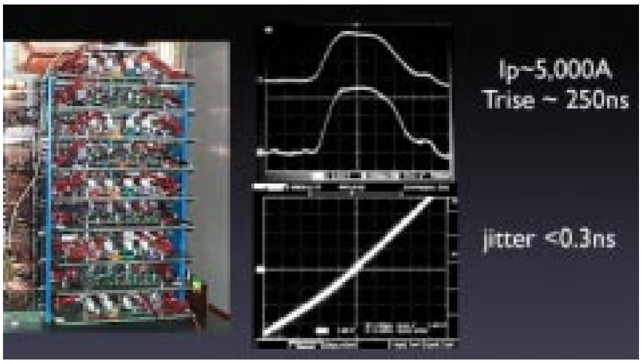
The first beam acceleration in this ring was succeeded in October of 2003. The picture shown in Fig. 10 shows the beam bunch signals and the rf voltage pattern. The beam after the injection was adiabatically captured by the rf bucket.

One of the features of the FFAG accelerator is a high repetition rate in beam acceleration. The repetition rate of this proton FFAG accelerator aims more than 100Hz and various technical problems such as the rf voltage have to be overcome. The fast kicker magnet and its power supply with high repetition rate are, among them, crucial ones for beam extraction. In ordinary kicker magnet, a cylatron type of current switches for PFN circuit has been commonly used. For the high repetition rate operation more than 100Hz, however, it is hard to use a cylatron type of switch because its lifetime becomes relatively short.

Because of this, we have developed a solid state type of switches which could sand for high repetition operation more than 100Hz. Two types of the solid state devices have been tried; one is IGBT and the other C-MOS FET. Figure 11-a and -b show the pictures of developed IGBT and C-MOS FET type of switched power supply, and their performance, respectively. In order to avoid the problems caused by de-synchronized gating to each devices, a new type of gating system, subordinated gating system, has been developed. Both switches have worked fine with this new system, however, it was difficult to decrease a rise time of the current pulse less than 250ns for IGBT type. On the other hand, the rise time for C-MOS FET type was about 150ns. In this proton FFAG accelerator, the revolution frequency of the beam at maximum energy was about 5MHz, therefore, only C-MOS FET type satisfied the requirement.

Using the kicker magnet with C-MOS FET type of switched power supply, the beam extraction test has been successfully carried out. The beam kicked out by the kicker magnet was well separated from the coasting beam and was observed at the position of the septum magnet which was placed after four cells behind the kicker magnet.

FFAG for ADS at Kyoto University



(a) IGBT type

(b) C-MOS FET type

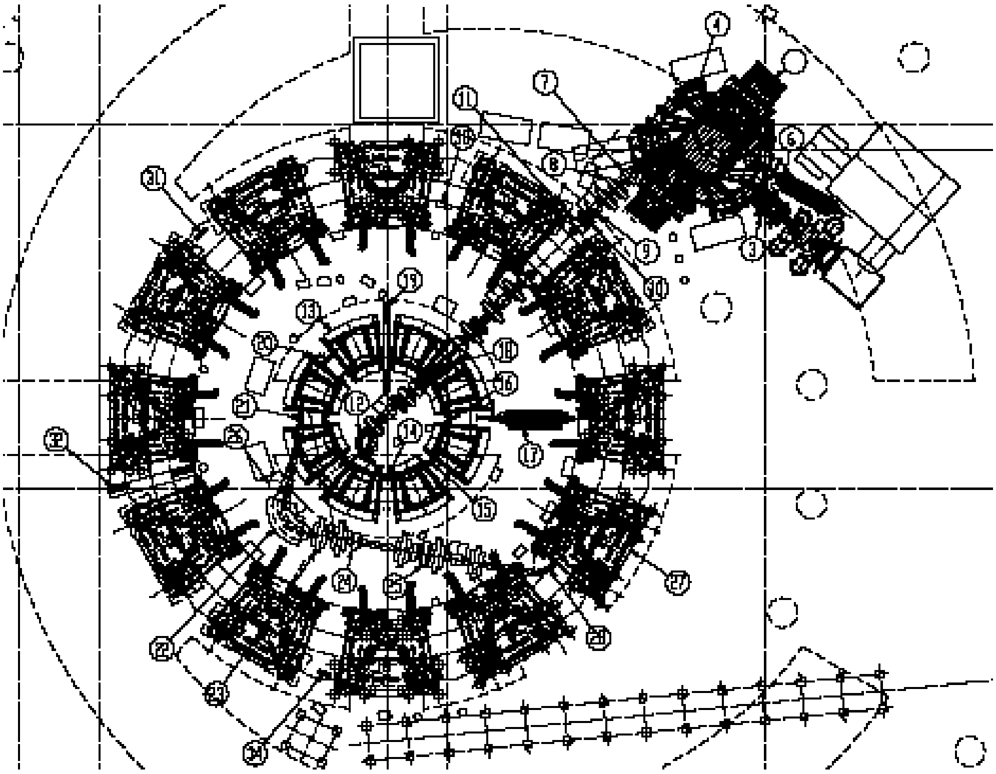


Fig.12 Schematic layout of the FFAG accelerator chain in KURRI.

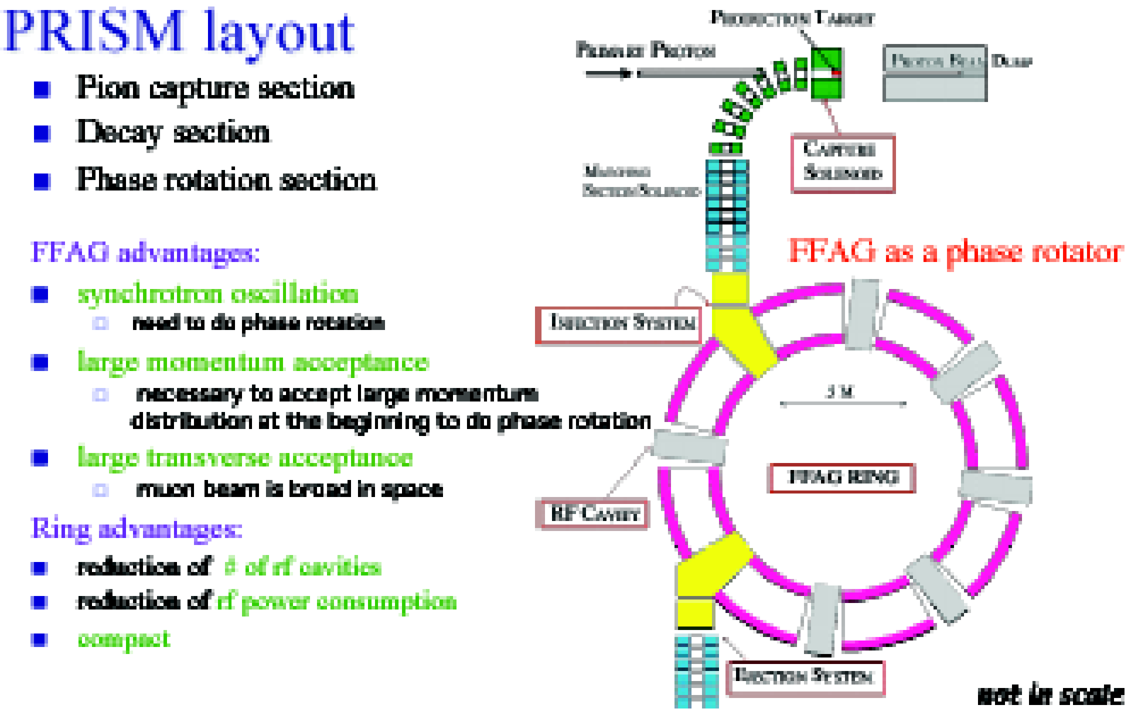
As a substitute for the 5MW reactor at Kyoto University(KUR), a neutron source based on the ADS concept has been proposed in 1966. Through the studies for this, the lack of reliable effective multiplication factor keff in the proton energy region between 20MeV and 150 MeV was realized. Thus a proton source which covers between 20MeV and 150MeV is required to extend the study on ADS system for our neutron source and an FFAG accelerator complex is under construction for this purpose. The FFAG accelerator complex composes a chain of three FFAG accelerators as shown in Fig. 12 and the main parameters of each accelerator are shown in Table 2.

Table 2 Main parameters of the accelerator chain.

	Injector	Booster	Main Ring
Einj	100keV	2.5MeV	20MEV
Eext	2.5MeV	20MeV	150MeV
Lattice	Spiral	DFD	DFD
Acceleration	Induction	rf	rf
# of cells	8	8	12
k value	2.5	4.5	7.6
coil/pole	coil	coil	pole
Pext/Pinj	5.00	2.84	2.83
Rinj	0.60m	1.42m	4.54m
Rext	0.99m	1.71m	5.12m

Construction of the building for the FFAG complex named “Innovation Research Laboratory” has been already completed. This laboratory aims to do many subjects such as nuclear physics, chemistry, material science and cancer therapy in future. The FFAG complex will be completed in the fall of 2005.

PRISM project at Osaka University



PRISM layout

- Pion capture section
- Decay section
- Phase rotation section

FFAG advantages:

- synchrotron oscillation
  - need to do phase rotation
- large momentum acceptance
  - necessary to accept large momentum distribution at the beginning to do phase rotation
- large transverse acceptance
  - muon beam is broad in space

Ring advantages:

- reduction of # of rf cavities
- reduction of rf power consumption
- compact

Fig. 13 Schematic layout of PRISM

PRISM (Phase Rotated Intense Slow Muon source) is a project to produce a pure and high brightness muon beam at low energy. PRISM aims primarily at searches for lepton-flavor-violating processes, such as μ–e conversion in a muonic atom. Energy spread of the PRISM muon beam can be narrowed by phase rotation at a FFAG (Fixed Field Alternating Gradient synchrotron) ring. The PRISM-FFAG ring with RF (Radio Frequency) cavities of a high electric field gradient, such as of exceeding 200kV/m, is being constructed at Osaka University. The construction of the PRISM-FFAG phase rotator will be completed by JFY2007. And by using it, phase rotation of a muon beam will be experimentally demonstrated.

A schematic layout is shown in Fig. 13. As seen in Fig.13, PRISM consists of

1. a pulsed proton beam (to produce a short pion pulsed beam),
2. a pion capture system,
3. a pion decay and muon transport system (in a long solenoid magnet of about 10 m long), and
4. a phase rotation system.

In a phase rotation, slower particles are accelerated and faster particles are decelerated by high gradient RF electric fields. Assuming the initial muon beam has a momentum spread of 68MeV/cÅ}30% and a time spread of Å}5ns for each momentum region, the final momentum spread of muon beam can be reduced to less than Å}3% by phase rotation. An option to use a linear accelerator has been considered to be a phase rotator. However, since the momentum spread of the incidence muons is large, a relatively low frequency RF, ranging 1Å|10MHz, must be used. In this case, a total length of a linear accelerator is expected to be 150m long beam line. On the other hand, when a circular accelerator is used, number of magnets can be reduced and a total cost can be kept down. Recently, FFAG has been demonstrated experimentally to accelerate protons at KEK. It is also suitable for the PRISM phase rotation ring, since (1) it has synchrotron oscillation, which is indispensable to phase rotation, and (2) it has large transverse acceptance and momentum acceptance to allow high intensity. A radial type FFAG with eight D-F-D triplet magnets is considered. The diameter of the ring is about 10m. Two straight sections are used for injection and extraction systems. A total of 12 RF cavities are installed to the remaining straight sections. In order to perform phase rotation efficiently, the high gradient electric field, exceeding 200kV/m, is required on RF. An RF wave shape has been studied with simulations. It shows that a saw-tooth shape could only yields narrower energy spread than a sinusoidal shape does. Then, a saw-tooth shape RF of 5 MHz will be made with the combination of different RFs of higher harmonics frequencies of sinusoidal-shape.

4. SUMMARY

Recent developments of scaling type of FFAG accelerators mostly in Japan are overviewed. New projects such as an electron model of non-scaling FFAG accelerator, particle therapy machine and neutron source are under discussion in the various places. The FFAG accelerator will open a new era in the accelerator science.

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