PROGRESS ON FFAG ACCELERATORS - TOWARD NEUTRINO FACTORY

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Abstract

A fixed-field alternating gradient accelerator was originally proposed by Ohkawa in 1953. Only electron models were built and no proton accelerating FFAG has been built so far. A proton accelerating FFAG model has been developed at KEK and the beam was successfully accelerated in June of 2000. The FFAG accelerator has large potentials. Among them, short lived particles such as muons can be accelerated with FFAG accelerators. The neutrino factory based on muon accelerator and muon storage ring has been proposed. In my talk, the experimental results of proton acceleration in the FFAG proof-of-principle (POP) proton model and also a neutrino factory based on FFAG accelerators will be presented.

1 INTRODUCTION

A fixed-field alternating gradient (FFAG) accelerator seems to be very attractive, because the repetition rate of the accelerating cycle could be raised ten times or more compared to that of the ordinary synchrotron. The idea of an FFAG accelerator was originally proposed by Ohkawa[1] in 1953, and later on Symon[2] and Kolomensky[3] have independently proposed this idea. Electron-beam machines demonstrating this principle have been successfully built in the MURA project, however only electron models were built and no proton accelerating FFAG has been built so far. The FFAG focusing is attractive for acceleration of high intensity beams and also short-lived particle beams such as muon beams because the acceleration cycle could be increased. The magnetic field of FFAG is static, therefore the acceleration time could be much shorter than that of an ordinary synchrotron if an efficient high voltage RF accelerating system becomes available. Recently, a new type of high gradient RF cavity using high permeability magnetic alloy (MA) has been developed[5] that makes FFAG synchrotrons very promising.

In order to clarify the feasibility of a rapid cycling FFAG synchrotron experimentally, a proof-of-principle (POP) FFAG model, which accelerates protons up to 1 MeV with 1 kHz repetition, has been developed at KEK. The first beam acceleration was successfully commissioned in June of 2000. The FFAG accelerator has large potentials. We have made several designs on high intensity proton accelerators with FFAG synchrotron for various applications such as spallation neutron source, proton driver for muon production and accelerator driven system for energy breeder. Among them, short lived particles such as muons can be accelerated with FFAG accelerators. The neutrino factory based on muon accelerator and muon storage ring has been proposed. In this, various R&D activities which have been carried out at KEK including the experimental results of proton acceleration in the FFAG POP proton model and also a neutrino factory based on FFAG accelerators will be presented.

2 FFAG ACCELERATOR

In the FFAG synchrotron, where the magnetic field is constant in time, the shape of the magnetic field should be such that the betatron tunes for both the horizontal and vertical planes should be constant for all closed orbit, and departing from all of the dangerous resonance lines. The condition above is called “zero-chromaticity”.

$$\frac{\partial}{\partial p}\left(\frac{K}{K_0}\right)\bigg|_{\vartheta=\text{const.}} = 0, \qquad \frac{\partial n}{\partial p}\bigg|_{\vartheta=\text{const.}} = 0 \tag{1}$$

A magnetic field satisfying the scaling conditions described above must generally have the form

$$B(r,\theta) = B_i\left(\frac{r_i}{r}\right)^n F\left(\theta - \varsigma \ln\frac{r}{r_i}\right) \tag{2}$$

where ς is a spiral angle. If ς is zero, the magnetic field does not depend on θ, and the corresponding orbit points are distributed on a radial vector. The type of having this magnetic shape is called “radial sector”. On the other hand, if θ behaves in a logarithmic manner, such that

$$\theta - \varsigma \ln\frac{r}{r_i} = \text{const.}\ , \tag{3}$$

the orbits remain geometrically similar, but move around the beam center towards larger radii. This type is called “spiral sector”.

The FFAG synchrotron is very attractive for the acceleration of intense proton beams as described above, and several proposals have been submitted[5][6]. However, no practical proton-beam machine has been built so far. One of the most difficult technical issues to realize a high-repetition FFAG synchrotron is rf acceleration. The requested accelerating rf voltage per one turn is

$$\Delta V = 2\pi(1+n)\left(\frac{dr}{dt}\right)p\ . \tag{4}$$

Here, dr/dt is the orbit excursion rate. If we chose a radial sector of ring configuration and each sector consists of a

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triplet focusing (DFD) (defocus-focus-defocus) lattice as shown in Figure 1, the linearized beam orbit parameters (beta function, dispersion) of the scaling type of FFAG ring can be estimated using an effective field index n with a circumference factor.

$$n = \pm k \frac{1 + \xi \cos\psi}{1 + 2\xi\cos\psi + \xi^2} \tag{5}$$

(+:focus, -:defocus)

where

$$\xi = \zeta - 1. \tag{6}$$

Here ζ is a so-called circumference factor and $\zeta = r_0/\rho$.

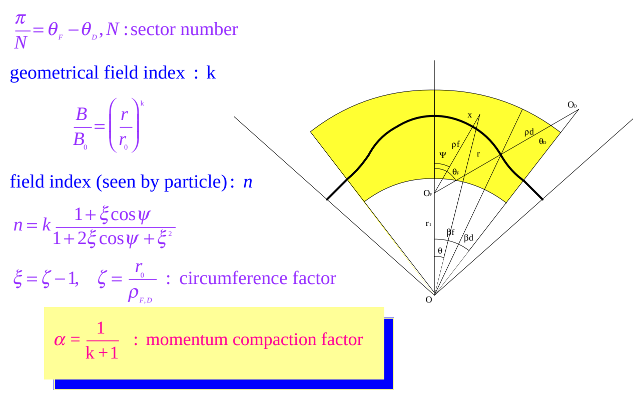


Fig 1. Linearized orbit configuration of a triplet radial sector (DFD) type of FFAG.

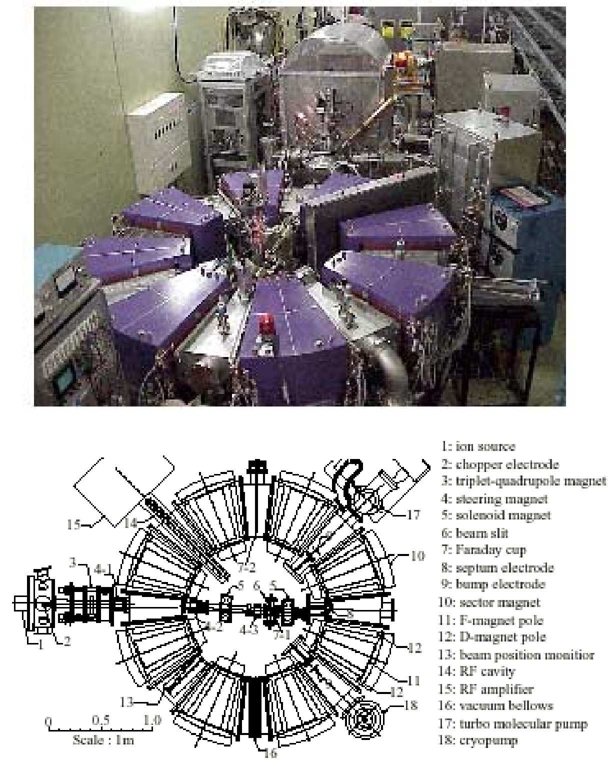


Fig 2. Photograph and schematic layout of the POP FFAG machine.

3 R&D ACTIVITIES OF FFAG ACCELERATORS AT KEK

3.1 POP FFAG Proton Model

In order to clarify the availability of very rapid cycling in FFAG synchrotrons, we have been developing a small proof-of-principle (POP) machine. The purposes of the POP machine are: 1) to verify the fast acceleration by FFAG synchrotrons, and 2) to demonstrate the large acceptance of FFAG synchrotrons. It should be noted that this POP machine is the world's first proton FFAG accelerator. In this POP machine, the maximum energy is limited to 0.5 MeV because of radiation safety, but the repetition rate of acceleration is 1 kHz. The magnet configuration is a radial sector type and eight-fold symmetry was chosen. Each sector consists of three dipole magnets which form a triplet focusing configuration DFD (defocus-focus-defocus) and field index of each dipole magnet is 2.5, respectively. The maximum magnetic fields of the focusing and defocusing dipole magnets are 0.5 T and 0.2 T, respectively. The magnetic field configurations in three dimensional directions are calculated with OPERA-3D (Fig. 2) and their results are used for beam tracking simulation. The average beam radius changes from 0.81 m to 1.14 m according to the increase of beam energy from 50 keV to 0.5 MeV. The half gap heights of the magnet at the radius of 0.75 m and 1.15 m are 73 mm and 25 mm, respectively.

The schematic layout and the picture of the POP machine are shown in Figure 2. The betatron tunes for horizontal and vertical directions are varied with field index and the product of the magnetic field and the effective magnet length (Bl-product). The design values of betatron tunes for horizontal and vertical directions are 2.25 and 1.25, respectively. The rf frequency changes from 0.61 MHz to 1.38 MHz. At the condition of the constant radial displacement as a function of time ($dr/dt =$ const.), the rf voltage has to be increased from 1.3 kV to 3 kV. This rf voltage can be easily obtained by a magnetic alloy (MA) loaded rf cavity[7]. Intensive accelerator studies were carried out in order to make the characteristics of FFAG accelerator clear. The major items of the accelerator study are as follows.

- Demonstration of the fast acceleration
- Betatron tune and synchrotron tune in various conditions
- Beam position in various energies
- Beam acceptance

Beam acceleration[7] Compared to an ordinary synchrotron, the acceleration time of the FFAG synchrotron is not restricted by the ramping time of a pulsed magnet. Thus, the higher the acceleration field is, the quicker the acceleration is completed. It is one of the prominent merits of the FFAG synchrotron. To demonstrate this feature

Table 1: 150MeV FFAG main parameters

No. of sectors	12
Field index(k-value)	7.5
Energy	12MeV - 150MeV
Repetition Rate	250 kHz
Max. Magnetic field	
Focus-mag.:	1.63 Tesla
Defocus-mag.:	0.13 Tesla
Closed orbit radius	4.4m-5.3m
Betatron tune	
Horizontal:	3.8
Vertical:	2.2
rf frequency	1.5 - 4.6MHz

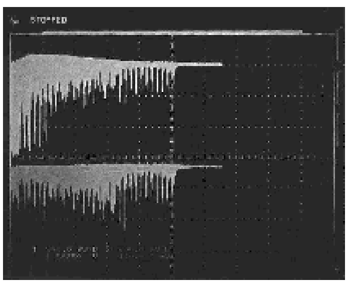


Fig 3. Typical beam signal observed with the inner and outer electrodes of the beam position monitor during acceleration of a proton beam.

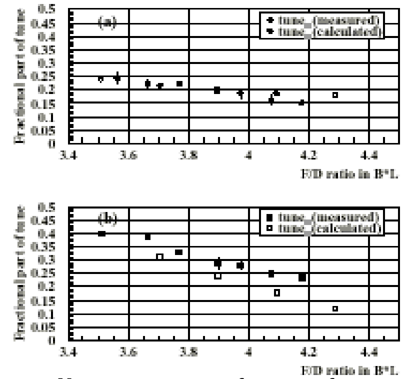


Fig 4. Measured betatron tunes as a function of F/D ratio.

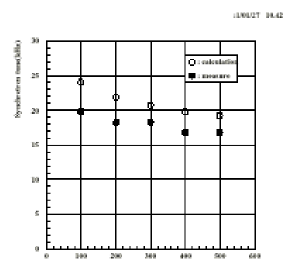


Fig. 5.Measured synchrotron tunes as a function of beam energies.

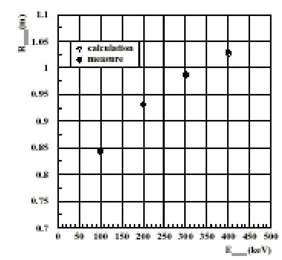


Fig 6. Measured beam position as a function of beam energy.

of the FFAG accelerator is one of the strong motivations to develop the POP machine. In the case that a synchronous phase is set to be 20 degrees, the rf voltage should be at least 1.3 kV during acceleration. We have developed an rf cavity using two rectangular FINEMET cores. The size of each core is 1.1 m (width)$\times$0.7 m (height). The thickness of the core is 25 mm. A 55 kW rf amplifier which consists of two tetrodes (Eimac 4CW25,000) was used. Figure 3 shows a typical beam signal observed by the inner and outer electrodes of the beam position monitor during acceleration of a proton beam. The beam has been successfilly accelerated up to 500 keV within 1 ms.

Tunes and beam position Betatron tunes were measured in injection orbit at the various field configurations. Figure 4 shows the measured betatron tunes as a function of F/D ratio. The results were consistent with the results of a computer tracking simulation. The synchrotron tunes for various beam energies from 50 keV to 500 keV were also measured. The results shown in Figure 5 agreed well with the expected values. The beam positions were measured for different energies ranging from 100 keV to 400 keV. The results were summarized in Figure 6. These are consistent with the simulation values within the systematics error.

3.2 150 MeV FFAG Proton Accelerator

After the success of the POP FFAG commissioning, a new proposal to construct a larger size FFAG accelerator was approved in Japanese fiscal year (JFY) 2000. In this project, an FFAG synchrotron to accelerate protons up to 150 MeV will be constructed. The main parameters are summarized in Table 1. The schematic view of this 150 MeV FFAG accelerator is shown in Figure 7. Compared to the POP FFAG, the 150 MeV FFAG has three new features for R&D work: 1) yoke-free magnets, 2) beam extraction from the FFAG ring, and 3) high repetition operation. The yoke-free magnet is also one of the key issues for the future FFAG-based neutrino factory. This type of magnet allows an easy access of injection and extraction of the beams and also gives a large flexibility for possible configuration of the beam apparatus. Thus, the demonstration of a yoke-free type of magnet is useful. As the second item, it

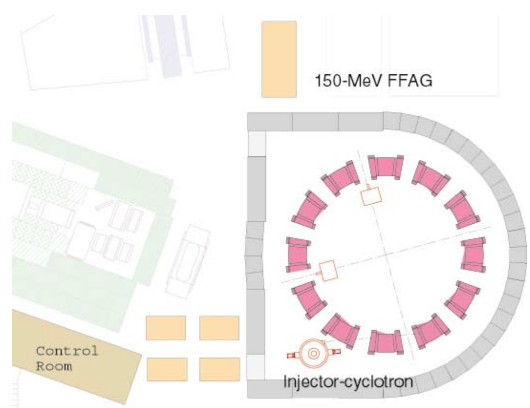


Figure 7. Schematic view of the 150MeV FFAG

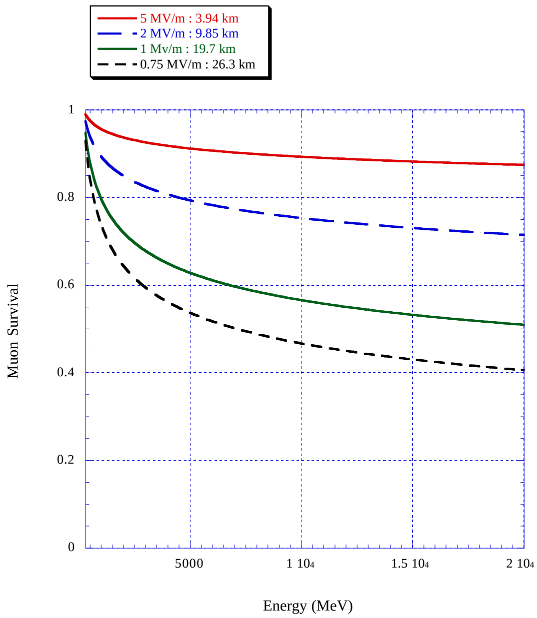
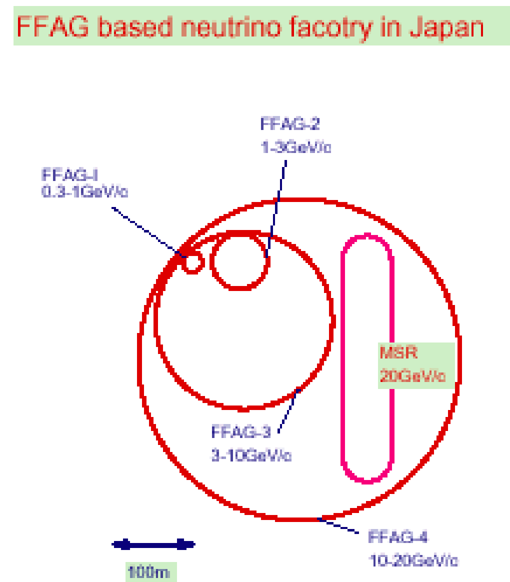


Figure 8. Muon survival during acceleration from 300MeV/c to 20GeV/c for various acceleratinggradients and fractional distances along the machine.



is now being considered to employ the following scheme. The beam in the FFAG ring is bent by a kicker magnet installed in the middle of the straight section. A typical field strength for the 150 MeV FFAG is about 600 gauss. A decay time of the magnetic field is less than 150 ns. In the next straight section, a DC septum magnet is installed to give further horizontal kick to the beam. The required field strength is about 2 kgauss. Finally, the beam is extracted from the ring. Figure 9 shows a typical beam extraction or-

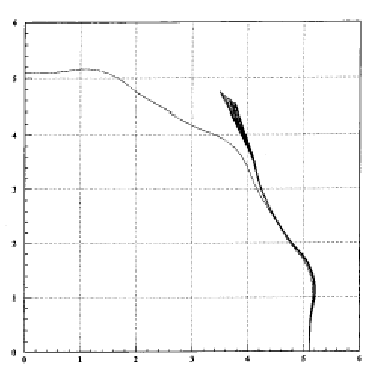


Fig 9. Typical extraction rbit of 150MeV FFAG operation

bit. As the third item, the capability of high repetition operation has already been demonstrated with the POP FFAG. The beam was accelerated within 1 ms. In the 150 MeV FFAG, a repetition rate of 250 Hz is planned. A fast kicker with high repetition rate using IGBT switching device is under development. It is hoped that beam commissioning of the 150 MeV FFAG will start at the beginning of JFY 2002.

4 FFAG BASED NEUTRINO FACTORY SCENARIO

A high-intensity accelerator-based neutrino source is definitely a next-generation facility of particle physics. It is required in order to push neutrino physics forward into an unexplored territory. One of the physics motivations for neutrino factories is to study the 3×3 neutrino mixing matrix, which is called the Maki-Nakagawa-Sakata (MNS) mixing matrix. This is a completely new field in the lepton sector that must pursued from now on, after many years of studies of the Kobayashi-Maskawa mixing matrix in the quark sector. The number of muon decays in the muon storage ring is aimed to be about $1\times10^{2}0$ muon decay/one straight section/year. The energy of muons is at most 20 GeV in the first phase (Phase-I), and will be improved to be $4.4\times10^{2}0$ muon decay/one straight section/year by increasing the primary proton beam intensity in Phase-II. The muon energy could be increased to 50 GeV if necessary. The conventional neutrino factory scheme, the so called "PJK" scenario, which is based on the linear accelerators and muon storage ring, has been proposed. A high accelerating gradient minimizes beam loss caused by muon decay. The muon survival for various accelerating field gradients when the muons are accelerated from 300 MeV/c to 20 GeV/c is shown in Figure 8.

When the accelerating gradient is less than 5 MV/m the total distance along the machine exceeds 4 km. Even if a recirculating linac system is used, the total cost becomes sub-

Table 2 Basic beam parameters of the FFAG muon accelerator complex.

momentum(GeV/c)	0.3 to1	0.3 to 1	1 to 3	1 to 3	3 to 10	1 to 20
	(normal)	(super)	(normal)	(super)		
average radius (m)	21	10	80	30	90	200
number of sector	32	16	64	32	64	120
k value	50	15	190	63	220	280
beam size at extraction(mm)	170x55	143x55	146x41	115x25	93x17	104x34

stantial. In the the linear accelerator-based scenario, the rf frequency used in the accelerating cavity has to be several hundred megahertz, at least, to achieve such a high accelerating gradient. The disadvantage of the high frequency system is its small beam. Thus, in this case, muon beam cooling becomes essential. Ordinary beam cooling, such as stochastic cooling, is obviously useless since the cooling time is much longer than the muon lifetime. Ionization cooling seems to be the only possible solution. Before ionization cooling, phase rotation to minimized the momentum spread of the muon beam should be essential, however the total beam loss through the cooling channel becomes very large according to detailed work by the FNAL group[9]. If a ring accelerator can be addopted to muon acceleration, this limitaion becomes modest. Many turns for acceleration in the same ring using the same accelerating system helps to reduce the total size of the accelerator and the total construction cost. As can be seen in Figure 8, even when the accelerating gradientis only 1 MV/m, the muon survival during acceleration up to 20 GeV/c is still more than 50%, which should not be so painful. Such a low accelerating field can be realized with a rather low frequency rf accelerating system. One of the advantages in using a low frequecy rf system is its large longitudinal acceptance. The typical longitudinal acceptance with such a low frequency rf system would be several eV·sec or more. The particles having central momentum and momentum spread of 300 MeV/c and ±50%, respectively, are well within the area of 5 eV·sec. This size of longitudinal acceptance can be realized by a low frequency rf accelerating system having an accelerating field gradient of 1 MV/m. Obviously a linear accelerator with such a low frequency rf system is not suitable for accelerating muons to high energy because the total distance becomes too long. Thus, a ring accelerator is practically the only scheme possible for muon acceleration with a low frequency rf system.

The ordinary synchrotron is obviously inadequate for accelerating muons. The magnetic field in an ordinary synchrotron must increase during acceleration and the ramping rate cannot be fast enough to compete with the muon lifetime. Thus, a static magnetic field must be used in ring accelerators for muon acceleration. The cyclotron is inadequate for accelerating muons to high energy. Keeping isochronous in this type of accelerator becomes rather difficult when accelerating relativistic particles. The FFAG accelerator seems to be adequate for accelerating muon to high energy[10].

Another advantage of the FFAG accelerator is that it has a large acceptance for both transverse and longitudinal directions. In the FFAG accelerators, there are two different types from the beam dynamics point of view; one is the scaling type and the other the non-scaling type. In the scaling type of FFAG accelerator, the beam orbit scales for different energies, which means that the betatron tunes for both horizontal and vertical directions are always constant during acceleration. This is the so-called “zero-chromaticity” condition.

The horizontal acceptance of the FFAG accelerator is every large because of this feature and normally exceeds 10πmm·rad in real phase space. The momentum acceptance is also very large and a beam having a large momentum spread of more than ±50% can be accelerated. Thus, both muon cooling and, accordingly, phase rotation should not be necessary. This may become a kind of “brute force” option for muon acceleration in the neutrino factory.

In Figure 4.2 a conceptual schematic layout of the FFAG neutrino factory with the 50 GeV proton driver at JJAERI Tokai site is presented. Since the practical momentum range from injection to extraction in the FFAG acceleration is about 3-4 time, there are four FFAG rings for accleration of muons from the momentum of 300 MeV/c to 20 GeV/c in this scheme. The detail of the design and beam optics configurations for each ring will be described later, but the basic beam parameters for each one are summarized in Table 2.

5 SUMMARY

Recent progress on FFAG accelerators, which are in development at KEK, is summarized.

6 ACKNOWLEDGMENT

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