FFAG DEVELOPMENTS IN JAPAN

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Abstract

Fixed field alternating gradient (FFAG) accelerator has been developed in many places for various applications in Japan. This paper presents the recent activities in the development of FFAG accelerators of Japan.

INTRODUCTION

Fixed field alternating gradient (FFAG) accelerator has various advantages. One is the strong focusing in 3D space where the AG-focusing is in the transverse direction and phase focusing in longitudinal direction with rf acceleration. This is just like synchrotron which brings large acceptance is 3D space. Various rf gymnastics such as bunching, stacking, coalescing,etc. become also possible. 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 first 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, the proton FFAG was not realized before the POP proton FFAG came out at KEK in 2000 [4]. Since then, development of FFAGs has been implemented in many places and several FFAGs were constructed.

Concerning the beam optics of the FFAG accelerators, there are two types:one is zero chromatic optics and the other non-zero chromatic optics. The ring with zero chromatic optics is called scaling FFAG and the other non-scaling FFAG. 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.

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BEAM OPTICS AND DYNAMICS OF SCALING FFAG

The betatron oscillation motions in cylindrical coordinates are expressed with the following equations in horizontal and vertical directions, respectively.

$$\frac{d^2X}{d\theta^2} + \frac{r^2}{\rho^2}(1 - K\rho^2)X = 0. \tag{1}$$

$$\frac{d^2Z}{d\theta^2} + \frac{r^2}{\rho^2}(K\rho^2)Z = 0. \tag{2}$$

Here, K is defined as a form with magnetic field gradient. Keeping the betatron tunes in transverse plane constant for different beam momentum, which means zero-chromaticity, the orbit similarity and constant geometrical field index must be satisfied. These conditions required for satisfying the zero-chromaticity lead the magnetic field configuration as shown in this formula.

$$B(r,\theta) = B_0(\frac{r}{r_0})^k f(\theta - \zeta ln\frac{r}{r_0}) \tag{3}$$

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.

So far the scaling FFAG lattice assumes a azimuthal symmetry, therefore, there are some disadvantages. It has relatively a large dispersion and the large orbit excursion which require a large horizontal aperture for the magnet and also for the rf cavity. Another disadvantage is that the length of the magnet-free straight section is rather small and the spaces for the injection/extraction devices and also for the rf cavity is sometimes not sufficient. Having the long straight lines keeping a scaling condition to satisfy the zero-chromaticity, reducing the dispersion and making a good match with circular scaling FFAG lattice, these difficulties can be overcome. What is a configuration of the magnetic field for scaling FFAG straight line? Obviously, it should not be presented in Eq. (3).

$$\frac{d^2X}{ds^2} + \frac{1}{\rho^2}(1 - K\rho^2)X = 0. \tag{4}$$

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$$\frac{d^2Z}{ds^2} + \frac{1}{\rho^2}(K\rho^2)Z = 0. \tag{5}$$

The equations describing the betatron motions in linear coordinates are expressed in Eqs. (4) and (5). To satisfy the zero-chromatic conditions in this frame just like in the cylindrical one, the orbit curvature should be kept constant and the field index should also be constant. And these leads that the magnetic field configuration should be just an exponential form, which is different from the circular ones. [5]

$$B_z = B_0 exp[(\frac{n}{\rho})x] \tag{6}$$

A design example of the scaling FFAG straight line for the proton beam where beam energy changes from 80 to 200 MeV is shown in Fig. 1. You may clear that orbit shapes for different energies are just similar and the betatron phase advances for horizontal and vertical directions are always constant as a function of the beam energy.

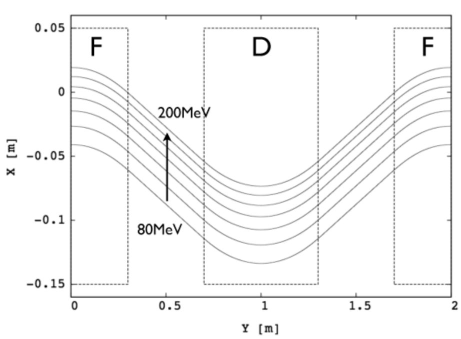

Figure 1: An example of the scaling FFAG straight line:particle is proton and energy range is 80MeV to 200MeV.

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.

$$\frac{k+1}{r_m} = \frac{n}{\rho} \tag{7}$$

The dispersion suppressor helps a lot for the accelerator design such as reducing the magnet aperture and making easier to use a high frequency rf cavity. In order to match the straight line with the circular FFAG lattice, the field configurations for both sides should equal as shown in Eq. (6), the the 1st order (linear) matching condition between two optics is expressed wit this formula. Some mismatches should occur caused by higher orders, however, the effects may not be so large.

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

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 [?], 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. [7] In the scaling FFAG, Hamiltonian describing the longitudinal particle motion can be analytically derived [8] and it shows a serpentine path accelerating either non-relativistic or relativistic particles exists as shown in Fig. 2.

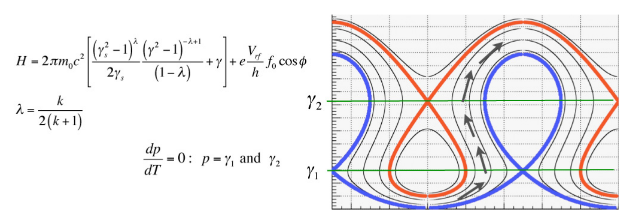

Figure 2: Serpentine acceleration in scaling FFAG.

VARIOUS ACTIVITIES IN JAPAN

Since the PoP-FFAG was developed at KEK in 2000, numbers of FFAG accelerators have been either constructed or under development for various applications in Japan.

Lepton FFAG

In Osaka University, Prof. Kuno and his group are searching for a new physics beyond Standard theory through the experiment with μ-e conversion rare events where the lower limit of branching ratio should be less than 10^{-18}. [9] To achieve this levels, the muon storage ring is essential to reduce energy spread and the pion background.

In this purpose, 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 proposed. [10] The expected muon intensity is about 10^{11}-10^{12} muons/sec and the energy of muon is about 20MeV. The momentum spread of the muons can be reduced to +-2% from +-20% with this device and the pion

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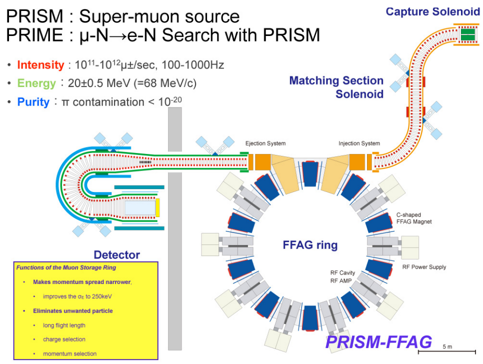

Figure 3: PRISM-FFAG for μ-e conversion in Osaka University.

background can be also reduced to less than 10^{-30} which could not be achieved with the ordinary beam line type of μ-e conversion experiment.

Before constructing full model, they have carried out the demonstration test of phase rotation for such large momentum spreading beam with α-particles. 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.

They are also now thinking an advanced scaling FFAG to be used for the real stage of PRISM ring and Fig. 3 shows a schematic layout of it.

In Kyoto University, Research Reactor Institute, design and some preliminary experimental works on muon accelerators have been carried out.

The neutrino factory which devotes the lepton flavor international collaboration experiment with high energy neutrino beams is based on the muon accelerator complex with non-scaling FFAG and RLA (Recirculating Linear Accelerator) as an injector of FFAG in the present reference design. However, the RLA is a cost-driving accelerator and people is seeking more cost effective muon accelerator. As an alternative of RLA, the scaling FFAG is under consideration and being designed at Kyoto University. [11]

Figure 4 shows a design of the scaling FFAG for muon acceleration in the neutrino factory. The energy range of muon is 3.6 to 12.6 GeV and the mean radius is about 160 m. The size is almost half compared with RLA and number of rf cavities could be reduced to about 2/3 of the RLA.

The beam acceleration is one of the biggest issues in this ring. Using the stationary bucket acceleration with constant frequency rf cavity, this problem was overcome. Figure 5 shows the results of full beam tracking in 6-D phase space. The injected beam emittance in each plane is the one which is assumed in the reference design of neutrino factory. There are no beam loss and not large emittance deteriorations during the acceleration.

In collaborating with Osaka University group, a new de-

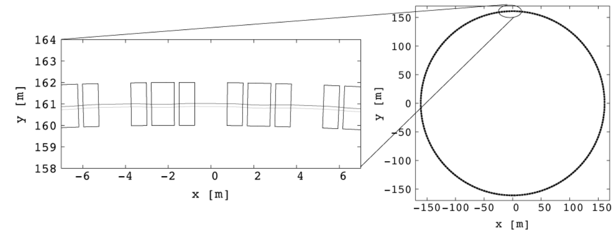

Figure 4: Design of muon FFAG accelerator for neutrino factory.

Table 1: Ring Parameters of a 3.6-12.6 GeV Muon FFAG Accelerator

Item	Parameter
Lattice type	FDF triplet
Injection/extraction energy	3.6/12.6 GeV
RF frequency	200 MeV
Number of turns	6
RF peak voltage (per turn)	1.8 GV
Synchronous energy	8.04 GeV
Mean radius	160.9 m
B_{max}(@12.6 GeV)	3.9 T
Field index k	1390
Total orbit excursion	14.3 cm
Harmonic number	675
Number of cells	225
Long drift length	1.5m
Phase advance	
Horizontal	85.86 degree
Vertical	33.81 degree

sign of PRISM-FFAG ring with advanced scaling FFAG optics is under development in Kyoto University, Research Reactor Institute, as shown in Fig. 7(a).[12] The ring uses long FFAG straight lines which make space feasible for beam injection/extraction and rf cavities.

Also, an experimental work for demonstrating the scal-

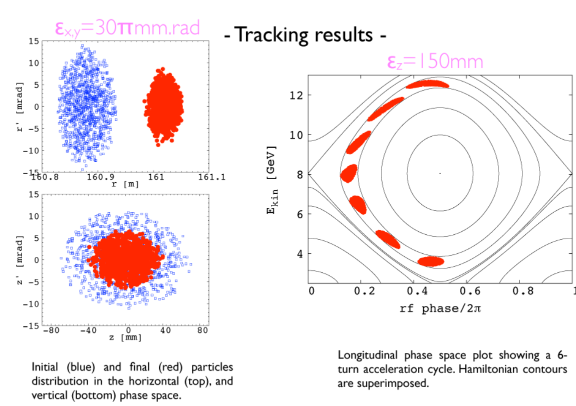

Figure 5: Simulation results of 6-D beam tracking for muon FFAG.

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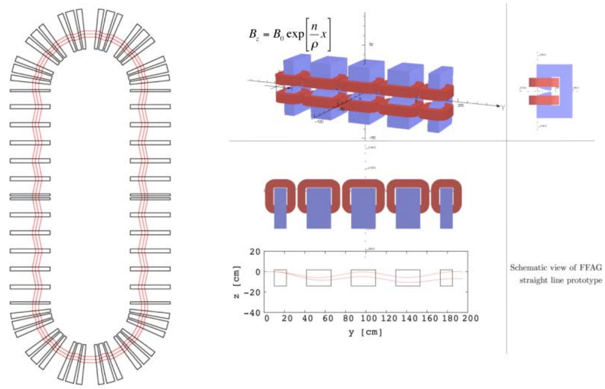


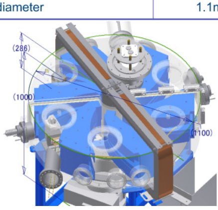
(a) (b)

Figure 6: (a)a new design of PRISM-FFAG with advanced scaling FFAG and (b)an experimental setup of scaling FFAG straight line.

ing FFAG straight line and also for clarifying the characteristics and performance of its beam optics is in progress. Figure 6(b) shows a schematic sketch of the experimental setup. In this line, the total phase advance in horizontal plane is just π.

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.[13] The beam energy is about 500keV and average beam current is about 20mA, and the diameter of the machine is 1.1 m as shown in Fig. 7. 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. In Mitsubishi Electric Co., a very compact electron accelerator based on the complex of FFAG and Betatron has been developed as shown in Fig. 8.[14] The specifications are shown in this table. The maximum beam energy is about 6MeV and the repetition rate is 1 kHz. 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.

Energy Inj. / Ext.	50 / 500keV
Orbit radius Inj. / Ext.	0.19 / 0.44m
Acceleration frequency	10kHz
Beam Current	100mA peak
Duty	20%
Outer diameter	1.1m



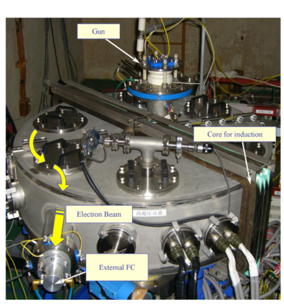


Figure 7: Electron FFAG developed at NHV Co.

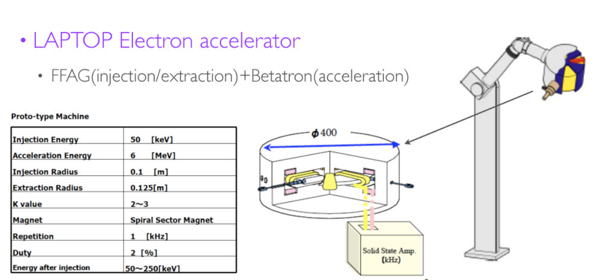


Figure 8: Electron accelerator developed at Mitsubishi Elect. Co.

Hadron FFAGs

In Kyusyu University, a 150MeV proton FFAG is now in re-installation. This machine was originally developed at KEK. [15]

This is a parameter list of 150MeV proton FFAG. The injector is a 10MeV cyclotron.

This is to be used as a multi-purpose machine for various application fields including the education of students. Among them, a unique research work regarding the AMS(Accelerator Mass Spectrometry) with Chloline 36 are being considered. This could become, if it is realized, a very powerful tool for various sciences as shown in Fig. 9. In nuclear physics and material sciences, acceleration of unstable nuclei and isomers can be very interesting. One of the problems in the acceleration of secondary particles is their large emittance, especially in the longitudinal direction. The FFAG has large acceptance, in principle, therefore, it can be very useful for such secondary particle acceleration.

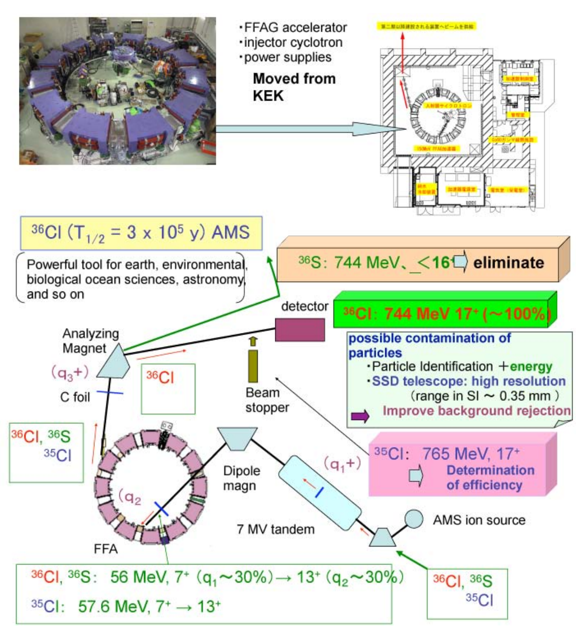


Figure 9: AMS using Chloline-36 with FFAG at Kyusyu University. (Courtesy of N. Ikeda of Kyusyu Univ.)

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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 output power of KUCA reactor is small like 100W, therefore, the requested beam power for the FFAG is about 1W. Also from the radiation safety, the beam current of the FFAG is limited less than 1nA. [16]

Figure 10 shows a schematic layout of the FFAG-KUCA system for ADSR experiment and a FFAG complex at KURRI. The 150MeV proton FFAG was installed at the newly constructed building called "Innovation Research Laboratory" and it is connected to KUCA with a long beam line, which is located just 1m below from the office ordinary people is living.

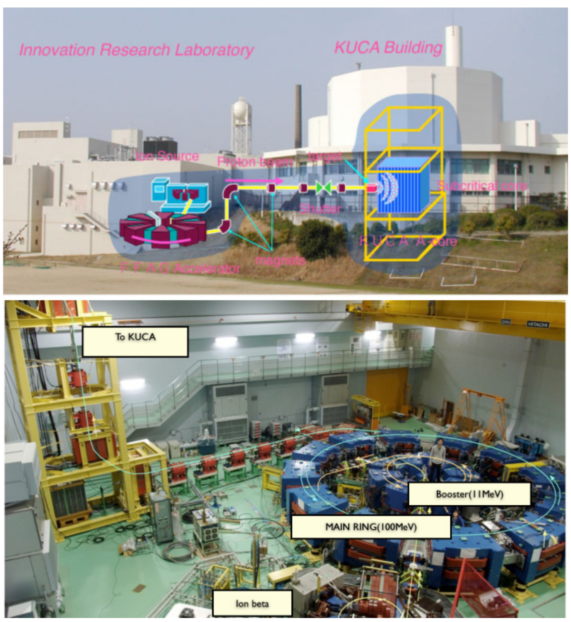

Figure 10: Schematic layout of the FFAG-KUCA system in ADSR experiment and the FFAG complex at KURRI.

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 of last year, the first beam from the FFAG was successfully injected into the KUCA reactor and we have started the ADSR experimental studies. 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 subcriticality as shown in Fig. 11.[17] Figure 12 presents the measured reactivity distribution in the different place of the reactor core.

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.

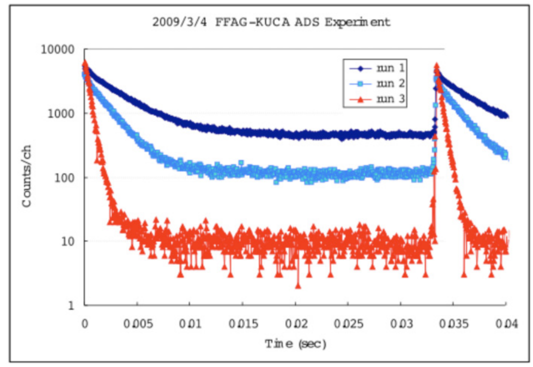

Figure 11: Time response of neutron yield for various sub-criticalities measured with the FFAG-KUCA system in ADSR experiment.

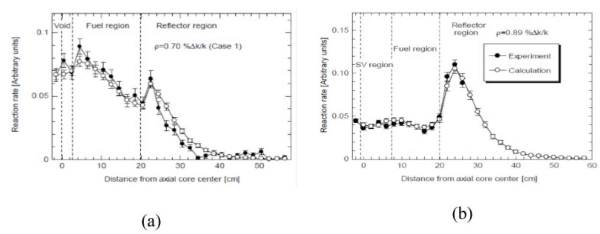

Figure 12: Measured spacial distribution of the reactivity in the ADSR experiment with FFAG-KUCA system at KURRI. (a) shows the core-axial and (b) the core-horizontal directions, respectively.

In this year, another memorial ADSR experiment was realized, which is the first ADSR experiment with thorium loaded core.

The ADSR experimental study with FFAG-KUCA complex has been successful, however, the study is somewhat limited because of the low output power of KUCA. In order to proceed the next stage of ADSR experiment, not only the basic reactor physics but also the nuclear engineering study is necessary at relatively high power. Therefore, we are thinking of a new high-power sub-critical system with the neutron output power of more than 10kW. For this purpose, the beam intensity of the FFAG has to be increased to the level of more than μA. Also other applications such as nuclear data taking and material science with spallation neutron source become feasible with the beam intensity upgrade.

With charge-exchanged H^- ion beam injection to the main ring, the beam intensity can be increase up to 10 micro-ampere with 120 Hz repetition rate operation. [18] The H^- ion beam can be provided by a 11MeV H^- ion linac which has been used for the compact neutron source described below.

We are also hoping to increase the energy upgrade of the FFAG. Using a spiral type of FFAG optics, the beam energy could be increased up to 0.7-1GeV. The size of the ring is rather compact, which is about 16m in diameter and can fit

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the present room. The detail design works are going on.

We have also developed a new type of compact neutron source called FFAG-ERIT(Emittance Recovery Internal Target). [19] In FFAG-ERIT neutrons are generated from the internal target placed into the proton FFAG storage ring. In order to suppress the emittance growth due to the Rutherford scattering, ionization cooling with energy recovering is adopted in this scheme.

Figure 13 shows a picture of FFAG-ERIT ring and the experimental results are also shown in the picture. The FFAG-ERIT ring has worked nicely, just as we expected and we have measured the neutron production with irradiation method and found that it had a capability of obtaining the neutron yield of more than 10^{13}n/sec with this device.

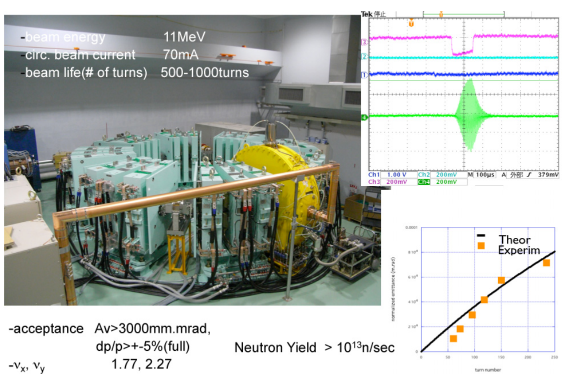

Figure 13: Picture of FFAG-ERIT and the experimental results of beam accumulation and emittance growth.

SUMMARY

Fixed field alternating gradient (FFAG) accelerator has been developed at many institutes in Japan since the first proton FFAG (PoP-FFAG) was demonstrated in 2000. This paper reviews the recent activities in the development of FFAG accelerator in Japan. In scaling FFAG accelerator, in particular, some advancements on beam optics and dynamics such as zero-chromatic straight line, dispersion suppressing and serpentine acceleration have been developed. With these developments, the FFAG accelerator could have various capabilities in many applications.

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