STATUS OF FFAG DEVELOPMENTS

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Abstract

Since its revival at KEK in late 1990s, FFAG accelerator draws increasing attentions in many fields including physics experiments, medical, energy, and industrial applications. Construction of prototype machine is going on in Japan and in Europe. We will show status of those activities and accelerator physics issues after some basic of a FFAG accelerator.

INTRODUCTION

What is FFAG?

FFAG stands for Fixed Field Alternating Gradient. Strictly speaking, it only specifies a way of transverse focusing. People, however, usually refer to FFAG focusing accelerator as "FFAG".

A modern synchrotron has Alternating Gradient (AG) focusing. It is sometimes called strong focusing by contrast with weak focusing which uses a magnet with small gradient. Therefore, the primary difference between FFAG and a synchrotron comes from whether magnet field is fixed or ramped.

A synchrotron consists of a dipole to bend a beam and a quadrupole to focus a beam. Bending angle θ and focusing length f of them are,

$$\theta = \frac{BL}{p/e} \quad , \quad (1) \qquad \text{and} \qquad \frac{1}{f} = \frac{(dB/dx)L}{p/e} \quad , \quad (2)$$

respectively, where L is magnet length and fixed. p is momentum and e is an unit charge. B and (dB/dx) have to be ramped to keep θ and f constant when momentum increases. If they are not ramped, bending radius becomes large to keep the same bending angle and to make an orbit close. In addition, focusing length becomes larger and betatron tune becomes lower.

Fixed field magnets cannot keep bending radius constant for different momenta, but we can make use of the orbit shift to keep betatron tune constant through acceleration. Orbit moves outward and focusing strength is $(dB/dx)L$ so that a magnet with steeper gradient and longer path length outward in principle can keep the betatron tune constant. In terms of bending field profile, it is presented as

$$B_z = B_0 \left(\frac{r}{r_0} \right)^k F(\phi) \quad , \qquad (3)$$

where r is radial, ϕ is azimuthal and z is vertical coordinates. F is a function which introduces azimuthal variation. k is called field index. Positive and large k means stronger bending field as the orbit moves outer, which sustain small orbit shift. At the same time, local gradient at the outer orbit is larger so that focusing is stronger.

That type of magnets can focus a beam only in one plane, but not in the other. In order to make an alternating gradient focusing, there are two ways. One is to flip the polarity of magnets alternatively. That changes bending direction as well as sign of focusing. This is called radial sector type FFAG. Another way to make it alternating gradient is to introduce edge focusing for vertical direction in addition to the focusing in the magnet body for horizontal direction. A sharp entrance angle for the all orbits makes the magnet shape spiral. This is called spiral sector type FFAG. Radial sector FFAG tends to be a larger machine compared with spiral one because of reverse bending magnets. It can have higher field index and therefore smaller orbit shift because focusing force comes from magnet body for both directions and can be strong as much as possible. On the other hand, vertical focusing of spiral sector FFAG is limited and that imposes a limit of field index.

What is advantage?

There are several advantages in FFAG compared with other type of machines. Firstly, machine repetition rate can be higher because there is no need to ramp the magnets. Secondly, particles per bunch can be the same or even higher than that of synchrotron because the similar strength of focusing in transverse as well as longitudinal direction is maintained. The larger aperture in horizontal plane even gives more space for particles. Thirdly, output energy can be higher compared with cyclotron because magnet size is smaller.

Beam power of an accelerator is the product of repetition rate, particles per bunch, and output energy. Therefore, compared with a synchrotron and a cyclotron, FFAG can have the potential to be the most powerful accelerator.

There are other advantages. FFAG is not only to be the most powerful accelerator, but with high energy efficiency in terms of beam power out of AC electric power. For example, FFAG with superconducting magnets needs only a power to a beam and the overall efficiency could be very high, which could be well above that of the present accelerators. As an accelerator for accelerator driven transmutation and energy breeder, FFAG has advantage over linac in that respect.

On more technical sides, rf frequency does not have to track magnetic field and horizontal orbit. That eliminates one feedback loop and makes machine operation easier. Also, FFAG has vacuum chamber covering injection to extraction orbits. Although that means physical cross section of the vacuum chamber is larger than that of synchrotron, it can accommodate momentum spread from injection to extraction.

Why FFAG draws attention NOW?

FFAG was invented in 1950s by Ohkawa [1], Symon [2], and Kolomensky [3], independently. In particular, there was intensive research at Midwestern University Research Associate (MURA) [4]. They made two electron models of radial and spiral FFAG and a bit larger FFAG to show a possibility of colliding beam machine. There seemed no major obstacles to go ahead, but it was just not right time for FFAG. At that time, primary driving force of accelerator development was to obtain as high energy beams as possible, not high intensity beams. Although there have been several activities around the world since MURA was shutdown in 1960s, no serious research and development has been started until recently.

Breakthrough was made at KEK, when Mori and his group constructed a proof of principle FFAG which accelerates a proton beam to 500 keV in late 1990s [5]. The time was ripe for surge of further development. People demand high intensity and high power accelerators for various applications. In particular, a strong community has been already established for neutron scattering, partially because of success of ISIS synchrotron, and muon science. They were talking about a pulsed beam from an accelerator with about MW beam power. Some of high energy physicist explore the possibility of Kaon/Neutrino factory in addition to an energy frontier facility. To make those secondary particles, high intensity proton driver is a must. Although people were (and are) not sure which acceleration scheme was the best to produce high intensity beam, SNS took accelerator complex of linac and storage ring and J-PARC took synchrotron. They are expected to deliver the MW beam in a few years time. FFAG is the third scheme which seems promising from the reason mentioned above.

The study of accelerator driven transmutation system and energy breeder against the world's energy problem is another motivation which drives FFAG development. In those systems, efficient use of electric power in an accelerator is essential as well as high intensity. FFAG is in the spotlight.

Nowadays, accelerator is not only a tool of high energy and nuclear physics, but also for many applications. Medical and industrial usage of accelerator has more cases than physics. Requirements of accelerator in those fields are somewhat different from those in physics experiment. A machine should be easy to operate because a specialist of accelerator may not be always near the machine. For medical application, it should be compact so that it can be fit in a hospital. You may think that accelerator for those applications do not have to be high intensity. However, if high intensity beams become available, it can provide a new technique such as spot scanning in medical treatment. Simple but high intensity potential makes FFAG a good candidate.

At last but not least, FFAG has a potential of accelerating exotic particles such as muons and unstable nuclei. The life time of muons is only 2.2 μs. Conventional scheme of acceleration, except linac, needs more time to complete acceleration. FFAG with high voltage rf seems a feasible option to accelerate muons. It will be discussed more later. The situation of unstable nuclei is similar to muon acceleration. In both cases, the beam emittance in both transverse and longitudinal phase space is huge because they are made as secondary particles. FFAG with large acceptance can accommodate those beams.

RECENT DEVELOPMENT

At KEK

As we have already mentioned, demonstration at KEK opened a new era of FFAG in late 1990s. Although it is not the first time to accelerate particles in FFAG, it had several major achievements. Firstly, it established a whole design procedure using modern tools such as 3D magnetic calculation software and particle tracking. Secondly, new type of an rf cavity with Magnetic Alloy (MA) was installed to have high gradient, wide frequency range and large aperture. It was the first time to accelerate protons with wide range of rf frequency swing. Thirdly, dynamic aperture was compared with tracking and it was shown that it indeed has a large acceptance. Finally, it creates a new community in accelerator research and people start thinking many possible applications using FFAG.

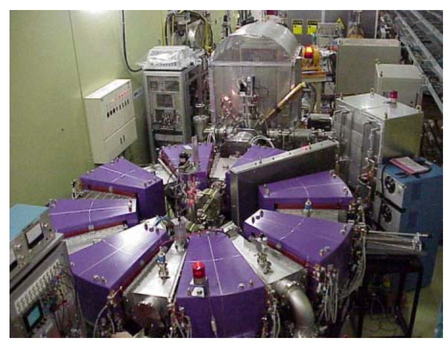

Figure 1: KEK 500 keV model.

One obvious target with FFAG is medical application with high intensity operation and high repetition rate. That makes a new way of shooting, namely spot scanning. Right after the success of small FFAG, Mori and colleague design a prototype of FFAG for medical use. Although the output energy is a bit low, simply because of available space in the lab, 150 MeV proton FFAG was constructed and the beam is extracted with an efficiency of more than 90% in 2005 [6]. The repetition rate of 100 Hz was also demonstrated.

At KURRI

Under Kyoto University, research reactor institute are operated. One of their future plans is to study accelerator driven sub critical reactor system. In particular, they are aiming to obtain the reliable "effective multiplication factor" in the proton energy region between 20 to 150 MeV. The project is called KART. FFAG was chosen as a promising accelerator for that purpose and the project was approved in 2002 [7]. It consists of three FFAG cascade: 100 keV to 2.5 MeV spiral sector, 2.5 to 20 MeV radial sector and 20 to 150 MeV radial sector FFAG. The third FFAG adopted the similar design of the KEK medical prototype and the second one is a sort of a scaled down model. However, the first stage of FFAG has impressive features such as spiral magnet with 32 distributed trim coil windings to control the field index and induction acceleration unit. By changing field index, momentum at the outer orbit can be controlled keeping the initial momentum constant. With adjusted field strength of the second and third FFAG, the output energy of the accelerator complex can be varied.

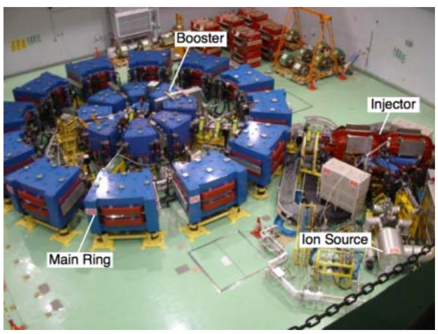

Figure 2: Cascade of three FFAG rings at KURRI [7].

At the moment, a beam is injected into the final FFAG and commissioning of extraction is continued. They are expecting extracted beam and the experiment with the sub critical core and the target for the neutron production pretty soon.

Another project now going on at KURRI is called ERIT, which produces high flux of neutrons for BNCT treatment [8]. An internal target in FFAG produces neutrons, and at the same time, the same target is used as material for ionization "cooling". The "cooling" actually does not make the emittance smaller, but does suppress the blow up due to scattering. The neutron intensity is supposed to be comparable to that from a nuclear reactor. Although there is no net acceleration, huge momentum acceptance and transverse acceptance of FFAG is a big advantage to circulate a beam whose emittance and momentum spread gradually increase. After about 1,000 turn revolution, the blow up beam is dumped and a new small emittance beam is injected.

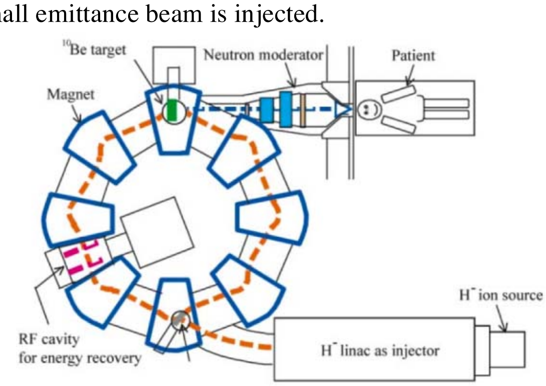

Figure 3: ERIT produces neutron for BNCT.

At Osaka University

Just using a feature of large momentum acceptance, Osaka University is constructing a FFAG for compression of muon momentum spread. This is called PRISM project [9]. Right after the target, muons (or pions) have large momentum spread. Since the time structure should be the same as primary proton beams, a tall muon beam in longitudinal phase space should be created when the proton bunch is shortened. When the tall beam is captured and rotated by a quarter of synchrotron oscillation, the beam becomes long in time and small in momentum. A muon beam stay for 5 turns in the FFAG and extracted. Magnets are ready now and some beam experiments with a few rf cavities are expected soon.

Figure 4: One of PRISM magnet.

At LPSC

RACCAM project is recently approved [10]. According to [10], its goal is, (1) participate to the on-going international collaborations in the field of FFAG and recent concepts of nonscaling FFAG (see the next section) with frames for instance, the neutrino factory, the EMMA project (see the next section also) of an electron model of a muon FFAG accelerator, etc., (2) design, build and experiment a prototype of an FFAG magnet proper to fulfill the requirements of rapid cycling acceleration with relevant momentum and geometrical acceptance, (3) develop the concepts, and show the feasibility, of the application of such FFAG beams to anti-cancer hadron therapy and to researches in radiobiology.

At Daresbury Laboratory

Acceleration of muon in FFAG for neutrino factory was first proposed in Japan [11]. It assumed radial sector type FFAG. Compared with linac and recirculating linear accelerator (RLA), a beam goes through the same rf cavity more times which would make the whole machine cost cheaper because the costly part of the machine is the rf system. The actual design of magnet for muon acceleration seems, however, relatively large because the orbit moves quickly on the low momentum side and the shift becomes less when a beam is accelerated. Although the field profile of Eq. (3) is required to keep the transverse tune constant, it may be an irrelevant requirement for muon acceleration because a muon beam circulates only for 10 to 20 turns. A beam may not see any effects even if the tune moves and crosses integer and half-integer tune.

A new type of FFAG called nonscaling FFAG was introduced to squeeze the magnet and letting tune move [12]. The conventional type of FFAG is then called scaling type because the orbits corresponding to different momenta are similar and focusing length is scaled to the average radius. Nonscaling FFAG is essentially a synchrotron without ramping magnets. It consists of only dipole and quadrupole magnets and orbit moves outward and tune becomes lower as accelerated. If we make, however, an optics such that dispersion function is minimized, orbit shift can be less than that of scaling one. Neutrino factory based on nonscaling FFAG became the baseline in the recent study as a cost effective scinario [13].

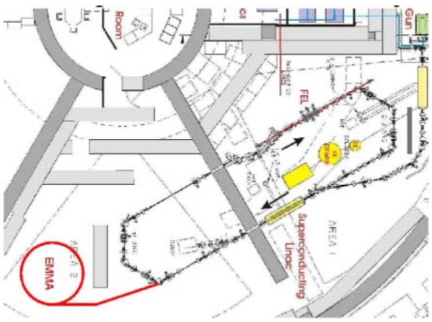

Figure 5: EMMA ring following ERLP machine.

It is, however, hard to convince people that nonscaling FFAG works as we expected. To demonstrate the nonscaling FFAG principle, just as a small FFAG model did at KEK in late 1990s, a low energy electron model was discussed in the community for years and finally Daresbury laboratory hosts the construction project called EMMA [14]. EMMA uses an electron beam from energy recovery linac prototype (ERLP) accelerator and accelerate it from 10 to 20 MeV in about 10 turns. The project will start this year.

ACCELERATOR PHYSICS ISSUES

Nonscaling FFAG and its variety

Idea of nonscaling FFAG makes people think that many variety of optics are possible once we give up the magnetic field profile of Eq. (3). Rees has actually shown that constant tune can be achieved if we have three different kinds of magnets and shape field profile in a proper way [15]. Preliminary results show that the lattice has smaller dynamics aperture than scaling and nonscaling FFAG, partially because of nonlinearity of the profile, so that it may not be applicable to muon beams. Constant tune with smaller orbit shift is, however, attractive and it is a good candidate for proton acceleration with reasonable size of emittance. Another electron model to prove the principle is proposed.

Muon acceleration with constant rf frequency

Either scaling or nonscaling FFAG does not have isochronism so that the frequency of rf cavitiy has to be, in principle, synchronized to the revolution frequency. It is not a problem if the repetition rate is the order of 1 kHz or 10 kHz if we use low Q cavities such as MA loaded one. For muon acceleration, however, the whole cycle is completed only in 10 to 20 turns and it is hard to modulate rf frequency, even though it is not impossible. There are two methods considered, one for each scaling and nonscaling FFAG. For scaling FFAG, rf voltage makes a single rf bucket whose bucket height is more than the momentum range of acceleration. A bunch injected in the bottom part of the rf bucket starts synchrotron oscillation and reaches the top part of the bucket after a half synchrotron period. Such a large bucket can be created with relatively low rf frequency such as 1 to 5 MHz.

Nonscaling FFAG, on the other hand, uses a different method [16]. In the process of lattice optimization, nonscaling FFAG lattice is adjusted such that the transition momentum is in between injection and extraction momenta. Because the particle is already ultra relativistic, entire variation of path length becomes minimum when the transition momentum was chosen in between. Now if we fix the rf frequency a bit higher than the revolution frequency at transition momentum, two stable fixed points appear in the longitudinal phase space: one above injection and the other below extraction momentum. A bunch injection below the first fixed point is now going outside the first bucket to the second one and reaches the final momentum. The rf frequency in this case is 200 MHz.

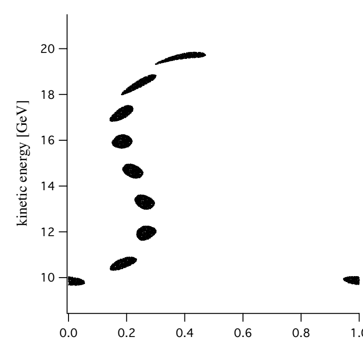

Figure 6: Acceleration outside buckets. One stable fixed points is located at (0, 12.5) and the other at (0.5, 17.5).

Harmonic number jump

There is one possible way of using constant rf frequency in FFAG. If the change of revolution frequency per turn is large enough, a bunch could be captured in a bucket above the current one [17]. The new bucket should have a different harmonic number: it increases if the momentum is above the transition and vice versa. If this scheme works, FFAG can accelerate beams continuously like a cyclotron. It makes the average beam currents even higher. In practice, one has to adjust the energy gain as a function of momentum. It requires the rf cavity whose field gradient varies in radial direction.

Resonance crossing

Scaling FFAG is supposed to have a constant tune. End fields and mechanical errors of magnets, however, slightly alter the scaling conditions and the tune starts to migrate around the ideal tune. In principle, iteration of 3D field calculation and particle tracking would tell the detailed shape of the end. However, the convergence is not always certain in practice.

If, on the other hand, we know the effects of resonance crossing and the way to correct the driving source, we can allow the tune migration to some extent. The mechanism of resonance crossing was studied with particle trapping model [18]. Since the scaling FFAG has inherent 0^{th} order octupole component, tune shift as a function of amplitude makes isolated islands when a beam cross a resonance. If the crossing occurs adiabatically, the trapped particles are brought to the large amplitude and got lost eventually. The study by Aiba showed the magnitude of adiabaticity to be avoided.

In nonscaling FFAG, there are more concerns about the crossing of linear resonance such as half-integer. Although people believe that it is not harmful if the crossing is fast enough, it is still not clear how fast is enough. Preliminary results show that what happens actually when a beam crosses a linear resonance is mismatch of optics between a cell, nothing like a "resonance" in a conventional sense [19].

Another study on resonance crossing in FFAG deals with space charge. Nonscaling FFAG in principle does not have any nonlinearity so that only linear resonance seems to be a problem. However, when space charge force is not negligible, it excites nonlinear resonance such as octupole and dodecapole. Lee shows that in some case, especially when the tune moves slowly, those space charge induced resonances make a beam blowup which imposes the fundamental limitation on the current in nonscaling FFAG [20]. It also shows how fast the crossing is supposed be to avoid the emittance deterioration.

Time of flight of large amplitude particle

A large emittance beam like muon cannot ignore the time of flight difference coming from transverse amplitude. This affects the energy gain of acceleration outside buckets. Chromaticity correction reduces the difference, but it also introduces nonlinearity and acceptance becomes an issue. It is one of problems to be solved [21].

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