CHALLENGES FOR HADRON (AND LEPTON) NON-SCALING FFAG*

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Abstract

We review the use of FFAG accelerators with Non-Scaling Lattice for several applications, and list their features and issues. Some of these issues are of major concern and need to be addressed either numerically or with experiments. In particular of great concern is the multiple resonance crossing due to the large variation of the betatron tunes during the acceleration cycle.

INTRODUCTION

Fixed-Field Alternating-Gradient (FFAG) accelerators were invented about 50 years ago by K. Symon [1] and T. Ohkawa [2], and two electron prototypes were soon built and operated at MURA during the late 50's and early 60's [3-5]. A higher-energy prototype of around 50 MeV [6] was also subsequently built, but the project was discontinued because it was soon found to be difficult to operate. The technology of that time could not provide satisfactorily solutions for the design and manufacturing of complicated magnet and RF structure, and at the same the FFAG was thought to be more expensive than conventional AG machine of same energy. There was a revival about 15 years ago with proposals to use FFAGs as Spallation Neutron Sources [7]. But then again the concept was dismissed. Soon after nevertheless new concepts for Muon Colliders and Neutrino Factories were conceived [8]. There is need to accelerate intense beams of muons to 20 GeV. Because of the short lifetime of the particles, the beam has to be accelerated quickly, and several accelerator scenarios were investigated: the Rapid-Cycling Synchrotron (RCS) was found to be too slow for the purpose; a SCL at 200 MHz was judged to be too cumbersome and too expensive; because of the very large betatron beam emittance re-circulation in Linacs was found difficult for the beam to merge and to separate in the arcs. The FFAG accelerator seems the only possible solution for the fast acceleration of muons. As a consequence a sequence of meetings were initiated about half a dozen of years ago to study acceleration of muons in a number of FFAG accelerators. At the same time two FFAG prototypes were built at KEK in Japan [9]. They were commissioned and operated successfully, the last one accelerating protons to 150 MeV. Obviously the interest of experts soon included also the possible acceleration of protons for a variety of applications.

As the name implies, FFAG accelerators have the important feature that the guiding (bending and focusing) magnetic field does not change and is constant in time (FF). With the present available technology, this allows a simplified engineering of magnet, power supply and vacuum design and operation. Since the field is not ramped, acceleration is fast, possibly at high repetition rate. The speed of acceleration depends on the available RF system. 100 Hz repetition rate has been demonstrated [10], and it may be possible to accelerate even faster (1 kHz). As a consequence, the beam spends only very short period of time during acceleration, with better stability and lower beam losses. FFAG performance and mode of operation is between RCS and Linacs. But the amount of momentum range allowed during acceleration is only a factor of three. This may force multiple rings solution. The AG feature allows compactness of the magnet design and of the particle orbits.

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FFAG LATTICE CHOICES

Two lattices have been proposed, studied and still under consideration and evaluation.

Scaling Lattice (KEK)

An alternating field profile is chosen so that all trajectories have the same optical parameters, independent of particle momentum, achieved with a nonlinear field $B = B_0\ (r/r_0)^{-n}$. This makes the ring operation easier and the beam orbit dynamics is expected to behave regularly well and stable. But a very large physical aperture is required to accommodate a large momentum range (±30-50%) with typically large bending fields and limited insertions. There may also be a high energy limitation. This lattice prefers a sequence of DFD triplets.

Non-Scaling Lattice (the Muon Collaboration)

The alternating field profile in this case is linear. This causes a large variation of optic parameters over the required momentum range. On the other side, with the use of FDF triplets yielding small dispersion, a compact physical aperture is achieved. Also large insertions are easier to be included, and the guiding field has a lower magnetic strength. Large energies are possible and this solution is expected to be more economical.

MUON VERSUS PROTON COMPARISON

Though at the present both studies assume FDF triplets and *Non-Scaling Lattice*, there are major differences in beam dynamics and engineering that we can summarize as follows:

(1) Space-Charge effects are important at injection for protons but not very relevant for muons.

(2) There is a considerably large betatron emittance for muons, that is 30,000 versus 100 π mm-mrad for protons.

(3) Muons are essentially ultra-relativistic with velocity $\beta \sim 1$ during the entire acceleration cycle. Whereas the velocity varies for protons.

(4) The guiding field is large in the muon accelerators where superconducting magnets are needed. The guiding

field is more modest in proton rings where room temperature, more conventional magnets can be used.
(5) Superconducting RF cavities are planned for muons operating at constant frequency since of the constant beam velocity. Whereas there is RF modulation for protons because their velocity changes so much.
(6) At the present muons are accelerated outside the RF buckets in order to obtain fast acceleration in about 10 to 50 turns. Protons are accelerated more slowly in about a couple of thousand turns (or less) and acceleration occurs more conventionally inside the RF buckets.
(7) Because of the larger intensity RF beam loading is significant in the case of protons, and less for muons.
(8) Because of the particular method chosen for the acceleration of muons, the lattice needs to be isochronous over the entire acceleration cycle. That is the lattice transition energy γ_T equals the energy value in the middle of the cycle. Whereas for protons $\gamma \ll \gamma_T$ at all times.

FFAG ACCELERATION OF MUONS

Presently acceleration of muons is proposed in three rings: from 2.5 to 5, 5 to 10, and 10 to 20 GeV [8]. In each ring the beam circulates at most only 10 turns. There is a very large super-conducting RF (200 MHz) System. The method of acceleration is skirting the RF buckets (Gutter Acceleration) [11]. Isochronism condition is required, that is γ at the center of the momentum range equals the lattice transition energy γ_T. That is required to minimize the Time of Flight (ToF) across the momentum range of acceleration. There is a very Large Betatron Emittance of about 30,000 π mm-mrad. Lattice studies done so far employ FDF triplets. Computer simulation of acceleration were done in the past to demonstrate acceleration with small betatron amplitude. More recent simulation [12] have now revealed that when the finite betatron amplitude is introduced, the ToF changes so much that particles are not accelerated for an emittance larger than 10,000 π mm-mrad. This is an issue that needs to be resolved either by correcting the nonlinear effects associated with the insertion of sextupoles or by modifing the acceleration scheme with a higher RF voltage.

FFAG ACCELERATION OF PROTONS

As an example of an FFAG accelerator using *Non-Scaling Lattice* we can refer to the proposal of a new injector to the AGS at Brookhaven as part of the Upgrade program to raise the average proton beam power at 28 GeV to 1(4) MWatt [13]. This ring accelerates protons from 400 MeV to 1.5 GeV in about 7 milliseconds at the repetition rate of 2.5(5) Hz (equivalent to 2000 revolutions), using a conventional RF cavity system matching that of the AGS. The ring is made of an unbroken sequence of FDF triplets shown in Figure 1, and has a circumference of about 800 m since it is to be located in the same AGS tunnel. The main parameters are listed in Table 1. An issue of this ring is the multiple resonance crossing as it is possible to observe in Figure 2 that gives the variation of both betatron tunes during the acceleration cycle.

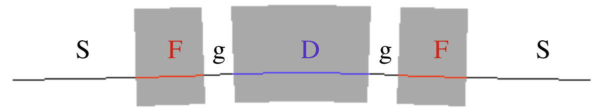

Figure 1. A Period with FDF Triplet used in the AGS-FFAG Injector Design

Table 1. Parameters of AGS-FFAG Injector at Injection

Circumference, C	807.091 m
Periodicity, N	136
Period Length, P	5.9345 m
Magnetic Rigidity, Bρ	31.8308 kG-m
Long Drift, S	2.5345 m
Short Drift, g	0.30 m
F-Sector Magnet	
Length, L_F	0.70 m
Bending Field, B_F	-0.7841 kG
Gradient, G_F	26.582 kG/m
D-Sector Magnet	
Length, L_D	1.40 m
Bending Field, B_D	1.8345 kG
Gradient, G_D	-23.296 kG/m

The following is a list of issues concerning the performance of the *Non-Scaling* FFAG accelerator for protons.
(1) Space-charge effects at injection are very large with a tune depression $\Delta\nu$ in proximity of 0.3 and even 0.5.
(2) A major application of the Proton FFAG accelerator is as a proton driver for the generation of neutrinos, and for such application a very high intensity is required of about 10^{13} - 10^{14} p/p. Moreover the mode of operation is pulsed at a repetition rate of 25-50 Hz that poses some concern about finding the best method for fast acceleration.
(3) The beam normalized full emittance is about 100 π mm-mrad, determined essentially by the space-charge at injection. When combined to the radial extension for acceleration, this gives an appreciable beam size that has to be confined in the magnet physical aperture.
(4) A feature of a proton FFAG accelerator is that there is no need to satisfy isochronous condition, since $\gamma \ll \gamma_T$ during the full acceleration cycle.
(5) There is though a large variation of the beam velocity during the cycle that may vary between 0.3 and 1. This requires special attention for the designing the RF acceleration system.
(6) The major feature of the FFAG is that since the field is constant there is essentially no limit on the operation rate. There is the question though of how fast can the RF be swept if cavities are loaded with ferrite, metal glass, or chemical alloy. Typically one requires about few MHz / msec. An alternative has been proposed recently to accelerate with constant high-frequency superconducting cavities. The method requires a pre-assigned energy gain at each cavity to allow an Harmonic Number Hopping (HNH) of one or few wavelength [14]. This method is at the present under close investigation as it is perceived that

it may be able to solve several issues concerning fast acceleration of protons in the FFAG.

(7) Possible CW mode of operation for a variety of applications is to be investigated [15]. That may be possible by exploiting the HNH method of acceleration even further.

(8) But of course the most fundamental issue for the operation of a FFAG with a linear *Non-Scaling Lattice* is the need to cross a sequence of several resonances, since it is not clear what are the consequences to the beam stability and confinement. The resonances may be intrinsically construed in the periodicity of the ring, or caused by imperfections, misalignments and magnet errors, and also driven by the space charge of the beam.

(9) Finally it is not obvious that a *Non-Scaling Lattice* FFAG in the low energy range (<250 MeV) can perform better than the demonstrated *Scaling Lattice* FFAG with similar energy and size There are two major effects that need to be investigated and that are just peculiar to the *Non-Scaling Lattice*: (i) As the ring size is reduced, the curvature effect on the beam focusing is more and more pronounced. This creates an asymmetry between horizontal and vertical motion with the vertical betatron tune getting lower than the horizontal. Since the tune decreases as the beam momentum increases, that eventually will push the lattice down closer to the stability limit on the vertical plane. (ii) The effect is even more severe when the edge angle effect from the magnets is included. It may be possible to avoid the effect for a reference orbit but not for all of them. Of course we are referring to a radial sector FFAG.

SPACE-CHARGE LIMITATION

S.Y. Lee [16] wrote "… For the non-scaling FFAG, the nonlinear resonances induced by the space charge potential can be the limiting factor. These resonances limit the phase advance of each basic cell to within $\pi/2$ to $\pi/3$, and thus the momentum acceptance is highly constrained…". He gives as the example the same FFAG ring designed for acceleration of protons mentioned above as the reference design. Space charge is indeed large at injection causing a tune depression $\Delta\nu = 0.343$. Acceleration cycle takes about 2000 turns. The range of stability is shown in Figure 2 and allows in principle acceleration only over a momentum range of ±20%. Of course the effect on the beam is to be better understood and a criteria produced relating space-charge tune-shift to the sweeping rate required for the beam stability [17].

ELECTRON MODELS

In both proton and muon applications, the adoption of a *Non-Scaling Lattice* raises the serious concern of multiple crossing of major resonances. Though muons circulates only 10 turns and protons only 100 to few 1000 turns depending on the ultimate mode of acceleration, it is obvious important to find out what is the effect on the beam size and stability when crossing a resonance. Theoretical and simulation work has been done and is still in progress. Nevertheless it is better to approach the problem from the experimental point of view and to build a small ring extrapolated in size and performance where electrons would be accelerated instead of protons and muons. Two approaches have been sought one for Muons [18] (EMMA) operating in $\beta \sim 1$ mode, and the other for protons with a variable beam velocity (SBIR) [19].

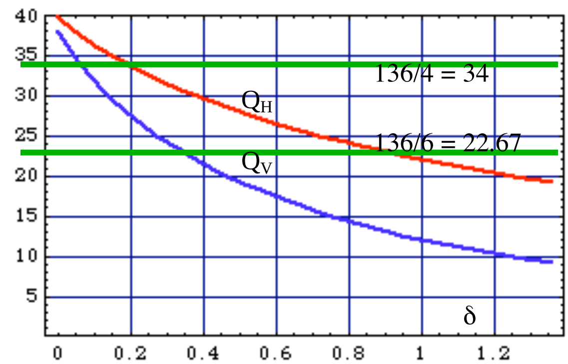

Figure 2. Betatron tune variation versus momentum deviation δ for the AGS-FFAG with range of stability according to S.Y. Lee between green lines.

CONCLUSIONS

Non-Scaling FFAG's features are: compactness, long insertions for cavities, beam transfer, higher beam energies, lower magnetic field strength, and maybe less costly. The main problem is the large variation of tunes during acceleration, that somehow need to be demonstrated to be safe to cross.

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