NEW CONCEPTS IN FFAG DESIGN FOR SECONDARY BEAM FACILITIES AND OTHER APPLICATIONS

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Abstract

Fixed Field Alternating Gradient accelerators offer much higher acceptances and repetition rates - and therefore higher beam intensities – than synchrotrons, at the cost of more complicated magnet and rf cavity designs. Perhaps because of the difficulty and expense anticipated, early studies never progressed beyond the stage of successful electron models, but in recent years, with improvements in magnet and rf design technology, FFAGs have become the focus of renewed attention. Two proton machines have now been built, and three more, plus a muon phase rotator, are under construction. In addition, more than 20 designs are under study for the acceleration of protons, heavy ions, electrons and muons, with applications as diverse as treating cancer, irradiating materials, driving subcritical reactors, boosting high-energy proton intensity, and producing neutrinos. Moreover, it has become apparent that FFAG designs need not be restricted to the traditional 'scaling' approach, in which the orbit shape, optics and tunes are kept fixed. Dropping this restriction has revealed a range of interesting new design possibilities. This paper will review the various approaches being taken.

INTRODUCTION

Following the discovery of alternating gradient (AG) focusing in 1952, FFAGs (Fixed Field Alternating Gradient accelerators) were proposed independently by Ohkawa in Japan, Kolomensky in the USSR and Symon and Kerst in the US[1]. With fixed magnetic fields, modulated radiofrequency, and pulsed beams, FFAGs operate just like synchrocyclotrons. The innovations were to break the magnet into radial or spiral sectors to provide edge and strong focusing, and (usually) to remove the central region – the same steps that convert a classic Lawrence cyclotron into an isochronous ring cyclotron (as at PSI, IUCF and RIKEN). The FFAG's place in the fixed-field accelerator (cyclotron) family is indicated in Table I. (Note, though, that some FFAG workers take a different perspective, claiming that cyclotrons are just special cases of the FFAG!)

Fixed magnetic fields lead to spiral orbits, so an FFAG's vacuum chamber and magnets tend to be larger and more costly than a synchrotron's. On the other hand, its beam intensity can be much higher, as the radial and momentum acceptances are larger, and the repetition rate is set purely by rf considerations.

Table I: The cyclotron family

Magnetic field gradient	Fixed frequency (CW beam)	Frequency-modulated (Pulsed beam)
Uniform	Classical	Synchro-
Alternating	Sector-focused	FFAG

The most intensive studies were carried out by Symon, Kerst and others at MURA (the Mid-western Universities Research Association) in Wisconsin, and culminated in the construction and successful testing of electron models of radial-sector and spiral-sector designs[2]. But the proposals for proton FFAGs were not funded at that time, nor in the 1980s when 1.5 GeV machines were proposed by the Argonne[3] and Jülich[4] laboratories as spallation neutron sources.

Over the last few years, however, there has been a resurgence of interest in FFAGs for applications requiring large acceptance and very high repetition rate (>50 Hz). Moreover, it has become apparent that FFAG designs need not be restricted to the 'scaling' approach explored in the 1950s. Dropping this restriction has revealed a range of interesting new design possibilities, which have been explored in a series of FFAG Workshops held at KEK[5] (five times), BNL[6], CERN[7], FNAL[8], LBNL[9], and TRIUMF[10].

SCALING FFAGS

Resonance crossing was a big worry in the early days of AG focusing, because of the low energy gain/turn. The *scaling* principle was therefore adopted, whereby the orbit shape, optics and tunes are kept the same at all energies. To first order the latter are given by:

$$\nu_r^2 \approx 1 + k \quad (1)$$

$$\nu_z^2 \approx -k + F\,(1 + 2\tan^2\varepsilon) \quad (2)$$

where
- the average field index $k(r) \equiv r\,(dB_{av}/dr)/B_{av}$
- the average field at radius r is $B_{av} \equiv \langle B(\theta)\rangle$
- the magnetic flutter $F \equiv \langle (B(\theta)/B_{av} - 1)^2\rangle$
- the spiral angle is ε.

Clearly, constant ν_r requires k = constant, implying a magnetic field profile $B_{av} = B_0(r/r_0)^k$ and a momentum profile $p = p_0(r/r_0)^{k+1}$. Consequently, constant ν_z requires constant $F\,(1 + 2\tan^2\varepsilon)$ - a quantity that must also be given a high value, since usually $k >> 0$ to minimize the radial aperture. MURA's recipe was to keep the flutter $F(r)$ = constant, by using constant profile $B(\theta)/B_{av}$ and:

- for spiral sectors: constant ε, so sector axis $R = R_0 e^{a\theta}$;
- for radial sectors: boost F by specifying $B_D = -B_F$.

Of course, reverse fields raise the average radius. The "circumference factor" is ≥4.5 if there are no straights[1], but smaller with them (1.8 for the KEK 150 MeV).

FFAGs operating or under construction

Recent years have seen the construction of the first-ever FFAGs for protons by Mori's group at KEK and the

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Table II: Scaling FFAGs built or being built

	E (MeV)	Ion	Cells	Spiral angle	Radius (m)	Comments/ 1st beam
KEK-PoP	1	p	8	0°	0.8-1.1	2000
KEK	150	p	12	0°	4.5-5.2	2003
KURRI	150	p	12	0°	4.5-5.1	120 Hz, 1 μA
-ADSR	20	p	8	0°	1.3-1.9	in 2005
	2.5	p	8	40°	0.6-1.0	[1kHz, 100μA, 200MeV later]
PRISM	20	μ	10	0°	6.5	Phase rotator

initiation of several more (Table II) - all following scaling principles. The 1 MeV POP (Proof of Principle) FFAG has eight sectors, each consisting of a DFD radial-sector triplet, and came into operation in 2000[11]. The larger 150 MeV FFAG (Fig. 1) is a prototype for proton therapy and neutron production. It has 12 sectors, also DFD, with the orbit radius increasing from 4.4 to 5.3 m. Beam injected from a 12 MeV cyclotron was accelerated to full energy in 2003[12] and has recently been extracted. Both machines have provided valuable confirmation of the predicted beam behaviour.

These machines introduced important innovations in both magnet and rf design. The DFD triplets are built and powered as single units, without a steel return yoke, forcing the return flux through the D and automatically providing reverse field. The open structure also facilitates injection and extraction. The rf innovation (remember the cumbersome rotary capacitors on synchrocyclotrons?) is the use of FINEMET metallic alloy tuners, which offer:

- rf modulation (with a 1.5-4.6 MHz sweep) at 250 Hz or more, and so high beam-pulse rep rates;
- high permeability, and so short cavities with high effective fields;
- low Q (≈1), allowing broadband operation without any need for active tuning.

A 150 MeV FFAG of the same design is being installed at the Kyoto University reactor, in collaboration with Mitsubishi, to test accelerator-driven sub-critical reactor (ADSR) operation. This is part of a 3-ring complex[13], with two further FFAGs (Fig. 2) acting as injector (a 2.5-MeV betatron with eight spiral sectors) and booster (20 MeV with eight radial sectors). Initially the repetition rate will be 120 Hz, yielding a 1 μA beam, and then later 1 kHz, providing 100 μA.

Figure 1: 150 MeV FFAG and cyclotron injector at KEK.

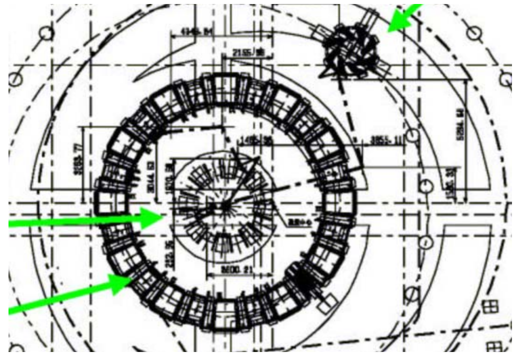

Figure 2: Kyoto three-stage FFAG for ADSR.

FFAGs are also of interest for muons. PRISM (Phase-Rotated Intense Slow Muon source)[14], based on a 10-cell DFD radial-sector FFAG of 6.5 m radius (Fig. 3), is under construction at RCNP Osaka for eventual installation at J-PARC. It will collect 5 ns wide bunches of muons at 68 MeV/c ± 30% and use a sawtooth rf field to rotate them in phase space, reducing the momentum spread to ±3%. With a repetition rate of 100-1000 Hz the muon intensity will be 10^{11}-10^{12}/s, making possible ultra-sensitive studies of rare muon decays. It is also planned to use PRISM for ionization cooling of muons.

Scaling FFAG studies

In addition, more than a dozen different scaling FFAG designs are being studied (Table III), especially in Japan. These range from a fist-sized 1-MeV prototype for electron irradiation, to medium-sized sources for proton and ion therapy, to the 240-m diameter 20 GeV muon ring proposed for a neutrino factory. Both radial- and spiral-sector designs are employed, the former all using DFD triplet cells.

For cancer therapy, FFAGs can provide advantageously high pulse repetition rates. For the Ibaraki Medical Accelerator[15], KEK is proposing a 230MeV proton FFAG with 8 spiral sectors and 20-Hz rep rate. The Mitsubishi Electric Co. (MElCo) has also studied a 230-MeV proton FFAG[16], but using a compact superconducting magnet with 3 radial sectors.

MElCo has also designed a two-stage FFAG for ion therapy[16], but with spiral-sectors. In this case a 12-sector booster would accelerate C^+ ions to 62 MeV/u, or protons to 230 MeV. The 16-sector main ring would take

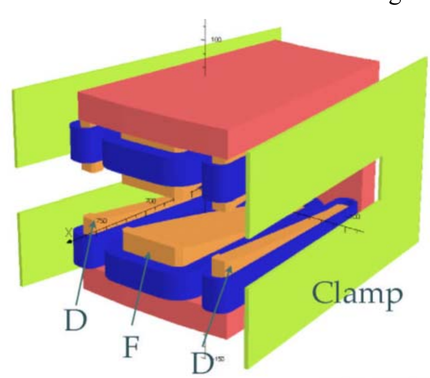

Figure 3: Magnet for the PRISM muon phase space rotator.

Table III: Scaling FFAGs - design studies

Accelerator	Energy (MeV/u)	Ion	Cells	Spiral angle	Radius (m)	Rep rate (Hz)	Comments
Ibaraki Medical Acc.	230	p	8	50°	2.2-4.1	20	0.1 μA
eFFAG	10	e	8	47°	0.26-1.0	5,000	20-100 mA
MElCo - Laptop	1	e	5	35°	0.023-0.028	1,000	Hybrid, Magnet built
MElCo - Ion Therapy	400	C^{6+}	16	64°	7.0-7.5	0.5	Hybrids =
(Mitsubishi Electric)	7	C^{4+}	8	0°	1.35-1.8	0.5	FFAG/synchrotrons
MElCo - p Therapy	230	p	3	0°	0-0.7	2,000	SC, quasi-isochronous
NIRS Chiba	400	C^{6+}	12	0°	10.1-10.8	200	Compact
- Ion Therapy	100	"	12	0°	5.9-6.7	"	radial-sector
Accelerators	7	C^{4+}	10	0°	2.1-2.9	"	designs
Muon Cooling Ring	160	μ	12	0°	0.95±0.08		Gas-filled
J-PARC	20,000	μ	120	0°	120		Δr = 0.5 m, ≈10 turns
Neutrino	10,000	"		0°	55		Superconducting
Factory	3,000	"		0°	30		magnets
Accelerators	1,000	"		0°	10		Broadband rf operation

the C^+ to 400 MeV/u. NIRS Chiba is also proposing FFAGs for ion therapy, but with three radial-sector rings operating at 6, 100 and 400 MeV/u[17]. The largest, with 12 sectors, has a circumference of 70 m. The complex is designed to operate at 200 Hz and provide a beam of 2 x 10^9 C^+ ions/s.

For industrial irradiation, CT scanning and radiation therapy, a Japanese collaboration has devised the 8-sector spiral eFFAG[18] to accelerate 20-100 μA electron beams to 10 MeV. MElCo has already built the magnet (Fig. 4) for a 1-MeV prototype of a similar project[16], appropriately named "Laptop"; the overall diameter is 10 cm and the mass a mere 2.8 kg!

For ionization cooling of 250 MeV/c ± 30% muons, Garren *et al.*[10] have studied a small 12-sector gas-filled FFAG with superconducting magnets (96 cm radius).

The KEK group's most ambitious plan[19] is to build a neutrino factory at J-PARC based on a sequence of four muon FFAGs with top energies of 1, 3, 10 and 20 GeV. The largest would have a radius of 200 m (with a total orbit spread of 50 cm) and consist of 120 cells, each containing a superconducting DFD triplet. Most of the cells would also contain rf cavities to provide an overall energy gain of around 1 GeV per turn, restricting the losses due to muon decay to 50% overall. The use of low-frequency rf (24 MHz) keeps the buckets wide enough to contain the phase drift occurring as the orbit expands. A major advantage of FFAGs over linacs - either single or recirculating - is that their large acceptances in *r* and *p* obviate the need for muon cooling or phase rotation. There are also significant cost savings on the accelerators themselves.

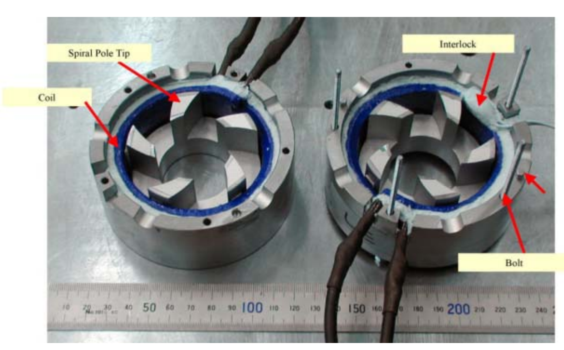

Figure 4: 5-Sector magnet for 1-MeV "Laptop" FFAG.

LINEAR NON-SCALING FFAGS

The rapid acceleration (<20 turns) essential for muons allows betatron resonances no time to damage beam quality. Scaling can therefore be abandoned, the tunes allowed to vary, and a wider variety of lattices explored - as pointed out in 1997 by Mills and Johnstone[20] in a study of FFAG arcs for recirculating linacs. Moreover, using constant-gradient "*linear"* magnets greatly increases dynamic aperture and simplifies construction, while employing the strongest possible gradients minimizes the real aperture. Johnstone[21] applied this *non-scaling* approach to a complete FFAG ring, showing that it would be very advantageous to use superconducting magnets with positively bending Ds stronger and longer than the Fs (*i.e.* both B_D and $|B_F|$ decrease outwards). The radial orbit spread could be reduced (allowing the use of smaller vacuum chambers and magnets), and the orbit length $C(p)$ shortened and made to pass through a minimum instead of rising monotonically as $p^{1/(k+1)}$ (Figure 5). The variation in orbit period is thereby reduced, allowing the use of high-Q fixed-frequency rf.

$C(p)$'s parabolic variation and its parametric dependence can be derived using a simple model[22], treating the

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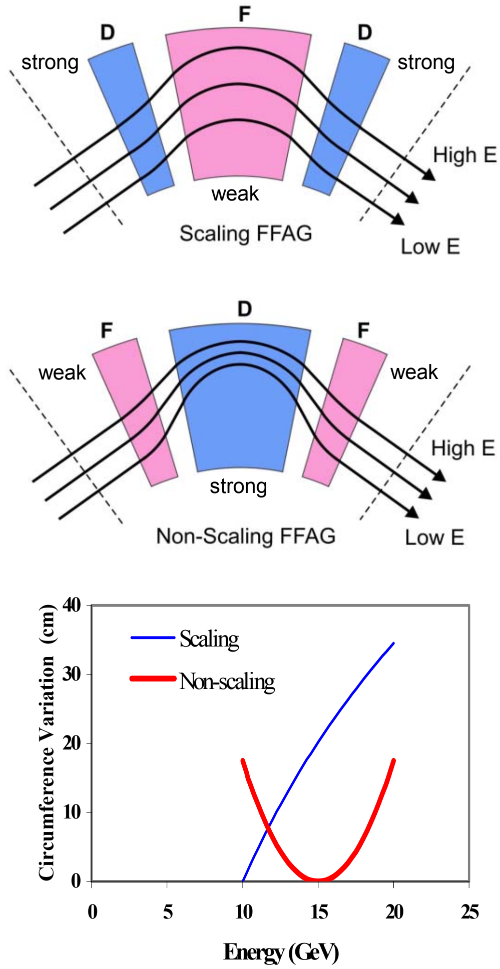

Figure 5: Scaling and non-scaling FFAG orbit patterns (above), and circumference variation with energy (below).

F and D magnets as thin lenses of equal strength q (gradient × length). For symmetric F0D0 or triplet cells:

$$C(p) = C(p_m) + (12\pi^2/e^2q^2NL_{FD})\,(p - p_m)^2 \qquad (3)$$

where N is the number of cells, and L_{FD} is the (shorter) F-D spacing. The minimum is at $p_m = (4p_c + eqL_{FD})/6$ where the p_c closed orbit is such that $B_F = 0$. The orbit radii $r(p)$ show similar dependence, with distinct p_{min}.

Lattices along these lines have been developed[5,6,10] by Johnstone at Fermilab, by Berg, Courant, Trbojevic and Palmer at Brookhaven, by Keil at CERN and Sessler at LBNL, and by Koscielniak at TRIUMF. The latest results from an ongoing cost-optimization study by Berg and colleagues shows that a 2.5-5.0 GeV FFAG would be similar in price to a linac, but that 5-10 and 10-20 GeV rings would be less expensive. The main ring, to be composed of around 100 doublet (or perhaps FDF triplet) cells, would have a circumference of about 700 m, with orbit lengths varying by only 20 cm. With the orbit time first falling and then rising, Berg[23] and Koscielniak[24] have shown that by exceeding a critical rf voltage an acceleration path can be created (Fig. 6) that stays close to the voltage peak (crossing it three times), snaking between neighbouring buckets (rather than circulating inside them) just as in an imperfectly isochronous cyclotron[25]. By using high-field superconducting 200 MHz cavities it should be possible to accelerate from 10 to 20 GeV in 16 turns, with a decay loss of 10% (25% in the three rings).

Table IV: Cost-optimized lattices for muon FFAGs

Energy	Circumference	Cells	Turns	Decay
2.5-5 GeV	246 m	64	6	6%
5-10 GeV	322 m	77	10	7%
10-20 GeV	426 m	91	17	8%

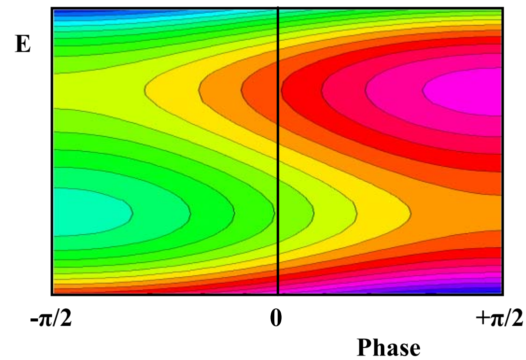

Figure 6: Serpentine acceleration path (yellow) in longitudinal phase space for linear non-scaling FFAG.

In order to demonstrate the novel features of such a design - particularly acceleration outside buckets and the crossing of many integer and half-integer resonances - the construction of a 10-20 MeV electron model is being considered[8,26]. Daresbury has offered to host the project and allow its 8-35 MeV Energy Recovery Linac Prototype (ERLP) to be used as injector.

Keil, Trbojevic and Sessler have looked into the use of linear non-scaling FFAGs for cancer therapy and report designs for 250-MeV proton and 400-MeV/u C^{6+} machines[27]. Their study shows that not unreasonable rf voltages (<1 MV at ~20 MHz) are needed to retain good beam quality while crossing more than a dozen integer and half-integer imperfection resonances (the design avoids all intrinsic resonances below 3rd order).

NON-LINEAR NON-SCALING FFAGS

Isochronous FFAGs

By using non-linear field profiles and a slightly more complicated dFDFd cell structure, Rees [5] has been able to design a muon ring that is exactly isochronous at 20 discrete energies from 8 to 20 GeV - a muon cyclotron! Although isochronous cyclotron designs in this energy range have been reported before[28], they have relied on spiral-edge focusing. What is remarkable here is that there is no spiral - the focusing stems just from flutter, alternating gradients and perhaps higher order terms omitted from (1) and (2) above, as suggested by Teng long ago[31]. Equally remarkable is that, in the latest version[8], four 8- or 10-cell insertions have been included, with good matching to the main arcs (Fig.7). The insertion cells are similar in structure to those in the arcs but with much

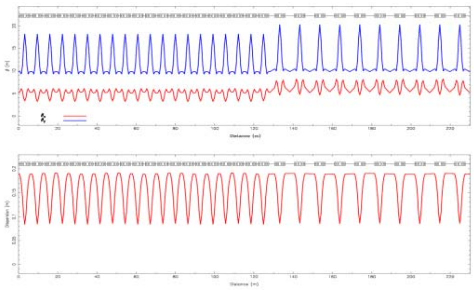

Fig. 7: Lattice function matching between normal cells and insertion cells in an isochronous FFAG at 14.75 GeV.

longer drifts, allowing the use of more efficient multi-cell rf cavities, and shortening the circumference to ≈900 m for 120 cells. Méot *et al.*[29] have carried out tracking studies on the earlier version using realistic magnetic fields and find small losses at some resonances.

An alternative 10-20 GeV scheme by Schönauer[5] uses 66 BFDbDFB cells with only 4 non-linear magnets per cell, so that the total of these is only 264, compared to 600 for Rees. This ring is not as closely isochronous, but has roughly constant ν_r and ν_z.

Adjusted-Field-Profile FFAGs

Another interesting avenue has been opened by Ruggiero[30], who has used non-linear magnets in non-scaling FDF cells to design a number of medium-energy proton FFAGs:

- 1.5 GeV replacement for the AGS Booster (R = 128 m, N = 136, 2.5 Hz, 40 μA)
- 1 GeV 10 MW proton driver (R = 32 m, N = 40, 1000 Hz, 10 mA)
- 250 MeV proton therapy FFAG.

As only modest rf voltages are assumed, no resonance crossings are allowed, but he is able to keep the tunes sufficiently constant (Fig. 8) by using "adjusted field profiles" (AFPs) that are non-linear in both r (a lot) and θ (a little), so that the changes in radial gradient balance those in flutter. The non-scaling virtue of low dispersion is retained by using FDF cells with stronger D magnets than F magnets.

The exploration of non-scaling lattices has only just begun, but the initial forays have already yielded some remarkable results. Who knows, maybe there are yet more varieties of FFAG waiting to be discovered?

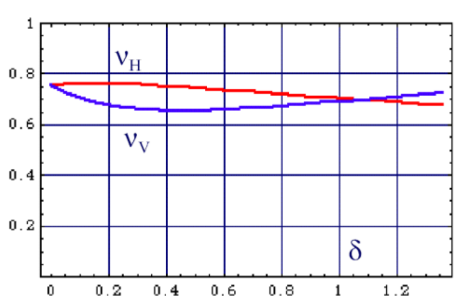

Figure 8: Tune variation with momentum for an AFP FFAG replacement of the 1.5 GeV AGS Booster.

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