HIGH INTENSITY AND OTHER WORLD WIDE DEVELOPMENTS IN FFAG ACCELERATORS

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Abstract

Here I present an overview of developments in Fixed Field Alternating Gradient accelerators, focusing on high intensity hadron accelerator designs. I will detail progress in studies of space charge effects and simulation, experimental characterisation of a 150 MeV proton FFAG at KURRI in Japan, experimental optimisation of FFAGs and novel FFAG developments for future applications.

INTRODUCTION

Fixed field Alternating Gradient (FFAG) accelerators combine strong focusing optics like a synchrotron with a fixed magnetic field like a cyclotron. Unlike a synchrotron, the magnetic field experienced by the particles is designed to vary with radius, rather than time. In the original types of FFAG invented in the 1950's and '60's, the vertical component of the magnetic field B_y varies with radius R according to the 'scaling law' according to

$$B_y = B_0 (\frac{R}{R_0})^k, \qquad (1)$$

with field index k, reference radius R_0 and field at that radius B_0. In the radial sector FFAG the alternating gradient is achieved with opposite sign 'F' and 'D' magnets, whereas in the case of the spiral sector FFAG, the polarity does not change but a spiral angle is used to gain additional focusing.

A revival of interest since the 1990s has seen a number of FFAGs constructed, including scaling and linear non-scaling variants for protons [1,2] and electrons [3] respectively. Since this time, the range of FFAG designs has rapidly diversified and there are now designs with non-linear field profiles and non-radial edge angles, racetrack shapes or super-periodic structures, dispersion suppression sections, vertical orbit movement and other innovations. While it would be impossible to give an exhaustive review of such developments here, I will highlight examples to direct the reader toward the general direction of travel in this constantly evolving field.

In recent years, the focus of the community has started to shift away from basic proof-of-principle designs and further toward designing FFAG accelerators for real world applications. This has led to a significant amount of novel development in the field, for example, through recent work towards recirculating FFAG arcs for the eRHIC project.

In the high intensity direction, work is underway to establish design principles for high intensity FFAG accelerators for applications including radioisotope production, neutron spallation sources and accelerator driven systems (ADS). This has highlighted the need to establish a better understanding of the limitations of these machines with high bunch charge. From 2013 an international collaboration between institutes in Japan, UK and USA has been formed to use an existing scaling proton FFAG accelerator at Kyoto University Research Reactor Institute (KURRI) in Japan to work toward exploring the high intensity regime in FFAG accelerators. Experimental campaigns have thus far been aimed at characterising this machine in detail. At the same time, a detailed simulation and code development programme is underway, highlighting the complexities of benchmarking observed FFAG dynamics to simulation models, particularly when imperfections exist in the machine.

Alongside this new direction, FFAG accelerators are considered to be a promising option for medical applications at lower intensity due to their capability of high repetition rate and variable energy extraction operation with no limitation on top energy. Detailed concepts of FFAGs for proton and ion therapy have now been developed taking into consideration the desire for proton tomography capability. As this field moves toward optimised accelerators with rapid variable energy extraction, the FFAG concept is particularly promising for beam-lines and gantries with large energy acceptance over the entire treatment range while maintaining a fixed magnetic field. This and other potential applications will be discussed in the latter section.

TOWARD HIGH INTENSITY

General Features of FFAGs for High Intensity

Fixed field accelerators which employ DC magnets lend themselves naturally to high power operation, as the repetition rate of the machine can be increased above the 50-60 Hz of rapid cycling synchrotrons up to 100 or 200 kHz, dependent only on the rf system. If the magnets are superconducting or permanent magnets, the energy efficiency may be improved over existing machines which employ rapidly ramped, resistive magnets.

In this regime, we have to differentiate between high power beams and high intensity beams. In a cycled machine such as a synchrotron, a beam with high power requires a very high intensity and very high peak current, whereas for a CW machine a very high power can be achieved with relatively low peak current. The peak current determines the space charge tune shift and the main beam dynamics issues to be addressed.

In the FFAG community ideas are being developed for CW cyclotron-like machines which maintain strong focusing to higher energies using edge angles and arbitrary field profile with radius [4–6]. Concepts which introduce additional degrees of freedom to the orbit shape or movement, such

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a vertical orbit variation in order to achieve isochronous orbits [7], could also achieve CW operation.

Regardless of the choice of CW or high repetition rate machines for high power, there are a number of features of the FFAG which are relevant to operation in this regime. FFAG accelerators typically have a large momentum acceptance and a large dynamic aperture, with a larger horizontal aperture than vertical. This leads to some novel features such as the ability for the horizontal emittance to be made larger than the vertical to mitigate space-charge effects.

For example the vertical space charge tune shift is given by:

$$\Delta Q_v = -\frac{n_t r_p}{\pi \epsilon_v (1 + \sqrt{(\epsilon_h/\epsilon_v)}\beta^2\gamma^3} \frac{1}{B_f}. \tag{2}$$

Where n_t is the total number of particles in the accelerator and r_p is the classical proton radius, $\epsilon_{h,v}$ are the horizontal and vertical emittances and B_f is the bunching factor. If one can vary the horizontal to vertical emittance ratio and increase the repetition rate of a pulsed machine, one might conceivably increase the average power by a large factor without increasing the number of particles in the machine. For example increasing the $\sqrt{(\epsilon_h/\epsilon_v)}$ factor by 3 and changing the repetition rate from 25 Hz to 100 Hz would increase the average beam power of a 1 MW machine to 8 MW for the same bunch charge. It is then still possible to increase the injection energy to take advantage of the $\beta^2\gamma^3$ factor.

The flexibility of the FFAG is also an advantage. As the magnetic field is temporally fixed, the rf profile can be varied to manipulate the beam in a flexible way. Beam stacking at high energy may allow a flexible repetition rate for extraction of beams for neutron users, for example.

KURRI-FFAG Experimental Collaboration

With these potential capabilities in mind, an international collaboration was established in 2013 to use an existing proton FFAG at Kyoto University for beam studies, using the 'main ring' 150 MeV proton FFAG at KURRI, Japan. This has recently resulted in a comprehensive characterisation [8] including orbit matching, tune measurement, field index measurement, closed orbit distortion and correction, dispersion measurement and a measurement of energy loss due to the beam stripping foil. The main machine parameters are shown in Table 1 and the ring is shown in Figure 1.

Table 1: Parameters of the 150 MeV FFAG

Parameter	Value	
r_0	4.54	m
Cell structure	DFD	
N_{cells}	12	
k, field index	7.6	
Injection Energy	11	MeV
Extraction Energy	100 or 150	MeV
f_{rf}	1.6-5.2	MHz
B_{max}	1.6	T

Figure 1: The KURRI 150 MeV FFAG is the larger ring shown here with the pre-2011 injector ring. H$^-$ charge exchange injection from the linac occurs in the top left of the image.

Future goals of the collaboration are to work toward operational regimes which demonstrate high intensity capability. This includes experimental work with asymmetric emittance operation, dynamic aperture studies, proof of principle of beam stacking [9] at high energy and re-shaping of the bunch timing structure. In hardware terms, the addition of an extra rf cavity will reduce beam losses during rf capture and throughout the acceleration cycle.

Simulations and Space Charge

There are a range of simulation codes now available to model FFAG accelerators. The beam orbit in an FFAG moves radially with momentum, as in a cyclotron. Synchrotron simulation codes which assume a central orbit independent of momentum are unsuitable for studying FFAGs as they do not reproduce the correct dynamics. A few codes which remove the constraint of the existence of the central orbit were selected to perform benchmarking, including OPAL, Zgoubi, SCODE, MAUS and EARLIETIMES, although others exist [10]. The detailed benchmarking of these codes against each other for basic dynamics and with space charge effects is ongoing [11]. An example of code benchmarking for the betatron tunes in the KURRI 150 MeV FFAG are shown in Fig.2. Note that a discrepancy exists between these benchmarked simulation results and real experimental results which is due to magnetic field imperfections. This has led to new ideas of how to correct FFAG dynamics in the presence of imperfectly scaling magnetic fields [12].

Of these codes, OPAL [13] incorporates a highly sophisticated 3D space charge solver, and has recently been updated to include variable frequency acceleration capability essential for modelling non-CW FFAGs.

Frozen model space charge effects are included in SCODE and have also now been included in one of the most frequently used tracking codes for FFAGs, called 'ZGOUBI'. [14].

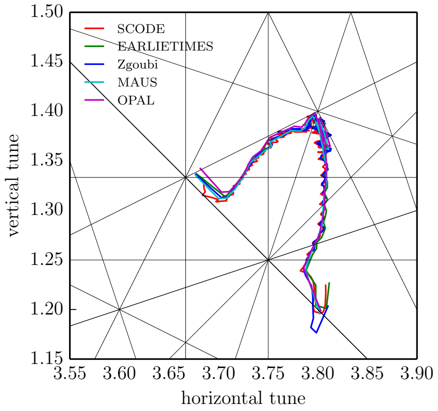

Figure 2: Benchmarking of simulation codes for betatron tunes in the KURRI-FFAG.

DESIGN STUDIES FOR HIGH POWER APPLICATIONS

Design Studies for Future Neutron Spallation Sources

In recent years, proton beam powers for neutron spallation sources have surpassed the 1 MW level. Future sources are expected to provide ever higher power beams with low losses, low energy consumption, low capital cost and with greater flexibility than current machines. In the UK, preliminary design studies are underway for a future neutron source in 15-20 years time. Two options are being considered at present; a rapid cycling synchrotron and an FFAG.

The main FFAG options being considered are the so-called ‘pumplet’ model [15] which uses five magnets per cell to achieve stable tunes and a new innovation called the ‘DF Spiral FFAG’ [16]. In this 1.2 GeV design a small negative field is introduced on one side of the main spiral magnet of a spiral FFAG. This increases the field flutter effect as in a cyclotron to overcome a limitation of regular spiral FFAGs which have relatively weak focusing in the vertical plane. It also introduces a new variable - the ratio between the F and D magnets - which can provide further control over dynamics.

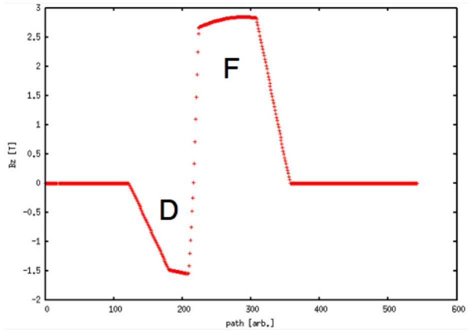

Figure 3: The vertical component of magnetic field experienced by a particle traversing a sector of the DF-Spiral FFAG.

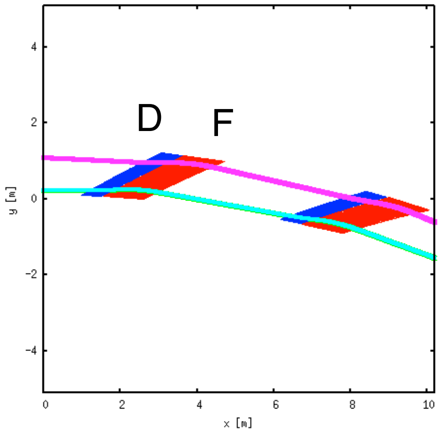

Figure 4: Layout of two cells of the DF-Spiral FFAG.

This design has the advantage of a long straight section of around 5 m for injection and extraction, however this long straight has some dispersion. The impact of dispersion in regions of injection, extraction, rf acceleration and collimation must be considered.

Perhaps the most unconventional idea for these machines is to use direct proton injection with a tilted septum to paint in 4D transverse phase space, rather than H^- charge exchange injection. This technique is currently under study, which will simplify the injection chicane and reduce issues of multiple scattering, thermal and lifetime effects associated with high power beams on stripping foils. Encouraging initial results show that a zero-loss system could be possible with up to 350 turns accumulated at injection for a spallation source type ring [17].

Design Studies for ADS

For the application to accelerator driven systems (ADS), a very high average beam power of 10 MW or higher is required in CW mode, which translates to an average beam current of around 10 mA. To achieve this, a number of proposals for fixed frequency rf FFAGs exist [18].

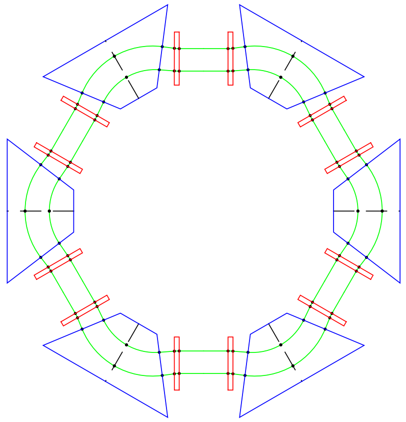

Figure 5: An example of a 6-sector 1 GeV FFAG design for ADS.

Johnstone et al., have developed designs in which the orbit at each momentum can be made proportional to velocity in order to achieve isochronicity and at the same time the betatron tune can be controlled through both edge and weak focusing [4–6]. This is in contrast to a classical cyclotron where the main field is predominately the dipole field, which has limitations in adapting the path length to velocity into the relativistic regime.

An initial simulation campaign showed promising beam stability at 10 mA. Further work remains to achieve isochronicity better than ±1%, full space charge simulation with acceleration and demonstration of sufficient turn separation at extraction. Initial engineering concepts for the main magnets and a superconducting rf solution exist.

Design Studies for Muon Transmutation

One future application of high intensity particle beams is the transmutation of long lived fission products (LLFP) through muon capture. A novel design incorporating energy recovery with an internal target is now under detailed study, which could produce 10^{16} negative muons from a 2.5 mA proton beam with fixed frequency radio-frequency system for re-acceleration [19, 20]. Muons are produced through interactions with an internal target. This idea builds on the successful demonstration machine ERIT (Energy Recovery Internal Target) [21] at KURRI, Japan, shown in Fig. 6.

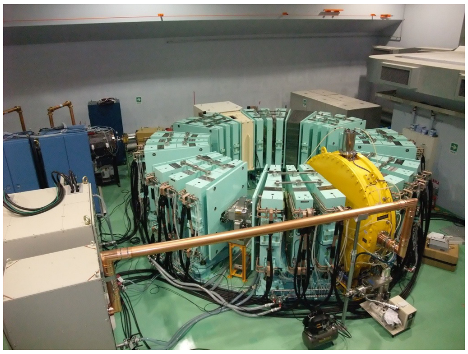

Figure 6: The ERIT accelerator at Kyoto University Research Reactor Institute, Japan.

Radioisotope production

Compact high current FFAGs may also be applied to radio-isotope production. One such design is the Proton Isotope Production (PIP) design [22] shown in Fig.7. This is a cyclotron-like FFAG being studied for proton energies up to 26 MeV for the production of radioisotopes, in particular $^{99\mathrm{m}}$Tc. The magnetic field varies from 0.99 to 1.03 T up to a 1.5 m radius and the gradient is optimised with the magnet geometry to stabilise the tunes and enhance beam focusing whilst maintaining isochronicity. The use of a thin internal target and recycled beam is being investigated as it could greatly improve production efficiency. At present, simulations with a 20 mA beam in OPAL show good transmission through the acceleration cycle of over 98%. Further studies into radial injection are ongoing.

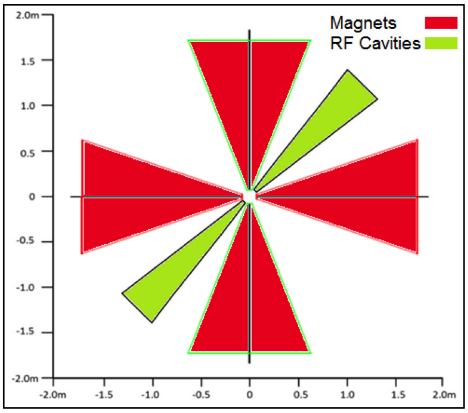

Figure 7: A view of the PIP ring. The internal target would be located in one long gap between sectors.

OTHER DESIGN STUDIES AND INNOVATIONS

Medical Applications

Developments continue for the design of medical FFAG accelerators. The PAMELA (Particle Accelerator for MEdicaL Applications) design study reduced the aperture size by implementing the second stability region of the equations of motion [23]. This was taken as the starting point for a normal-conducting proton accelerator up to 330 MeV for proton tomography as part of the NORMA design study [24]. This further study included an extension to a racetrack design, detailed parameter scans of the working point and dynamic aperture.

Continued work on non-scaling arbitrary field FFAG designs now includes a concept for ions including Helium and Carbon from 70/90 to 430 MeV/u [25, 26]. The design is based on a racetrack configuration which allows long straight sections, where an extraction system based on a bipolar field is located. While this has not yet been demonstrated in an operating machine, it would allow a fast variable energy extraction system with no degrader. The design is near to isochronous for CW operation, which leads to a large cyclotron-like radial aperture for both the magnets and rf system.

One of the most promising applications for FFAG optics in the medical field is in the treatment gantries. The FFAG concept is able to support a fast variation in beam energy to scan depth-wise during treatment without the need to adjust the field strength. Recent work in this direction includes a lightweight permanent magnet gantry for proton therapy and a compact superconducting gantry for ion therapy [27]. A novel type of asymmetric Halbach magnet has been designed and prototyped for this application.

Other Applications

It is worth noting that there has been a lot of recent development in the lepton non-scaling FFAG field as part of the eRHIC project, where one proposal is to use FFAG arcs for the energy recovery recirculating linac design. This reduces the number of required arcs as multiple energies can travel through a single FFAG arc, but does lead to the requirement of matching and correction with multiple simultaneous orbits. This has led to innovations in adiabatic matching techniques to adjust optical parameters smoothly between FFAG arcs and straight sections [28], novel permanent magnet designs [29], modelling of synchrotron radiation in FFAG arcs as well as detailed beam dynamics calculations.

Continued developments are also seen in particle physics applications such as the NuPIL (Neutrinos from PIon beamLine) [30] design and for the generation of neutrino beams in nuSTORM [31] facility to provide a muon beam for precision neutrino physics, where long straight sections and matching sections are well developed for scaling FFAGs.

DISCUSSION

The FFAG idea is often considered a completely different class of accelerator, but in reality it is just a generalised fixed field accelerator. It should be noted that in cyclotrons, reverse magnetic fields are now being incorporated into next generation high power designs. As FFAG designs continue to evolve, some are heading toward CW mode operation like a strong focusing version of a cyclotron, while others have a flexible structure and superperiods like a synchrotron. Particularly for high intensity and high power hadron designs, there is a good opportunity for the accelerator community to work together to share experience from operational high power cyclotrons and synchrotrons particularly in terms of hardware, injection and extraction systems where these are appropriate.

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