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Review of Current FFAG Lattice Studies in North America

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Abstract

There has been a revival of interest in the use of fixed field alternating gradient accelerators (FFAGs) for many applications, including muon accelerators, high-intensity proton sources, and medical applications. The original FFAGs, and those recently built in Japan, have been based on a so-called scaling FFAG design, for which tunes are constant and the behavior in phase space is independent of energy with the exception of a scaling factor. Activity in the US and Canada has instead mostly focused on non-scaling designs, which, while having the large energy acceptance that characterizes an FFAG, do not obey the scaling relations of the scaling FFAG. Most of these designs have been based on magnets with a linear midplane field profile. A great deal of analysis, both theoretically and numerically, has occurred on these designs, and they are very well understood at this point. Some more recent work has occurred on designs with a nonlinear field profile. Since no non-scaling FFAG has ever been built, there is interest in building a small model which would accelerate electrons and demonstrate our understanding of non-scaling FFAG design.

INTRODUCTION

FFAG research in the US has focused primarily on what are sometimes called "non-scaling" designs, which do not obey the scaling laws of the original ("scaling") FFAGs [1]. FFAGs were originally (re-)considered in the US in the context of muon acceleration: they were interesting because they allowed for rapid acceleration (needed to prevent muon decays) while not having the complex switchyards of a recirculating accelerator or the requirement for magnets with rapidly changing fields (as in a synchrotron). A different kind of FFAG was considered for two reasons: first, a large dynamic aperture was needed, and the highly nonlinear magnets in a scaling FFAG were thought to lead to a reduced dynamic aperture. Second, the large magnet apertures required for scaling FFAG magnets would be expensive. Thus, lattices were developed with the large energy acceptance found in scaling FFAGs that instead used linear magnets [2, 3] to give a large dynamic aperture, or that attempted to minimize the magnet aperture [4].

Since then, the non-scaling designs with a linear magnetic field profile in the midplane ("linear non-scaling FFAGs") have undergone thorough study, and are very well understood. We describe here the most recent results of studies of linear non-scaling FFAGs, including an analytic description of the lattices, understanding of the lattices gained from automated design and optimization of the lattices, and tracking results on the lattices. Non-scaling FFAGs are now being considered for applications other than muon acceleration, and we describe some of those applications here. In particular, non-scaling designs with nonlinear midplane field profiles are being looked at for some applications. Finally, there is interest in building a test model for a linear non-scaling FFAG to demonstrate acceleration in that type of machine.

APPLICATIONS

Since FFAGs do not require magnets with varying fields (except for injection/extraction kickers), they are a natural choice when rapid acceleration is desired. A linac could be used for rapid acceleration, but RF is very expensive, so an FFAG is an attractive alternative which allows multiple passes through the RF.

The eRHIC electron-ion collider [5] requires the construction of a machine to accelerate polarized electrons to 10 GeV. One solution for avoiding depolarizing resonances is to accelerate rapidly through those resonances. Thus, an FFAG was proposed [6] to replace the baseline recirculating linac design. It is based on a triplet design with a linear midplane field profile. It accelerates from 3.2 GeV to 10 GeV. There are 273 cells, one of which is shown in Fig. 1.

There is a desire to upgrade the AGS, a 28 GeV proton accelerator at Brookhaven National Laboratory, to operate at 1 MW average beam power. This will require shortening the acceleration cycle and increasing the beam current in the machine. Essential to this process is a replacement for the 1.5 GeV booster ring by a device that can rapidly accelerate the entire beam that will fill the AGS. The base-

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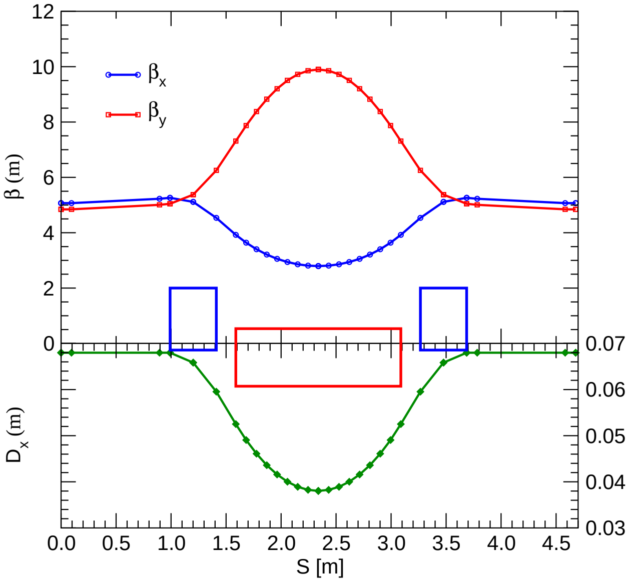

Figure 1: Beta (top) and dispersion (bottom) functions at the reference energy in the eRHIC lattice. Magnet positions are shown in the center.

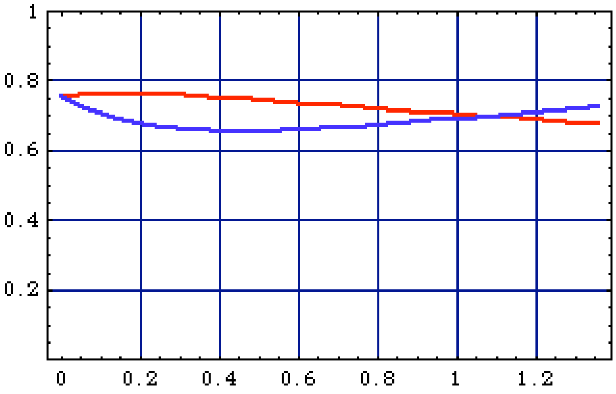

Figure 2: Fractional tunes as a function of energy in the 1.5 GeV nonlinear FFAG.

line scenario is to have a superconducting linac replace the booster [7], but an FFAG may be a much more cost-effective alternative.

A Nonlinear Non-scaling FFAG Design

The design of an FFAG for the AGS upgrade presented unique problems. Since protons or ions are being accelerated, the acceleration did not need to be extremely rapid: only small compared to the desired repetition period of the AGS (400 ms). For slower acceleration, a scaling FFAG is often desirable since its tunes are constant, and therefore resonances can be avoided. However, preliminary attempts to design a scaling FFAG for the booster replacement required fields that were higher than 0.3 T, which would preclude operation with H^- ions. Thus, a non-scaling design was needed which had a small tune variation.

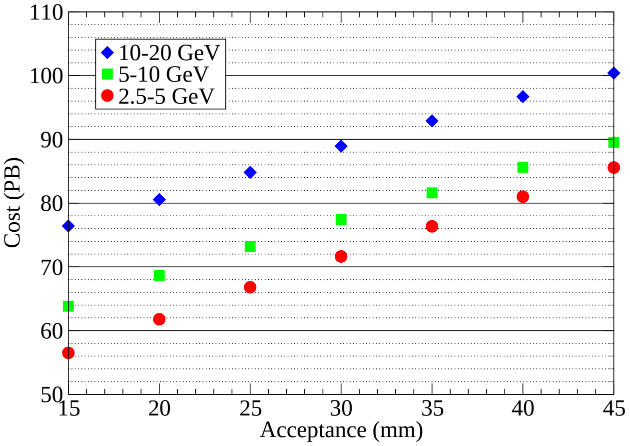

Figure 3: Dependence of muon FFAG cost on transverse lattice acceptance for various energies.

In [8], Ruggiero describes a method for achieving this: constructing a magnet such that on the closed orbit the gradient is proportional to the momentum. This not only requires a nonlinear transverse field profile, but a field profile that varies along the length of the magnet. While this method does not make the horizontal tune perfectly constant (and with end effects neither tune is perfectly constant), the deviations are small and decrease as the number of cells increases. Based on this, a 1.5 GeV FFAG was designed which would replace the booster [9]. It has 136 FDF triplet cells for a total circumference of just over 800 m. The fractional tunes as a function of energy are shown in Fig. 2, showing the high degree to which the tunes are constant (the integral parts of the tunes are 39 and 37). Furthermore, full-turn resonances should be relatively weak due to the fact that every cell is identical.

OPTIMIZING DESIGNS

Since FFAGs consist of a single simple cell repeated around the ring, they are in principle very straightforward to design. One can even use automated techniques to design a minimum-cost lattice, according to some cost function. In [10], a cost model was used to do such designs for muon acceleration with linear non-scaling FFAGs. Several things (applicable to muon machines with high-frequency (200 MHz) RF), and in many cases beyond that) were learned from performing these cost optimizations:

- A doublet is a more cost-effective lattice cell than either a triplet or a FODO. While the triplet requires less RF voltage than the doublet, having three magnets per cell instead of two makes it more costly.
- For modest and even somewhat large sizes, a longer ring was less expensive than a shorter one, even ignoring RF costs. This is because the dispersion gives a significant contribution to the aperture in FFAGs, and the dispersion decreases as the number of cells increases in the ring. In many cases, the aperture de-

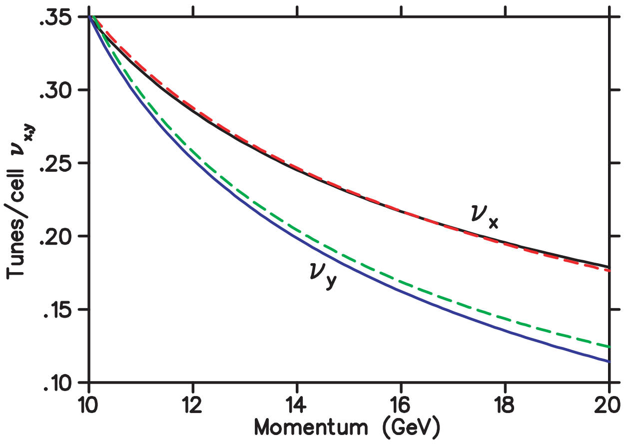

Figure 4: Tune as a function of energy in a triplet lattice, showing the "exact" solutions computed with COSY [11] (dashed) and using the analytic approximation (solid).

crease reduces the cost more quickly than the cost is increasing from the increased number of cells. Thus, the least expensive ring sometimes has unacceptable levels of decay; thus, the cost of the decay is incorporated into the optimization.

- Due to constraints of fitting the beam into the pipe and other tradeoffs, the cost optimum lattices have specific tune profiles which depend only on the type of lattice and the ratio of the initial and final energy. The tunes are split significantly over the entire energy range.
- The cost per GeV for a low energy FFAG is significantly higher than for a higher energy FFAG. Thus, for accelerating muons using high-frequency RF, FFAGs are unlikely to be useful in low-energy stages (below about 5 GeV).

The dependence of cost (and other merit factors) on various input parameters is easily obtained by these techniques (see Fig. 3 for an example).

ANALYTIC MODELS

Optimization techniques, especially if one wants reasonable accuracy over a large energy range, can be rather slow, requiring repeated tracking for finding the solution for the closed orbit and the linear map about it. For linear non-scaling FFAGs, one can make analytic approximations to the orbits in the magnets, and use that to find closed orbits and linear lattice functions [12]. This can then lead to much more rapid design and optimization of these lattices. An example of the approximation's accuracy is shown in Fig. 4. The accuracy is excellent except for very compact rings, since exact analytic formulas don't fully take into account the reference orbit curvature.

Simpler models using thin-lens approximations have also been used to compute lattice properties and design lattices for linear non-scaling FFAGs [13, 14]. While these methods are not as accurate, they have had some success in being used to produce lattice designs [14].

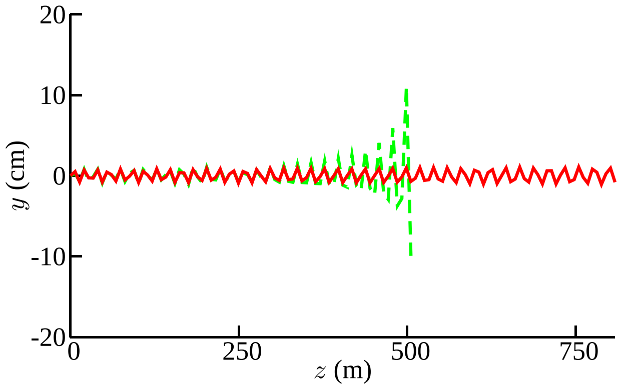

Figure 5: Tracking a large amplitude particle with uniform acceleration in a 5–10 GeV FFAG. The dashed line shows tracking with sextupole components on the ends of the magnet and no correction in the body, and the solid line shows the same thing with a body sextupole component to correct the particle loss.

TRACKING RESULTS

Linear non-scaling FFAGs are a relatively new invention, and until recently, very little tracking has been done on them. One must carefully consider the nonlinear effects in these machines to find the dynamic aperture. The magnets are relatively short compared to their apertures, and thus end effects in the magnets become very important. So whatever tracking code is used must properly include these effects. COSY Infinity [11] has excellent built-in handling of magnet ends, but its use of truncated power series can at times (but not always) be problematic for the large energy acceptances required for FFAGs [12, 15]. ICOOL [16] has extensive facilities for handling end fields, as does ZGOUBI [17], and both of these codes have been used to do tracking for FFAGs [18, 19].

In particular, a linear non-scaling FFAG was examined using ICOOL, including sextupole contributions expected on the ends of the magnets [18]. When the sextupole ends were added, it was found that there was significant particle loss at a particular energy, apparently due to a 1/3 resonance. This loss could be corrected, as shown in Fig. 5, by adding a sextupole component to the body of the magnet. The integrated sextupole required to eliminate the loss was determined by tracking to be only 0.68 times the integrated sextupole strengths of the ends.

Tracking using ICOOL has also been done on the PRISM lattice [20]. It was demonstrated that there is a large difference between the horizontal dynamic aperture when there is no vertical amplitude and a small vertical amplitude. Furthermore, if the scaling PRISM design was replaced with a non-scaling design, there was a substantial increase in the dynamic aperture [21], as shown in Fig. 6.

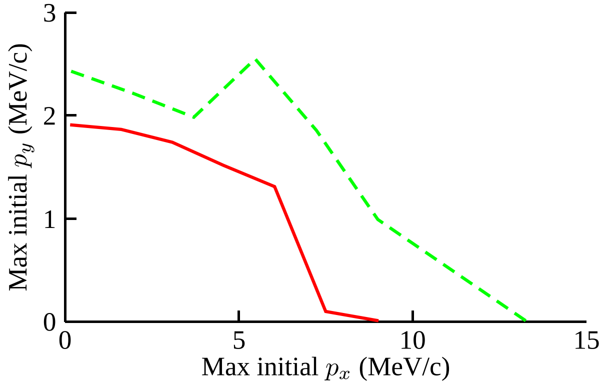

Figure 6: Dynamic aperture for PRISM using a scaling lattice at 68 MeV/c (solid) and linear non-scaling lattice at 80 MeV/c (dashed).

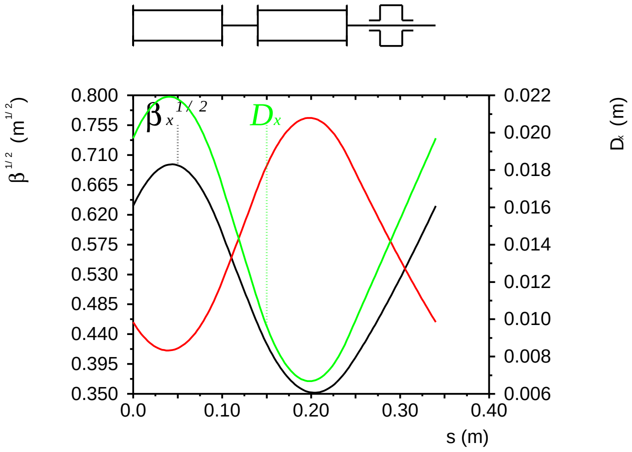

Figure 7: Lattice functions at the central energy and layout for an electron non-scaling FFAG demonstration ring.

ELECTRON MODEL

While several scaling FFAGs have been built [23, 24, 25, 26], a non-scaling FFAG has never been built. There is great interest in building a model of a non-scaling FFAG that accelerates electrons, to demonstrate both our understanding of the transverse dynamics in such a lattice as well as the unique longitudinal acceleration mode that will probably be used for muon acceleration with high-frequency RF [22].

Several authors have produced parameter sets for electron models [27, 28, 29, 14, 30, 31]. Two [28, 31] have been more extensively analyzed, including hardware considerations. Figure 7 shows a cell from one of the lattices; that lattice consists of 45 cells, and accelerates electrons from 10–20 MeV.

CONCLUSION

Extensive progress has been made recently in the design of non-scaling FFAGs. Understanding of how to optimally design linear non-scaling FFAG lattices for various applications has increased, and we are beginning to perform more detailed nonlinear analyses of these lattices. The idea of non-scaling lattices is even being extended beyond the linear non-scaling lattices. Finally, we are considering the idea of building a low-cost model of a linear non-scaling FFAG to demonstrate our understanding of these machines.

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