RECENT PROGRESS ON FFAGS FOR RAPID ACCELERATION

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Abstract

When large transverse and longitudinal emittances are to be transported through a circular machine, extremely rapid acceleration holds the advantage that the beam becomes immune to nonlinear betatron resonances. Uncooled muon beams exhibit large emittances and require fast acceleration to avoid decay losses and would benefit from this style of acceleration. The approach explored here employs a fixed-field alternating gradient or FFAG magnet structure and a fixed frequency acceleration system. Acceptance is enhanced by the use only of linear lattice elements, and the fixed-frequency rf enables the use of cavities with large shunt resistance and quality factor. The problematic rf phase adjustment associated with rapid acceleration is specifically addressed and resolved. This paper reports significant progress on both a lattice and rf system for a high-energy FFAG in the context of rapid acceleration.

1 INTRODUCTION

Acceleration of beams with simultaneously large transverse and longitudinal emittances, present a challenging new direction in accelerator design. Synchrotrons or linacs cannot support acceleration of ultra-large emittances. *Scaling* (radial- or spiral-sector) FFAG accelerators display an almost unlimited momentum acceptance, but transverse acceptance remains restricted. The approach developed here is a *nonscaling* FFAG wherein the ideal optics demonstrate strong linearity. The discerning feature of the nonscaling version, is that the betatron functions and tunes are not held constant, as in the scaling machine, but change slowly with momentum.

The inclusion of slowly-changing optics in combination with rapid acceleration suppresses discrete resonances and nonlinear effects, thereby minimizing beam blowup and corresponding beam loss. Rapid acceleration has further application when the beam suffers from decay losses.

A signature of fixed field acceleration is that orbit length unavoidably changes with energy; it can be substantial and can result in a significant phase-slip relative to the accelerating waveform. This poses a nonstandard problem which must be addressed by the rf system; and a number of solutions are being advanced[1]. Outside of the obvious solutions of broadband rf, or very low radio-frequency, this paper outlines alternative approaches using high-Q, high-frequency rf systems.

* Work supported by the Universities Research Association, Inc., under contract DE-AC02-76CH03000

† TRIUMF receives funding via a contribution agreement through the National Research Council of Canada

1.1 Application of nonscaling FFAG

A compelling example of the application of a *nonscaling* FFAG is for intense muon sources; e.g. a Muon Collider[2] or a Neutrino Factory[3] where acceleration must occur rapidly to avoid heavy decay losses. The exceptionally large acceptance of the *nonscaling* FFAG, both transversely and longitudinally, makes it well suited to muon acceleration and eases the degree of beam cooling required. For rapid acceleration, its acceptance appears limited only by the physical apertures of the components and can accomodate less-cool beams than Recirculating Linacs, or even *scaling* FFAGs. These studies of FFAG accelerators also represent an effort to reduce cost.

2 FFAG LATTICES

In a fixed-field circular accelerator, the orbits are not fixed as in a ramped machine, but rather move across the magnet aperture during acceleration. The three types of structures used in FFAG lattice design are: (i) Traditional scaling FFAG; (ii) Triplet-based scaling FFAG; (iii) Nonscaling FFAG[4]. The scaling FFAG[5] is comprised of combined-function short FODO cells with edge focussing and magnetic fields which scale with momentum. The triplet-based FFAG is a recent innovation[6], based on the scaled-field concept, allowing longer straight sections.

2.1 Optics principles of a Nonscaling FFAG

In the nonscaling FFAG, not only do the central orbits move across the aperture, but also the optics functions vary with the central momentum. The beam can be accelerated through an integer, or other resonance-driving "global" tunes if the tune remains constant for only a fraction of a turn. With a fast acceleration cycle the lattice's optical parameters may also change with momentum. One then has the freedom to choose machine parameters optimal for acceleration; such as minimizing the circumference to limit intensity loss from decay and maximizing the transverse dynamic aperture through the use of only linear elements, This approach is termed a *nonscaling* FFAG accelerator.

Two steps are important in minimizing the machine circumference. First, the reverse bends required by the criterion to maintain constant optics can be eliminated yielding $\approx$ 20% decrease in circumference. Next, the magnet configuration in the FODO cell is chosen to provide the maximum net bend per cell for a given peak excursion of the orbit during acceleration. This is accomplished by positioning the dipole bend field over the defocusing quadrupole element. The allowed bend is further increased by the choice of focussing strength and cell length: the injection momentum experiences a cell phase advance approaching π while the extraction momentum approaches zero. The nonscaling approach yields the smallest design circumference of any lattice and can approach a factor of two less than that of a scaling lattice.

The example which provides the focus of this paper is a 6-20 GeV non-scaling FFAG cell optimized for ultra-rapid, stable acceleration. The lattice components and parameters, are given in [7]. The optic functions are plotted in figures 1 and 2.

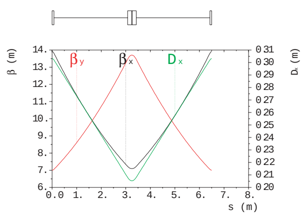

Figure 1: Lattice functions at 16.5 GeV

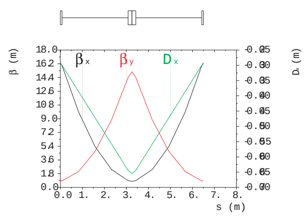

Figure 2: Lattice functions at 6 GeV

2.2 Pathlength Dependencies in FFAGs

A drawback to FFAGs is the large changes in pathlength as a function of energy; these are linear with momentum for radially-staggered, parallel orbits as in the radial-sector scaling case, but it is *parabolic* in non-scaling FFAGs. This comes about when the transverse excursion of orbits as a function of momentum is larger than the contribution from the longitudinal pathlength change. Of course, the cell traversal times must be synchronized with the waveforms in the RF cavities responsible for acceleration.

3 FFAG ACCELERATION

In a circular machine, particles make repeated passages through the same cavities; and so on every revolution the frequency and phasing of each cavity must be readjusted. To make this possible, the demanded phase change per cavity filling time should be small. If no attempt is made to adjust the frequency or phase, then errors accumulate linearly with time and inversely as harmonic number.

For a thousand, or more, turns acceleration, moderate-Q cavities (10^5 or 10^6) can be utilized and their phases made to track the changing orbit length, so as to make an approximation to conventional, synchronous phase acceleration. The longer timescale, however, makes the *nonscaling* FFAG more sensitive to the optics design and the impact of resonances.

3.1 Rapid acceleration

When acceleration is to be completed in a few turns, the large energy gain per turn forces one to consider on-crest acceleration as in a cyclotron. In this case, the rf is used almost entirely to provide acceleration. One may envisage use of low-Q ($\leq 10^3$) cavities and *on-crest* operation with phase shifting of accelerating stations to make up for non-isochronous behaviour of orbits in the FFAG. A more affordable approach for rapid acceleration employs high-Q ($\geq 10^6$) and high frequency ($\geq$ 100 MHz). Because high-Q cavities cannot be rephased on a rapid acceleration timescale, acceleration does not remain fixed at the crest of the waveform, but rather crosses over it one or more times.

Near-crest regime: Cavity frequency and phases are selected to keep the beam as near crest as possible, reducing the total accelerating voltage and providing an almost constant acceleration rate. The usual ideas of synchrotron longitudinal dynamics, such as RF bucket and synchronous phase, are not relevant to this type of machine. With proper optimization, this mode is the most conserving of longitudinal phase space, but acceleration is limited to a few turns else the machine acceptance is compromised.

Ideal phases: Let us set aside the technological problems of *on-crest* operation. For a sinusoidal waveform, the ideal phases at cavity arrival times are zero since $\cos(0) = 1$.

Best frequency and phases: The cavities are assumed to operate at a single frequency that we are free to optimize along with individual starting phases so that *near-crest* acceleration results.
Results from *ideal phases* serve as a benchmark against which the more practical *best phases* scheme is judged.

3.2 Optimization strategy for best frequency

We report an optimization strategy which aims to give the reference bunch the maximum acceleration each turn.

Cavity phasing: The ideal arrival times t_{ij} cavity-by-cavity (index $j = 1, \ldots M$) and turn-by-turn (index $i = 1, \ldots N$) are recorded for a synchronous particle assuming ideal energy gains. One makes an initial guess at the frequency ω and then calculates the phases $\phi_{i,j} = \omega t_{ij}$ at the ideal gap-crossing times. Next, one then forms the square deviation summed over all rf stations and turns: $S = \sum_{i=1}^{N} \sum_{j=1}^{M} (\phi_{ij} - \bar{\phi}_j)^2$ where $\bar{\phi}_j = \sum_i^N \phi_{ij}/N$. A search is made for the frequency which minimizes S. If, at the start of the first turn, each cavity phase is set equal to $-\bar{\phi}_j$, then the phase at subsequent traversals will best approximate the ideal zero value.

Over-voltages: Because particles arrive displaced from the ideal phase, the acceleration must be made tolerant of poor phasing. One increases the voltage beyond the nominal accelerate-on-crest value to compensate for arrivals which lag or lead the wave.

3.3 FFAG RF system

The upstream cooling channel leads us to consider 100 and 200 MHz. There are CERN designs available for 200 MHz normal conducting (NC) and super conducting (SC) cavities. A design with $R = 14$ Mohm, $Q = 7 \times 10^4$ and 2 MV gap voltage is within reach of present NC technology and the peak rf power is some 250 MW distributed between 1800 cavities. Given the large power requirement of NC cavities, a FFAG for rapid acceleration would clearly benefit from the adoption of SC cavities with quality factors ranging from 10^7 to 10^9. In either case, NC or SC, pure sinusoid operation is the only mode possible.

4 LONGITUDINAL SIMULATIONS

The simulation model assumes complete decoupling of the longitudinal from the transverse motion. The 6-20 GeV ring, of 2.04 km circumference, is divided into 314 identical cells each with an RF station. The energy gain is lumped in a single element. Initially, the longitudinal phase plane is uniformly flooded with trial particles, but with a momentum spread limited to $\pm 10\%$. Particles which then accelerate to within $\pm 10\%$ of the nominal *extraction* energy are considered to be within acceptable limits. The particles that survive these output cuts are recorded and used to map out the corresponding input admittance of the machine. Although a wide variety of cases (including 100 MHz) has been considered and is reported elsewhere[8], here we present indicative cases using 200 MHz rf and describe trends in machine performance.

4.1 200 MHz acceleration

To reduce electric field gradient one attempts to stretch near-crest acceleration over several turns. Although numerous cases were studied involving 5-10 turns, here we consider acceleration in five (5) turns of the FFAG which has been found to be, more or less, a practical limit.

Ideal phases: When the ideal turn-by-turn re-phasing, and the nominal RF voltage of 2.8 GV/turn, is used an input admittance of 1.18 eV.s is successfully accelerated to 20 GeV in 5 turns; see figs. 3 and 4. Notice, that despite the ideal phasing, the transport is non-linear. If one adds second harmonic, then the admittance rises to 2.12 eV.s.

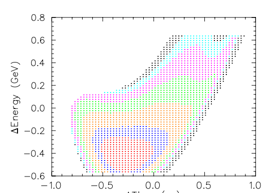

Figure 3: $\pm 10\%$ Band from input acceptance

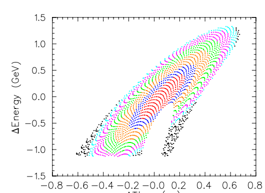

Figure 4: Maps to the output emittance.

Best frequency and phases: If one uses a single frequency, and fixed initial cavity phases, then the desired acceleration is not achieved unless an over-voltage is employed. A 25% over-voltage yields a 1.5 eV.s admittance (Fig. 5). If one adds 2nd harmonic (Fig. 6), then the admittance rises to 2.28 eV.s. The number of accelerating stations has little influence on beam quality. Ranging from 100 to 600 stations, there is no systematic variation and the admittances span 1.2 to 1.5 eV.s.

Conclusion: For 5-turn acceleration, there is little difference in the output emittance between the use of "ideal phases" versus using a combination of "best phases" and an over-voltage. When second harmonic is employed, the useful acceptance is typically doubled. In all cases, although the overall transport is non-linear, the emittance of the central region (comprising roughly one half of the full admittance) is reasonably well preseved. Since few beams approach such large longitudinal emittances, nonlinear transport issues do not pose serious concerns.

To first order, the phase slippage will increase linearly with time; and so one expects the transmission to *fall* as the number of turns is increased. We have not achieved useful acceleration over more than five turns unless either (i) the ideal phases are used; or (ii) dual harmonic; or (iii) one allows each cavity (or groups of cavities) to run at its own individually optimized frequency. In the former case, up to 10-turn; and in the latter cases 7-turn and 6-turn, respectively, acceleration is possible.

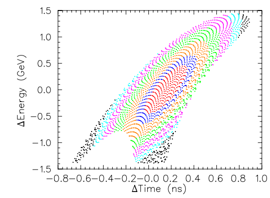

Figure 5: Output emittance, single harmonic.

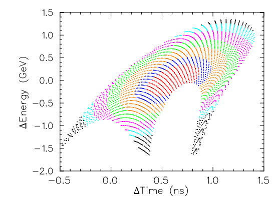

Figure 6: Output emittance, dual harmonic.

5 SUMMARY

Nonscaling FFAGs appear to have a strong advantage in applications requiring rapid acceleration of large-emittance beams by displaying a transverse admittance beyond the conventional *scaling* FFAGs. In particular, this approach provides the necessary acceptance match to high-energy muon beams with little or minimal cooling in place. Further, this work represents the first successful study of the application of reasonably high-frequency and high-Q cavities to rapid acceleration in a fixed-field accelerator, thereby dramatically reducing the rf power required in previous solutions. In conclusion, the *nonscaling* FFAG coupled with the rf approach developed here presents not only a solution to rapid acceleration, but also a new acceleration technique. Ultra-large emittances are successfully transported in a conventional machine with minimal complexity in components. Based on this work, it looks promising to build a chain of muon accelerators from FFAGs.

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