NEW NONSCALING FFAG FOR MEDICAL APPLICATIONS*

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Abstract

A hybrid design for a Fixed-Field Alternating-Gradient (FFAG) accelerator has been invented which uses edge and alternating-gradient focusing principles applied in a specific configuration to a combined-function (CF) magnet to stabilize tunes through an acceleration cycle which extends over a factor of 6 in momentum. Using normal conducting magnets, the final, extracted energy from this machine can attain slightly more than 400 MeV/nucleon without the use of superconducting elements. By using fixed-fields, the machine proposed here has the high current advantage of the cyclotron yet retains important features of the synchrotron: smaller radial aperture, variable energy, and both kicker-based and resonant extraction. This machine, without modification, supports a proton and a carbon ion beam in the energy range of interest for cancer therapy. Competing machines for this application include superconducting cyclotrons[1], synchrotrons[2], and, more recently, scaling FFAGs. As such this machine represents a broad innovation in therapy machines.

INTRODUCTION

In recent years, fixed-field alternating gradient (FFAG) accelerators have been successfully designed using only linear fields for applications requiring rapid acceleration, where a variation of optics with momentum can be tolerated. Historically[3], these nonscaling FFAGS, accelerate a factor of 2-3 in momentum, and execute on the order of ten turns. Slow acceleration, where beam executes hundreds to thousands of turns in the machine, greatly reduces rf requirements and expense, but requires that, at a minimum, the tune be stable in order to avoid resonances and beam blow up and loss. Position in a fixed field accelerator is always energy dependent, and for tune stabilization the integrated magnetic field must therefore scale with the energy of the beam, and accurately track the position of the beam as it moves outward across the magnetic aperture during acceleration. In scaling FFAGs strong, high-order multipole fields are incorporated directly into the magnetic field components to achieve this change (as in the radial sector[4] FFAG), or supplemented by elaborate edge shaping (as in the spiral sector[5] FFAGs). All such scaling-type magnet designs require sophisticated 3D field modeling to ensure accurate scaling optics.

The new concept proposed here is to stabilize tunes without directly introducing nonlinear field components by using a linear-gradient magnetic field to provide the bulk of the transverse beam confinement (or tune) combined with a significant edge angle to compensate for the energy change. The field in the body of the magnet has only a linear dependence on transverse position, i.e. a CF magnet with both quadrupole and dipole components. Using only linear fields and associated edge-focusing means that not all of the optical functions can be constrained as a function of energy – but most importantly the tune can be.

Even though the transverse field profile is linear, the technique does not strictly obey linear optics. A sextupole component[6] arises when the quadrupole body field is combined with an edge angle. Still this approach provides a unique and advantageous combination of multipoles which cannot be achieved through the introduction of individual multipole fields. Further, there is only one magnetic-field configuration which works when one considers both quadrupole focusing and edge-focusing effects on the transverse beam envelope, and that is the one described here. The background and rationale for the new transverse beam confinement scheme will be discussed in the following section.

DISCUSSION

Tune is perhaps the most important optical indicator of stable particle motion, since it determines when particles in the beam, executing periodic motion around the accelerator, return to the same transverse position relative to a central, or reference orbit in the machine. In a fixed-field machine such as an FFAG or cyclotron, this reference orbit moves with energy. In a synchrotron, the magnetic field increases proportional to energy and therefore particles are confined about a laboratory-based reference trajectory independent of energy.

In a scaling FFAG design, the beam optics remains constant with energy – the beam envelope and tunes along with all other optical parameters remain fixed. The nonscaling FFAG relaxes this condition and aims only for stable beam during acceleration. If the acceleration is quick, then tune variations can be tolerated. If the acceleration is slow the tune must be more controlled (although some tune variation can be accommodated or compensated for if the acceleration cycle is slow enough).

Tune and Transverse Envelope Control

Three conventional methods exist for controlling the beam envelope and phase advance using linear fields, i.e. dipole and quadrupole field components. (Here we refer to the linear lattice functions and the linear tune.) One is the weak focusing principle used in classical cyclotrons in which changes in pathlength through the magnetic field as

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a function of transverse position focus the beam (in the bend plane, typically horizontal). Vertical control is achieved by radial shaping of the poletip and this is weaker than the focusing from pathlength differences. With alternating gradients, two strong-focusing techniques can be applied: edge focusing from the fringe fields of a dipole and/or linear gradient, or quadrupole, focusing which is the main technique used in a synchrotron. Strong-focusing techniques are capable of focusing equally in both planes with much stronger envelope focusing. This results in larger phase advances, shorter focal lengths, and corresponding higher machine tunes than in weak-focusing machines.

The FFAGs generally apply both principles—scaling machines specifically require edges plus quadrupole and higher multipole fields to achieve constant optics. A new type of FFAG, a linear-field nonscaling FFAG which does not use edge-angle focusing specifically nor nonlinear field gradients was proposed by the authors for rapid acceleration. Note that the envelope must still be stable across all energies or beam particles are bent out of the ring by the main fields. This implies constraints on the range in cell phase advance: for realistic magnets and machines, the tune stability limits are ~0.7π - 0.2π radians per cell. A combination of magnet aperture and phase advance limits the momentum range of practical linear-field nonscaling FFAGs for muon acceleration to ~2-3, where magnets are simple rectangular ones. Sector magnets can be applied also, but the result is similar. Clearly the short acceleration cycle requires a tremendous amount of radiofrequency accelerating cavities to be installed in order to accelerate the beam quickly and there are no fine controls over the beam. This design is therefore not suitable for many applications. However, if the tune were more stable, then the momentum reach of the machine increases, and acceleration can progress slowly, over thousands of turns as in a conventional cyclotron or synchrotron with a modest rf system. A new nonscaling approach therefore is proposed here: one which constrains the tune to allow for a longer acceleration cycle. The new concept entails combining weak and strong focusing principles in a specific configuration to a fixed-field (DC) combined-function magnet to stabilize the tune over a very large energy range (currently a factor of 6).

TUNE-STABLE NONSCALING FFAG

One can combine the different focusing principles to mitigate tune variations with energy in a nonscaling FFAG and still maintain much smaller apertures and the sole use of linear fields as compared with scaling FFAGs. Only one magnetic-field configuration succeeds and that is the one described in this work.

To hold the tune constant and confine a finite beam transversely as its energy increases applying linear gradients only, i.e. quadrupole fields, require the beam to traverse longer and longer paths through the magnet. (Here we are addressing transverse-amplitude focusing, not the net curvature of the central or reference-particle orbit which is determined by the constant, or dipole, field.) This can be accomplished by a wedge magnet since higher-energy particles follow outer radii orbits.

The problem, however, is not as simple as scaling pathlength with energy since, when a vertically-oriented (horizontally-bending) dipole field is present, the physical magnet edge angle brings with it a horizontally focusing or defocusing effect, or no effect in the case of a rectangular magnet. Weak focusing by the dipole field in the body of the magnet does not affect the vertical plane. However, the focusing effect which depends on the angle through which the beam traverses the fringe field of the magnet is similar to a quadrupole located at each magnet edge: it can be either focusing horizontally and defocusing vertically, or the reverse. (A normal entrance angle has no focusing effect.) The fringe-field traversal angle can be utilized to work with the body quadrupole field in one magnet and against it in the other. The combination of the different magnet edge and entrance/exit angle effects indicate that the problem is not straightforward, but, in principle, a preferred and optimal solution exists. The solution proposed here is to use different combined function magnets (dipole + quadrupole) for the horizontally-focusing element and the vertically-focusing element. In the horizontally focusing element the combined function fields can be configured such that weak plus edge focusing effect adds with quadrupole focusing, thereby increasing the net horizontal focusing of the beam envelope in the outer-radii region of the element. In this way, the factor of 6 increase of pathlength through a quadrupole field from injection to extraction can be reduced to approximately a factor of two and still constrain the tune.

For the vertical plane, the same is true in the vertically-focusing element, but from the fringe field effect alone. In this magnet the field configuration is such that the net vertical focusing also increases with radius and again the required pathlength difference is mitigated from injection to extraction. Note also that the orbits are not parallel as in a scaling FFAG, but instead are drawn together in this new nonscaling configuration decreasing the magnet aperture and cost.

Lattice Design

The ring must be completely periodic and here a FODO cell containing two CF magnets was chosen as the base structure. A minimum 0.5m length has been imposed on the two drifts in each FODO cell to accommodate the acceleration cavities. A target cell tune of 90°, was chosen to facilitate injection/extraction from the ring, and the observed variation, without optimization, was calculated to be ~0.24 ± 0.06 between the injection and extraction points, considering both the horizontal and vertical. A graph of the tunes as modeled using MAD at different momentum values is shown in Figure 1. Comparison with the tune variation/cell for the nonscaling FFAG for rapid acceleration is given in Figure 2.

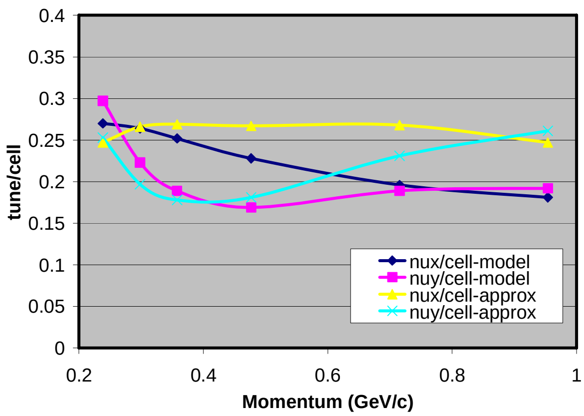

Figure 1. Dependence of cell tune on momentum in a nonscaling, linear-field FFAG which is tune-stabilized for medical therapy. In the legend, approx means the solution obtained from solving a set of approximated optical equations and model means the tune as modeled in MAD using these solutions.

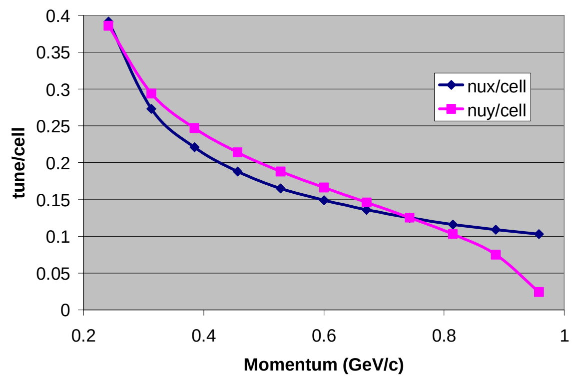

Figure 2. Dependence of cell tune on momentum in a nonscaling, linear-field FFAG designed for muon acceleration.

Table 1: General Parameters of the 400 MeV design.

Parameter	**Injection**	**Extraction**
Energy range	18 MeV/nucleon	400 MeV/nucleon
Tune/cell (ν_x / ν_y)	0.27 / 0.30	0.18 / 0.19
Circumference	40 m	
No. cells	14	
Straight	>1m	0.5m
Peak field	1.5 T	1.5 T
Apertures	~1m	

General magnet and ring parameters which attain 400 MeV/nucleon are detailed in the following Table 1. The net drift or length between components varies from injection to extraction due to the non-rectangular configuration of the magnets. Preliminary tracking studies at the injection energy using MAD indicate a reasonable, full, geometric dynamic aperture of 10-20π mm-mr.

Extraction

A strong advantage of this design is the potential for synchrotron-like extraction. Variable energy and multi-port extraction is possible along with fast and slow resonant extraction. These extraction options greatly enhance the applications of this new nonscaling FFAG over the previous design. For a kinetic energy of 400 MeV/nucleon, the kicker strength is modest: only 5 mr or 0.5 kG is required to divert beam ~1 cm into a septum magnet. Clearly the lower loss extraction characteristic of the synchrotron is another attractive feature.

SUMMARY

A hybrid design for a FFAG accelerator has been developed which successfully applies weak, edge, and linear-gradient focusing principles to a fixed-field (DC) combined-function magnet to stabilize tunes. In this approach, the momentum reach has been enlarged from a factor of 2-3 to a factor of 6 when compared with an equivalent muon accelerator design. The quadrupole gradient provides the majority of the phase advance per cell and weak and edge focusing from dipole fields provide the change in focusing strength needed to track the change in momentum during acceleration. With stabilized tunes, this FFAG behaves more like a synchrotron with multiple energies available for extraction and use, and with the attractive low-loss feature characteristic of synchrotrons. With its fixed fields, the magnets and power supplies are simple and this machine can be effectively operated continuously with potentially high output beam current which is the noted strength of the cyclotron. The designs here specifically apply only normal conducting fields and still attain carbon therapy kinetic energies of 400 MeV/nucleon. Lower energy proton beams are simultaneously supported. Also like the synchrotron and unlike the cyclotron, there are multiple places to extract beam supporting multiple treatment rooms or other applications.

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