TUNE-STABILIZED LINEAR-FIELD FFAG FOR CARBON THERAPY*

C. Johnstone[#], Fermilab, Batavia, IL 60510, U.S.A.

S. Koscielniak[†], TRIUMF[‡], Vancouver, BC 60439, Canada

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 magnet to stabilize tunes through an acceleration cycle which extends over a factor of 2-6 in momentum. Using normal conducting magnets, the final, extracted energy from this machine attains 400 MeV/nucleon and thus supports 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. The machine proposed here has the high average current advantage of the cyclotron with smaller radial aperture requirements that are more typical of the synchrotron; and as such represents a desirable innovation for therapy machines.

INTRODUCTION

A hybrid design using edge and alternating gradient focusing principles are applied in a specific configuration to a fixed-field (DC) combined-function magnet to stabilize tunes over the acceleration cycle, a cycle which historically[3] has covered a factor of 2-3 increase in momentum for linear-field, nonscaling FFAG designs. Tune stabilization is required for slow acceleration cycles – when the particle beam executes hundreds to thousands of turns around the machine. Without stable tunes, the beam crosses numerous "resonances" or regions of unstable particle motion as it accelerates and consequentially experiences losses and blow up of beam size. For consistent particle motion as the energy changes, fixed-field accelerators must introduce position-dependent nonlinear changes in fields which track the position of the beam as it moves outward across the magnetic aperture during acceleration. (Position in a fixed field accelerator is always energy dependent.)

Previous work on fixed-field alternating gradient (FFAG) accelerators have required the use of strong, high-order multipole fields directly incorporated into the magnetic field components to achieve this effect as in the radial sector[4] FFAG, or through elaborate edge shaping as in the spiral sector[5] FFAGs. The potential exists for compromised dynamic aperture, for example, if a high k value is used for the field index in the radial sector FFAG. All scaling-type magnet designs require sophisticated 3D field modeling to ensure accurate scaling optics.

Another approach, the adjusted field profile (AFP), instead, shapes the poletip along the length of the magnet which can also stabilize tunes during acceleration. In the the AFP approach[6], an almost unusable transverse beam acceptance has already been demonstrated and this approach is not presently being pursued.

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. To maintain the tune, or transverse stability, as the energy increases, requires an increase in either the net or integrated quadrupole strength. Since the beam orbit moves outward radially, the integrated strength can be achieved, in part, by adding a significant edge angle (20 degrees or more, for example) to the CF magnet — the length of the magnet, and, therefore, the integrated field gradient, simply increases with energy. The impact on the beam, however, is not confined to an increase in the pathlength: the edge angle also has a body and a fringe-field focusing effect on the horizontal beam envelope. In the vertical plane non-normal entrance and exit angles through the magnetic fringe fields also produce either a net defocusing or focusing effect on the vertical envelope. These entrance/exit angles depend on energy as the orbit changes through the periodic lattice.

This is not to say that the technique obeys linear optics despite the linear transverse field profile. Nonlinear multipoles, although not added individually as in the scaling machines, appear rather through edge effects associated with the linear body fields. This approach, however, provides a unique and advantageous combination of multipoles which cannot be achieved or duplicated 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.
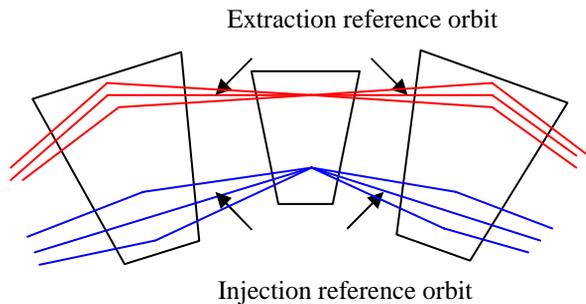
Figure 1: 1½ cells of a nonscaling, linear-field FFAG which is tune-stabilized for medical therapy.

LATTICE DESIGN

The technique developed is presently restricted under a provisional patent, hence only macroscopic parameters and general descriptions will be disclosed here pending a full patent. Detailed optics will await the patent process for publication. The ring is completely periodic, with a FODO-based cell containing two CF magnets. Figure 1 depicts the layout across 1½ cells for clarity (one cell would begin at the entrance to the first magnet and extend to the entrance of the last magnet.) The peak fields in both magnets are constrained to 1.5T to avoid superconducting components. At this point the rf has not been addressed, but a minimum 0.5m length has been imposed on the two drifts in each FODO cell to accommodate the acceleration cavities. To solve for the configuration parameters which stabilize the tune, a set of coupled equations were developed which rely on desired technical choices and constraints such as geometric closure of orbits. Approximations were necessarily involved and when compared with actual modeling of the solutions, clearly a variation was expected and observed; for example, with the cell tune set to 0.25 (90°/cell), the range in tune values 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 2.

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.

Either slow or fast extraction can potentially occur at any intermediate energy depending on the extraction design. The tune has been stabilized near 90° to facilitate injection and extraction modes and straights exist for such components and rf. Depending on the amount of rf installed, multiple extraction points and treatment lines are potentially available.
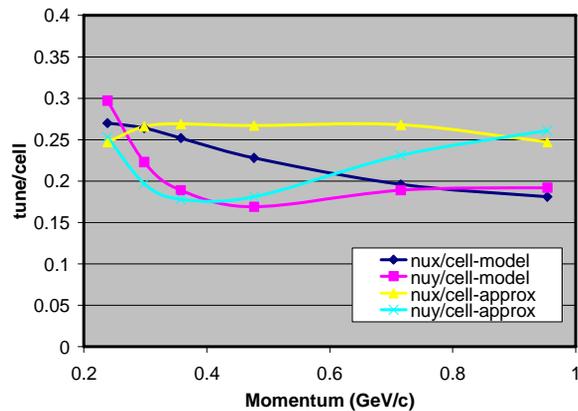

Figure 2: Dependence of cell tune on momentum in a nonscaling, linear-field FFAG which is tune-stabilized for medical therapy. In the legend, approx means the solution obtained from the approximated equations and model means the tune as modeled in MAD using these solutions.

Table 1: General Parameters

Parameter	Injection	Extraction
Energy range	30 MeV/nucleon	400 MeV/nucleon
Tune/cell (ν_x / ν_y)	0.27 / 0.30	0.18 / 0.19
Circumference	40 m	
Straight	>1m	0.5m
Apertures	~1m	

COMPARISON WITH MUON FFAGS

Clearly the linear-field nonscaling FFAG depicted in Figure 3 for muon acceleration represents a similar and presently a competing machine even though the tune is allowed to vary from injection to extraction over a large range (rapid acceleration has been shown to mitigate the effect of resonance crossing). In Figure 4, for example, muon accelerators typically begin injection with a tune of near 0.35/cell and end near 0.1/cell over only a factor of 2 in momentum. The primary focus of nonscaling linear-field FFAGs for short-lived muons has been aperture reduction of components through high momentum-compaction optical designs in combination with an ultra-large dynamic acceptance. Beyond a few GeV, the ring lattice components become superconducting. In the new application, the components are non-superconducting with solid iron cores (no laminations). Hence, aperture is less of a concern, but tune stability and resonances are. The solution for tune stabilization using only linear fields schematically depicted in Figure 1 is inherently different from the muon acceleration scheme of Figure 3. Table 2 offers more comparative information.
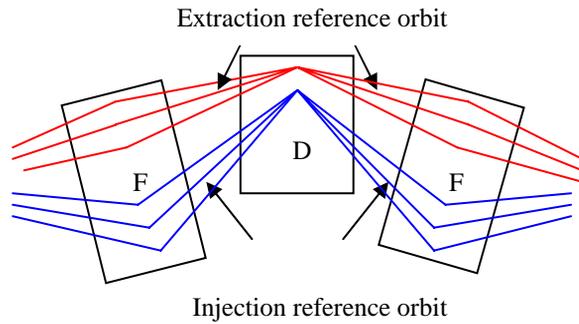
explore and optimize an edge contour which stabilizes the tune even further and a code which can successfully handle the extreme change in orbits and a complex edge effect accurately.

Preliminary tracking studies at the injection energy using MAD indicate a reasonable, full, geometric dynamic aperture of $10\text{-}20\pi$ mm-mr. Although almost 3 orders of magnitude less than the comparable muon accelerator, which requires an exceptionally large acceptance for muons, this value is yet acceptable for the small emittances associated with proton and carbon beams. Tracking this lattice through the full acceleration cycle in a high-order code with rf, and accurate off-momentum and edge simulation will be performed next.

Figure 3: 1½ cell of a nonscaling, linear-field FFAG for muon acceleration showing the compression of orbits in particular in the center magnet.
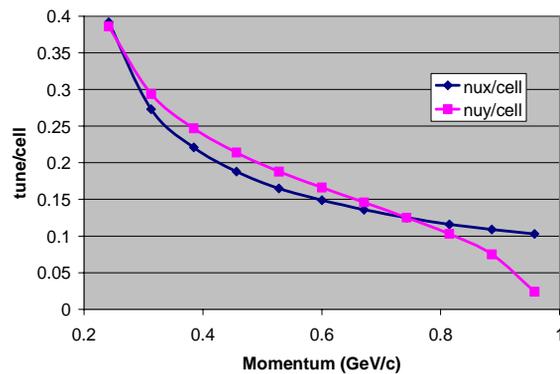

Figure 4: Dependence of cell tune on momentum in a nonscaling, linear-field FFAG designed for muon acceleration as modeled using MAD.

Table 2: Parameters for a similar Muon Accelerator

Parameter	Injection	Extraction
Energy range	30 MeV/nucleon	400 MeV/nucleon
Tune/cell (ν_x / ν_y)	0.39/0.39	0.10 / 0.02
Circumference	41 m	
# of cells	16	
Cell length	2.578 m	same
Straight	0.5m	0.5m
Apertures	~1m	

FUTURE WORK

A simple linear edge angle and simplifying approximations were imposed on the constraints and analytical expressions used to generate and eventually solve the resulting set of coupled equations which stabilize tunes at injection and extraction. Many simulation codes are presently inadequate to find closed orbits and optics for the far off-momentum orbits encountered. Therefore, solutions for individual points during the acceleration cycle had to be obtained via these simplified equations and the results placed into MAD for each point plotted. It is clear that a linear edge angle, while achieving a tremendous reduction in the tune variation, can be improved upon. Work is underway to

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