NONSCALING FFAG VARIANTS FOR HEP AND MEDICAL APPLICATIONS

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Abstract

A new type of non-scaling FFAG has been invented in which the machine tune is stable over an extended acceleration range, a factor of six or more in momentum, making it an ideal machine for hadron cancer therapy and proton driver and muon acceleration schemes for High Energy Physics. Sophisticated simulation tools within the advanced accelerator code, COSY INFINITY, have been developed to describe the FFAG's complex magnetic fields and high-order dynamics - including realistic edge-field effects. Predicted performance promises tune stability, and a sustainable slow acceleration rate. Further, with the emphasis in cancer therapy potentially shifting to light ion and carbon beams, the ability of the FFAGs to embed sequential rings, accelerate different ion species, with different energies, permit a cost-effective, staged approach to cancer therapy; a simple upgrade path takes a facility to carbon yet retains proton capability and the critical compact footprint inclusive of multi-specie rings.

INTRODUCTION

The drive for higher beam power, duty cycle and reliability, and precisely controlled beams at reasonable cost has generated world-wide interest in Fixed-Field Alternating Gradient accelerators (FFAGs)[1]. FFAGs have the potential to combine both the energy variability and small radial aperture of the synchrotron with the high duty cycle of the cyclotron. The Fermilab Research Association has elected to patent the concept for a new tune-stabilized FFAG accelerator design. What is exciting about the new technique is that a generalized version of the radial sector FFAG has been achieved, with optimized high-order fields replacing the scaling laws. A strong collaboration to simulate, optimize, and demonstrate the technical feasibility of this approach is underway - to be followed by a commercial engineering design.

New simulation tools were required to accurately describe the FFAG's complex magnetic fields, and to study and analyze the dynamics. These tools are based on transfer map techniques unique to COSY INFINITY[2]. With these new tools, closed orbits, transverse amplitude dependencies, and dynamic aperture are determined inclusive of nonlinear fields and kinematics to arbitrary order. These tools, combined with powerful internal optimizers were critical in achieving the required (and design) performance of this new generation of accelerators: successfully demonstrating the promised tune stability, and a sustainable slow acceleration rate effected by a modest RF system. Extraction is either by fast kicker or resonance excitation.

An example of the new non-scaling, FFAG accelerator, a compact 8-cell design that achieves a 250-MeV extraction energy for protons, is presented here with full simulation results and a preliminary magnet conceptual design. This design is then extended to carbon, showing an outer "upgrade" ring which circumscribes the proton ring; with common utilities and services.

CLASSES OF FFAGS

The FFAG concept in acceleration was invented in the 1950s independently in Japan, Russia and the U.S. The field is weak at the inner radius and strong at the outer radius, thus accommodating all orbits from injection to final energy. Focusing is provided by an alternating-pole strength in the body and from crossing the magnet edges at an angle. There are two nominal classes of FFAGs: scaling and non-scaling. The former (either spiral or radial-sector FFAGs) are characterized by geometrically similar orbits of increasing radius: application of a radial magnetic field law and edge focusing maintains a constant tune and controls other important optical functions during the acceleration cycle thus avoiding low-order resonances.

The idea of a non-scaling FFAG was invented in 1997 (C. Johnstone and F. Mills) and a working lattice published in 1999[3] as a solution for the rapid acceleration of muon beams. In a scaling FFAG design, many optical parameters remain constant with energy – in particular the tunes remain fixed. The non-scaling FFAG proposed for muon acceleration, utilizing combined function magnets, relaxes this condition and aims only for stable beam during acceleration. Without constant tune, it is not suitable for slow acceleration. The first of these linear-field FFAG accelerators is under construction at Daresbury Laboratory[4]. Historically, FFAGs of this type accelerate only a factor of 2-3 in momentum, and can only execute tens of turns.

Slow acceleration, where the ion beam executes hundreds to thousands of turns in the machine, greatly reduces RF voltage requirements and expense, but requires, at a minimum, a stable tune in order to avoid resonances and associated beam blow up and loss. An innovative non-scaling approach to slow acceleration was proposed in which the constant tune feature was successfully combined with the simplicity of the linear-field, non-scaling FFAG components[5]. It is a hybrid design where weak and strong focusing principles (edge and quadrupole focusing) are applied in a specific configuration to a fixed-field combined-function magnet, with canted entrance and exit faces, to stabilize tunes. However, this linear-field, linear-edge type FFAG was found to be somewhat restrictive in terms of allowed machine parameters. Generating stable tunes required either large component apertures, similar to the radial-sector FFAG, or imposition of a comparatively limited acceleration range. Although significant improvement in range was achieved compared to the rapid acceleration model - a factor of 6 vs. 2 to 3 - by applying a simple linear edge cut, the approach still falls short of the compactness and enhanced cycle and tune stability needed for most applications including proton therapy.

This concept has since been generalized and extended beyond the initial, linear-field invention, primarily through incorporation of higher, unconstrained field expansions to advantageously impact component apertures, acceleration reach, and machine tune variations. Implementation of field profiles which are independent between the two magnets was imperative to increase compactness by reducing the radial excursion of orbits, and consequently footprint. This approach can be considered a generalized radial-sector FFAG. The "D" magnet remains reverse-bending, relative to the "F", but with a different, independently optimized multipole content, and neither component follows field scaling laws.

This innovation combined with an entirely new methodology (described later), achieves not only independent optics between the vertical and horizontal planes, but also an unprecedented 1) range in acceleration energy, 2) control over the physical features of components, and 3) control over technical specifications such as magnetic fields, all within the nonscaling FFAG framework.

LATTICE FOR SLOW ACCELERATION

To automate the new design approach for lattices that can sustain slow acceleration, a powerful new methodology was pioneered for FFAG optics design using control theory and native optimizers in *Mathematica*® to develop executable design scripts. Constraint criteria, that a fixed-field machine design must fulfill, were implemented in *Mathematica*® to explore potential solutions. These procedures allowed global exploration of all important machine parameters specific to this approach, confirming optimization and a robust starting point for advanced simulations in COSY INFINITY. In this way, very compact lattices were developed for 250-MeV proton accelerators that exhibit stability in both tune and performance for over a factor of 5-10 in momentum. An 8-cell triplet design, with a single, 1.2 meter-long straight insertion in each cell (vs. the 2 straights in a FODO pattern) is the one described in this work. The single long straight per cell conserves footprint and accommodates rf, injection, multiple extraction lines, and diagnostic straights. It also provides sufficient space to allow superconducting magnet technology combined with a warm rf acceleration system.

The figures and table below represent 1) layout of an inner proton ring and outer carbon ring in Figure 1 required to take $^{12}C^{6+}$ from 65 MeV/nucleon to the required 400 MeV/nucleon for carbon therapy, 2) conceptual design, Figure 2, of a 4T SC magnet for the proton ring and Bz field vs. radius, 3) machine tunes and radial dependence of orbits in Figure 3, 4) general ring parameters of three nonscaling FFAGs, Table 1, 5) dynamic aperture and phase space portraits at 112 MeV.

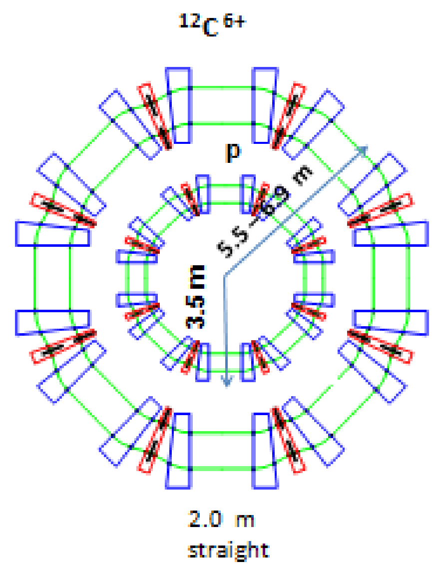

Figure 1: To-scale version the 250 MeV proton (65-MeV carbon) ring showing orbits near extraction @269 MeV and injection, @30 MeV embedded in the outer, final 400-MeV/nucleon carbon ring.

NONSCALING THERAPY FFAGS

Notably, three nonscaling versions have been advanced for proton therapy with larger, add-on rings for carbon. A synopsis of the three lattices including the one described in this work are presented in Table 1. What is particularly revealing is the progression from a linear-field, rectangular component design based on the muon systems (Trbojevic, or T-lattice [6]) to a variant which utilizes nonlinear scaled fields, but rectangular SC magnets, and truncates the field scaling law at decapole (Machida or M-lattice[7]), and finally, the work here (Johnstone, or J-lattice) which is a completely nonlinear representation of the radial sector with arbitrary, independent field orders in the F and D magnets coupled to an independently optimized edge contour (at this time constrained to a linear hard edge cut).

CONCLUSIONS

The table illustrates the progressing design of the nonscaling FFAG from the muon-based concept, through a hybrid nonscaling version to the most general form of the nonscaling FFAG, with unconstrained field content and edge contours. The progress in compactness and tune stability – while preserving adequate space for rf – is notable. Dynamic aperture of the J-lattice, displayed at a median energy, is exceptionally large and characteristic of the entire acceleration cycle. Although the aperture is largest in J-lattice, the design is preliminary with more optimization and field strength available. A new generation of FFAG accelerators with broad applications to HEP, industry and cancer therapy is emerging.

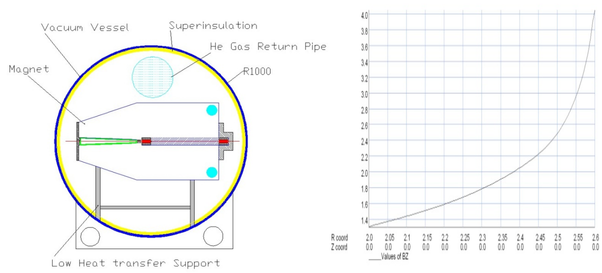

Figure 2: SC magnet and cryostate design (left) and Bz field distribution (right) in mid-plane at 300 kA current.

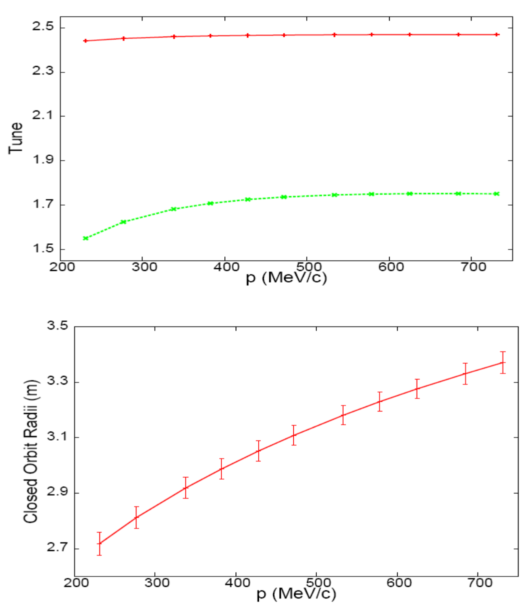

Figure 3: Machine tunes (top) and radial dependence of orbits for the 250 MeV nonscaling proton FFAG.

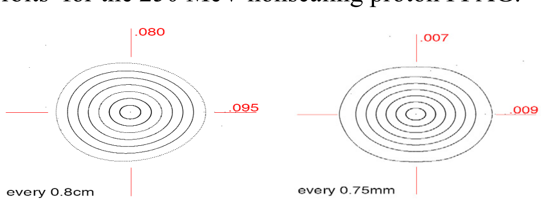

Figure 4: Dynamic aperture a midpoint, 112 MeV. DA at all energies for both planes is extremely large.

Table 1: General Parameters of the 30-250 MeV nonscaling FFAG designs: Trbojevic-lattice (doublet), Machida-lattice and Johnstone-lattice (both triplets).

Parameter	*T-lattice*	*M-lattice*	*J-lattice*
Ext. Radius (m)	4.28	6.25	3.39
# Cells/Magnets	24 / 48	12 / 36	8 / 24
Ring ν_x / ν_y Inj Ext. (2π rad)	7.92/7.20 3.36/1.20	9.16/2.10 9.23/2.13	2.48/1.75 2.48/1.55
Straights: Long, Inter-magnet (m)	0.38 0.08	1.70 0.31	1.17 0.25-0.30
Peak Field F/D (T)	1.8/1.5	4.25/4.00	3.13/3.41
Magnet Size F/D (m)	0.22/0.44	0.31/0.31	0.65-0.80/ 0.13-0.18
Apertures F/D (m)	0.24/0.15	0.26	0.63/0.55

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