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A CW FFAG FOR PROTON COMPUTED TOMOGRAPHY

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Abstract

An advantage of the cyclotron in proton therapy is the continuous (CW) beam output which reduces complexity and response time in the dosimetry requirements and beam controls. A CW accelerator requires isochronous particle orbits at all energies through the acceleration cycle and present compact isochronous cyclotrons for proton therapy reach only 250 MeV (kinetic energy) which is required for patient treatment, but low for full Proton Computed Tomography (pCT) capability. PCT specifications need 300-330 MeV in order for protons to transit the human body. Recent innovations in nonscaling FFAG design have achieved isochronous performance in a compact (~3 m radius) design at these higher energies. Preliminary isochronous designs are presented here. Lower energy beams can be efficiently extracted for patient treatment without changes to the acceleration cycle and magnet currents.

INTRODUCTION

Cyclotrons presently dominate proton therapy partly due to fixed rather than ramped magnetic fields which simplifies operational overhead, but mainly it is due to their capability to deliver low-intensity, CW beam. CW beam is desirable not only from a treatment (integrated dose control) standpoint, particularly for pencil beam scanning[1], but also for compatibility with recent innovations in pCT technology and image reconstruction[2]. PCT has noted advantages in imaging, including minimal current/delivered dose and enhanced tissue identification as briefly discussed below.

While proton therapy benefits from the spatial specificity of dose due to the Bragg peak, significant range uncertainties remain in treatment planning due to intrinsic limitations from X-ray and MR imaging. These imaging modalities do not map tissue density correctly to proton-specific stopping powers, with systematic errors and uncertainties arising from the conversion of Hounsfield numbers [3,4,5]. PCT directly measures the energy loss of protons of higher energy than required for treatment over a number of fields (the protons must pass through rather than stop in tissue). Patient size, resolution requirements in the downstream detector, and the desire to minimise Coulomb scattering [6] in the patient imply a proton energy of at least 330 MeV is needed for PCT. This energy is beyond what is presently available from commercial proton therapy systems. Specifically isochronous (CW) compact cyclotron technology is yet to be developed (a synchro-cyclotron is more technically likely).

Nonscaling FFAGs, however, offer a route to these higher energies, maintaining not only the constant dose characteristic of cyclotrons, but additionally providing for rapid energy variation [7]. If a cyclotron were to be developed that provides 330 MeV beam, degrading to the lower treatment energies (<150 MeV) would likely be prohibitively lossy. Already at 250/230 MeV, beam transmission at the lower energies is a fraction of a percent with significantly higher associated emittances.

A CW FFAG machine provides a new accelerator technology that can deliver continuous beam with high efficiency, but also reliably with “turnkey” operation from the standpoint of fixed magnetic fields and fixed RF frequency. Significant work is progressing on a stable, CW 30-330 MeV isochronous FFAG that can support both pCT and proton therapy with minimal interruption. Dual extraction energies (230-250 MeV or 330 MeV) is envisioned for successful integration of this accelerator into conventional cyclotron facilities; i.e. this machine is compatible with existing degrader, beamlines, and treatment rooms (including gantries).

NONLINEAR HIGH ENERGY CW FFAG

Recently, the concept of isochronous orbits coupled to constant machine tune has been explored and developed for the most general type of FFAG (termed non-scaling) using powerful new methodologies in fixed-field accelerator design [8,9,10]. The property of isochronous orbits enables the simplicity of fixed RF and by inference, CW operation, as in the cyclotron, but with strong focusing. By tailoring a nonlinear radial field profile, the FFAG can remain isochronous with stable tune, well into the relativistic regime and hence at 330 MeV.

Here isochronous, non-scaling FFAG conceptual designs with stable tune are presented for a 30-330 MeV acceleration range. An injection energy of 30 MeV was chosen to be compatible with a 30 MeV, variable-energy injector cyclotron developed for a similar FFAG medical accelerator, the RACCAM project [11]. Variable energy injection allows the downstream FFAG accelerator to change energies very simply and utilize extraction septum or even resonant extraction in an energy-independent way.

CW FFAG Lattices

Two preliminary 30-330 MeV nonlinear non-scaling FFAG lattices are under development:

- A 4-cell non-scaling FFAG based on a DFD triplet layout, isochronous to ±0.7% (Figure 1 and Table 1).
- A 5-cell non-scaling FFAG also based on a DFD triplet layout, isochronous to ±1.26% (Figure 2 and Table 2).

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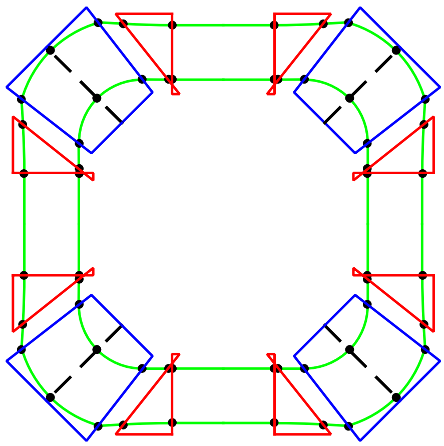

Figure 1: Layout of 4-cell 30-330 MeV FFAG.

Table 1: General parameters 4-cell, 30-330MeV FFAG

Parameter	30 MeV	151 MeV	330 MeV
Avg. Radius	1.923 m	4.064 m	5.405 m
ν_x/ν_y (cell)	0.264/0.366	0.358/0.405	0.-/0.441
Field F/D	0.97/0.00 T	1.24/-0.09T	1.51/-0.16 T
Magnet Size F/D	1.28/- m	2.4/0.92 m	3.18/2.08 m

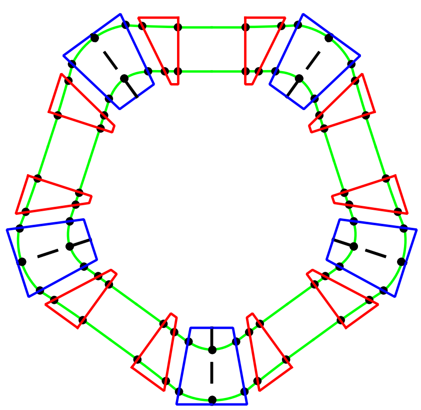

Figure 2: Layout of 5-cell 30-330 MeV FFAG.

Table 2: General parameters 5-cell, 30 to330-MeV FFAG

Parameter	30 MeV	151 MeV	330 MeV
Avg. Radius	2.983 m	5.063 m	6.428 m
ν_x/ν_y (cell)	0.281/0.392	0.300/0.342	0.343/0.356
Field F/D	1.07/-0.0 T	1.27/-0.7T	1.53/-0.16 T
Magnet Size F/D	0.94/- m	1.91/1.41 m	2.58/2.40 m

Discussion

A FDF layout of magnets minimizes the peak value of the dispersion function [12] thereby producing the most compact magnet aperture. However, extraction occurs in the long (2m) straight at the symmetry point between the F quads. At this point the horizontal beta function and beam size is a maximum with increased potential for extraction losses on a septum. The DFD configuration produces the smallest horizontal beta function and beam size at extraction (cyclotrons effectively extract at this point also). Even for low-current machines such as the medical ones under design here, the smallest horizontal beam size will reduce losses and aperture artifacts in the extracted beam distribution.

Initially a 4-cell DFD lattice was explored for isochronous performance and isochronism was achieved at a level of about ±0.7%, although the tune stability over the full acceleration range appears to require a higher order field expansion. A 5-cell version of the lattice was also developed. One can deduce the approximate apertures of the three machine lattices presented from their extraction vs. injection radius. More compact apertures and footprint will require higher orders in the magnetic field expansion than used for this preliminary study and smaller radii of injection.

Magnet Field Profiles

Of particular interest are the nonlinear field profiles and development of the special wedge-shaped magnets. The following Figures 3-4 show the nonlinear profiles that correspond to the parameters and lattices of Figures 1-2 and Tables 1-2.

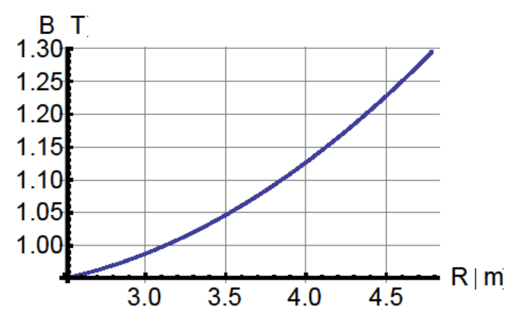

Figure 3: F magnetic-field profiles for a 4-cell 30-330 MeV isochronous FFAG.

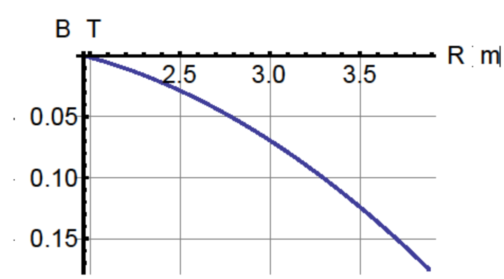

Figure 4: D magnetic-field profiles for a 4-cell 30-330 MeV isochronous FFAG.

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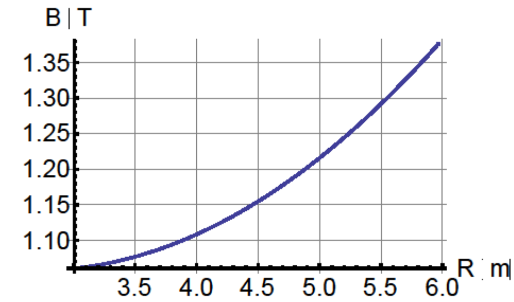

Figure 5: F magnetic-field profilea for a 5-cell 30-330 MeV FFAG.

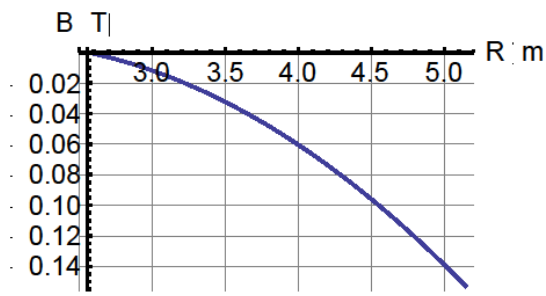

Figure 6: D magnetic-field profile for a 5-cell 30-330 MeV FFAG.

SUMMARY

With isochronous behavior, and strong-focusing optics, these new, advanced non-scaling FFAGs definitely have the potential for a low-loss CW machine for combined application in proton therapy and pCT. The high reliability and turnkey operation of fixed-field accelerators make them ideal for medical and commercial purposes. Although a variable-energy injector cyclotron is proposed here for variable energy extraction, another interesting approach to explore with a CW FFAG is fast resonant extraction (resonant extraction has been investigated for the PAMELA project in the U.K.[7]) which would allow rapid changes in extraction energy; i.e. dynamical range shift. (One would likely still require the capability to form a spread-out-Bragg peak, however, as fine control over the treatment dose still requires conventional approaches.) This work represents the first CW design of a relatively compact accelerator for pCT and proton therapy and one which could potentially replace cyclotrons in many existing facilities.

Clearly these are initial lattices for the purpose of demonstrating isochronous performance. Optimization of field content and periodicity is next, along with high-order modelling and tracking. However, the performance is anticipated to be comparable to previous FFAG lattices recently developed which exhibit stable dynamics under conditions of modest acceleration.

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