1 GeV CW NONSCALING FFAG FOR ADS, AND MAGNET PARAMETERS

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Abstract

Multi-MW proton driver capability remains a challenging, critical technology for many core HEP programs, particularly the neutrino ones such as the Muon Collider and Neutrino factory, and for high-profile energy applications such as Accelerator Driven Subcritical Reactors (ADS) and Accelerator Transmutation of Waste for nuclear power and waste management. Work is focused almost exclusively on an SRF linac, as, to date, no re-circulating accelerator can attain the 10–20 MW capability necessary for the nuclear applications. Recently, the concept of isochronous orbits has been explored and developed for nonscaling FFAGs using powerful new methodologies in FFAG accelerator design. Work is progressing on a stable, high-intensity, 1 GeV isochronous FFAG. Initial specifications of novel magnets with the nonlinear radial fields required to support isochronous operation are also reported here.

INTRODUCTION

Multi-MW proton driver capability remains a challenging, critical technology for many core HEP programs, particularly the neutrino ones such as the Muon Collider and Neutrino factory, and for high-profile energy applications such as Accelerator Driven Subcritical Reactors (ADS) and Accelerator Transmutation of Waste for nuclear power and waste management.

Nuclear power is a critical source of clean energy and the neutrons required to drive a sub-critical reactor can be generated by directing a high power proton beam onto a target. Since nuclear reactions cannot occur without the accelerated beam, accelerators are a means to safer nuclear power. This same technology can also drive a nuclear reactor that burns the transuranic elements and other long-lived fission products in the spent fuel from a light-water reactor. Such a reactor, Accelerator Driven Transmutation, not only generates energy, it transforms problematic nuclear waste into short-lived isotopes - reducing the comparable radiotoxic lifetime of spent nuclear fuel from 300,000 years to 500.

Work on ADS and ATW systems have been focused almost exclusively on an SRF linac, as, to date, no re-circulating accelerator can attain the 10–20 MW capability necessary for the nuclear applications. Recently, the concept of isochronous orbits has been explored and developed for nonscaling FFAGs[1] using powerful new methodologies in FFAG accelerator design. The FFAG can remain isochronous beyond the energy reach of cyclotrons and with fixed magnetic fields and strong focusing coupled to recent advances in tune stability, dynamic aperture, and footprint, serious study is underway on a potential application to the ADS problem.

A CW FFAG machine provides a new path to deliver high power with high efficiency, and also reliably from the standpoint of fixed magnetic fields and fixed RF frequency. Significant work is progressing on a stable, high-intensity, 1 GeV isochronous FFAG along with development and characterization of novel magnets with the nonlinear radial fields required to support isochronous operation.

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[2, 3]. 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. With isochronous orbits, these machines are demonstrating the high average current advantage and duty cycle of the cyclotron in combination with the strong focusing, smaller losses, that are more typical of the synchrotron.

Here isochronous, non-scaling FFAG conceptual designs with stable tune are presented for a 1 GeV output beam, which is ideal for the ADS application.

CW FFAG Lattices

Several 1 GeV nonlinear nonscaling FFAG lattices and magnetic field profiles are being developed:

- A 0.25–1 GeV 4-cell nonscaling FFAG lattice based on a FDF triplet magnet layout, with an isochronous performance of $\pm 3\%$.
- A 0.33–1 GeV 6-cell nonscaling FFAG based on a DFD triplet layout, isochronous to $\pm 0.9\%$.
- A 0.33–1 GeV 7-cell nonscaling FFAG based on a DFD triplet layout, isochronous to $\pm 1.2\%$.

Discussion

A FDF layout of magnets minimizes the peak value of the dispersion function[4] thereby producing the most compact magnet aperture. However, extraction occurs in the

Table 1: General Parameters, 4-cell 1 GeV FFAG

Parameter	250 MeV	585 MeV	1000 MeV
Avg. Radius [m]	3.419	4.307	5.030
ν_x/ν_y (cell)	0.380/0.237	0.400/0.149	0.383/0.242
Field F/D [T]	1.62/−0.14	2.06/−0.31	2.35/−0.42
Magnet Size F/D [m]	1.17/0.38	1.59/0.79	1.94/1.14

Table 2: General Parameters, 6-cell 1 GeV FFAG

Parameter	330 MeV	500 MeV	1000 MeV
Avg. Radius [m]	5.498	6.087	7.086
ν_x/ν_y (cell)	0.297/0.196	0.313/0.206	0.367/0.235
Field F/D [T]	1.7/−0.1	1.8/−1.9	1.9/−3.8
Magnet Size F/D [m]	1.96/0.20	2.79/0.20	4.09/0.20

long (2 m) straight at the symmetry point between the focusing 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 by the way extract at this point also). Therefore for high-current machines the DFD structure is preferred for high-current extraction.

Initially a 4-cell FDF lattice was explored for isochronous performance and this was verified at the level of ±3%[5]. Further improvements led to developing the DFD isochronous lattice. One can deduce the approximate apertures of the three machine lattices presented from their extraction vs. injection radius. As the periodicity is increased, the aperture generally decreases along with the length of the F magnet, which is inward bending. Also the isochronous performance was greatly improved, from ±3% to ±1%.

Magnet Field Profiles

Of particular interest are the nonlinear field profiles and development of the special wedge-shaped magnets; particularly considering that the fields outside of possibly the 4-cell version, are superconducting. Figures 4–6 show the nonlinear profiles that correspond to the parameters and lattices of Figures 1–3 and Tables 1–3.

Simulation Results

Simulations have been performed in both COSY INFINITY[6] and ZGOUBI[7] for the 4-cell 1-GeV isochronous FFAG confirming both isochronous performance and a large dynamic aperture. In the latter, acceleration has been added and the results are shown below. Stable acceleration maintaining a large DA has been demon-

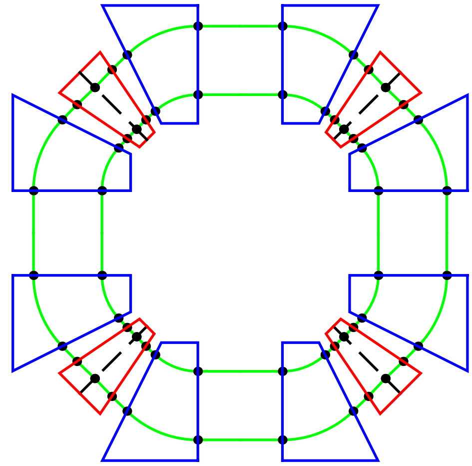

Figure 1: Layout of the 4-cell 0.25–1 GeV FFAG.

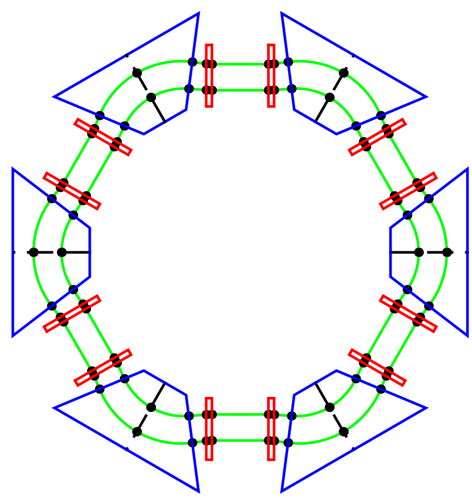

Figure 2: Layout of the 6-cell 0.33–1 GeV FFAG.

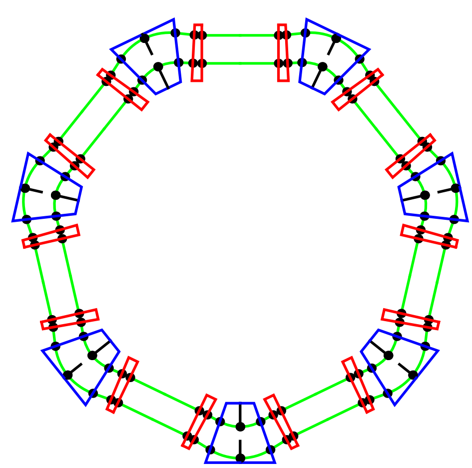

Figure 3: Layout of the 7-cell 0.33–1 GeV FFAG.

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Table 3: General Parameters, 7-cell 1 GeV FFAG

Parameter	330 MeV	500 MeV	1000 MeV
Avg. Radius [m]	4.354	4.816	5.126
ν_x/ν_y (cell)	0.250/0.250	0.243/0.242	0.252/0.251
Field F/D [T]	3.3/−0.07	3.3/−0.7	3.8/−3.0
Magnet Size F/D [m]	0.79/0.25	1.10/0.25	1.67/0.25

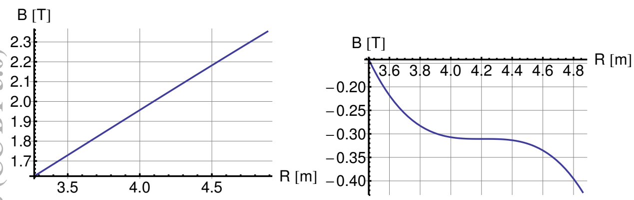

Figure 4: F (left) and D (right) field profiles for the 4-cell 0.25–1 GeV FFAG.

strated in this advanced simulation[8], see Table 4. Space charge studies have also been initiated on this machine[5] with very promising preliminary results.

SUMMARY

With isochronous behavior and space-charge resistant, strong-focusing optics, these new, advanced non-scaling FFAGs definitely have the potential for a high-intensity proton driver, possibly exceeding the cyclotron in current capability. (Linacs will likely remain the highest current accelerator, but, in general, remain costly, and, at GeV energies, are long.) Further, FFAGs have been specifically earmarked for future studies with reference to ADS[9]. The high reliability requirement can imply either accelerator redundancy or unused beam which can be re-directed. Duplicate linacs would be prohibitively expensive, but not necessarily an FFAG option. An 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.) which could moderate the beam intensity delivered to the reactor on a fast, sub-microsecond timescale and is less insensitive to individual bunch population. With multiple RF cavities, due to the stable nature of the FFAG, an RF trip simply slows the full acceleration cycle rather than entirely interrupting beam—a very strong advantage.

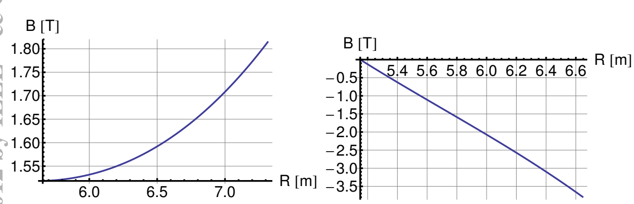

Figure 5: F (left) and D (right) field profiles for the 6-cell 0.33–1 GeV FFAG.

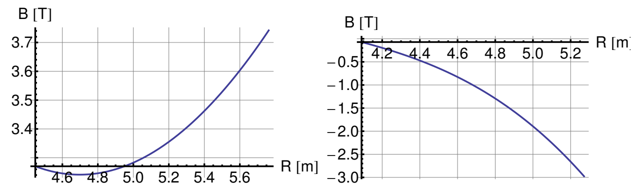

Figure 6: F (left) and D (right) field profiles for the 7-cell 0.33–1 GeV FFAG.

Table 4: Dynamic Aperture with Acceleration

Acceleration rate	Number of turns	Dynamic aperture (π mm mrad normalized)
None (@250 MeV)	1000	>420
1 MV/turn	750	374
2 MV/turn	375	411
4+ MV/turn	188	>450

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