NON-SCALING FFAG PROTON DRIVER FOR PROJECT X*

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Abstract

The next generation of high-energy physics experiments requires high intensity protons at multi-GeV energies. Fermilab's HEP program, for example, requires an 8-GeV proton source to feed the Main Injector to create a 2 MW neutrino beams in the near term and would require a 4 MW pulsed proton beam for a potential Neutrino Factory or Muon Collider in the future. High intensity GeV proton drivers are difficult at best with conventional re-circulating accelerators, encountering duty cycle and space-charge limits in the synchrotron and machine size and stability concerns in the weaker-focusing cyclotrons. Only an SRF linac, which has the highest associated cost and footprint, has been considered. Recent innovations in FFAG design, however, have promoted another re-circulating candidate, the Fixed-field Alternating Gradient accelerator (FFAG), as an attractive, but as yet unexplored, alternative. Its strong focusing optics coupled to large transverse and longitudinal acceptances would serve to alleviate space charge effects and achieve higher bunch charges than possible in a synchrotron and presents an upgradeable option from the 2 MW to the 4 MW program.

INTRODUCTION

One scenario being developed for the neutrino physics programs at Fermilab is based on a 3GeV cw linac, that provides a 1mA [1] proton beam (Project X). This linac would then feed an accelerator to take beam to 8GeV for injection into the Main Injector (MI), and this subsequent accelerator must be upgradeable to provide 8GeV beam at 4MW with different bunching requirements for future needs. Although a rapid-cycling synchrotron or pulsed linac is being considered, a synchrotron cannot be upgraded to such intensities and a pulsed linac is mismatched to the present 3-GeV cw linac source.

A FFAG (fixed-field alternating gradient) accelerator is capable of accelerating protons from 3 to 8GeV using a modest (few MV) of swept-frequency RF as would be required in a synchrotron, but without correspondingly ramping the magnet field. (Ramped magnets restrict the duty cycle to ~50 Hz with associated high costs in power supply and regulation systems. RF systems can be typically swept in the 100 Hz to kHz range.) The dominant consideration is that the magnets have an enlarged size needed to accommodate stable orbits over the full momentum range, but this can be minimized to a technically practical aperture. An upgrade to the requirements of a facility (such as a Neutrino Factory or Collider) is also relatively straightforward in the case of a FFAG. With fixed-field magnets, only the RF is required to be switched to higher-power and faster sweeping capacity (the RF frequencies would also be changed to fit the different bunching requirements). Further, the larger FFAG apertures may actually be required to accommodate the larger emittance demands of the Neutrino Factory, in particular, so the larger apertures are not a drawback to the use of a FFAG.

FFAG DESIGNS FOR PROJECT X

The FFAG concept in acceleration was invented in the 1950s independently in Japan, Russia and the U.S. Recently Y. Mori has initiated a renaissance in the FFAG approach by building and operating several FFAGs. [2]. 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 body gradient (which alternately focuses in each transverse plane) or through body gradient focusing in one plane (nominally horizontal) and strong gradient-dependent edge focusing in the other (vertical) plane.

There are two general classifications for FFAG accelerators. The so-called scaling FFAGs (either spiral or radial-sector FFAGs) are characterized by geometrically similar orbits of increasing radius. Direct application of high-order magnetic fields and edge focusing maintains a constant tune and other constant optical functions (such as zero chromaticity) during the acceleration cycle, thus avoiding low-order resonances. To achieve stable optics in the presence of nonlinear magnetic fields, such fields follow a scaling law as a function of radius: $B(r, z) = B_0(z)\,(r/r_0)^k$, where k is the FFAG field index. The scaling condition is relaxed in the non-scaling FFAG with stable acceleration the primary goal. Initially non-scaling designs had a large tune dependence with momentum, which limited beam lifetimes to a few turns [3]. With tune 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) subsequent non-scaling designs were developed with constant or acceptably small-variation in tunes. These recent innovations in non-scaling FFAG design therefore exhibit the many-turn stability needed for a proton driver. [4, 5].. The specific non-scaling design for a 3-8 GeV application will be compared here.

Beam Requirements

For the near-term, the MI will provide both a 60-GeV, 2 MW beam (~1.25Hz repetition rate) and 120-GeV beam

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(~0.67Hz) for long baseline neutrino beams, which requires ~1.6 × 10^{14} protons/pulse. The injection energy remains 8 GeV and matching to the present cycle, and using the Recycler as an intermediate stacking ring implies ~26ms of 1mA beam is required from the 3-GeV cw linac. The FFAG would then boost the particle energies to 8 GeV. For a FFAG approximately the size of the present Fermilab Booster (~500m), then 6 cycles at 10Hz or more, with each cycle accelerating ~2.7×10^{13} p, would fill the 3320m circumference Recycler for subsequent transfer to the MI. Each FFAG injection cycle would require 4½ ms of charge exchange injection from the upstream cw linac. To upgrade to a 4 MW proton source and a 60 to 15 Hz repetition rate for a Neutrino Factory (NF) or muon collider (MC) would require 4 bunches of ~1.3 × 10^{13} p at 60Hz (NF mode) or 4 bunches of 5 × 10^{13} p at 15 Hz (MC mode). For these modes, 50% of the 3GeV 1mA cw beam would be needed for injection; a 3GeV accumulator ring accepting 8.3 mA-ms (NF) or 33mA-ms (MC) of cw H^- linac injected beam could be used. Protons would be transferred from the accumulator to the FFAG for 3 to 8 GeV acceleration. (The protons would need to be formed into 4 short, ~3 ns bunches. This could be accomplished in the FFAG ring itself or in an additional buncher ring.)

Scaling FFAG Solutions

Two scaling FFAG designs have been discussed in a paper also submitted to these proceedings[6]. One is a 3—10 GeV 400m-circumference FFAG synchrotron[7] developed by Rees and Kelliher for the Neutrino Factory International Design Study [8] based on a series of "pumplet" cells, each of which contains 5 combined-function magnets in an f D F D f configuration (D-magnets are also negative bends) with 4 or 6m long straights.. The orbit excursion (low to high energy) of this lattice only ~10 cm. A second, radial-sector scaling FFAG lattice has also been developed based on a triplet geometry. Depending on the maximum magnetic field (5.5/7.4 T), the circumferences are 958 and 474m, respectively, and are presently being modelled. Given the high currents, SC magnetic fields must be evaluated for quenching and tolerated beam loss.

Two nonlinear non-scaling FFAG lattices were also pursued and one which allows a smaller orbit excursion and lower magnetic fields are discussed in these proceedings [6]. The first lattice utilizes rectangular magnets with higher order fields to control tune. The second, presented here, utilizes gradient and edge focusing in combined-function magnets to control tune and chromaticity with the latter close to zero. These magnets have linear, but arbitrary edge profiles and a field gradient with independent sextupole and octupole components in the both F and D magnets, as shown in Figures 1 and 2. Tune dependence on momentum of the cell is shown in Figure 3. Slight adjustments of the fields near injection are anticipated to stabilize the tune further for completely stable acceleration. Gross parameters are given in Table 1.

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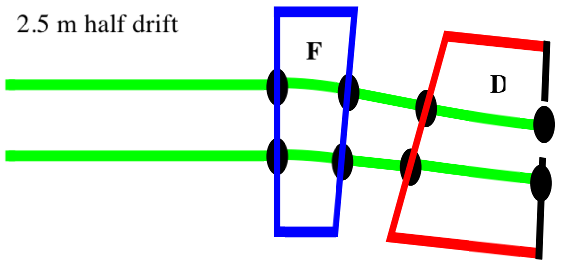

Figure 1: Half a cell in a nonlinear non-scaling FFAG with edge angles and focusing to control tune.

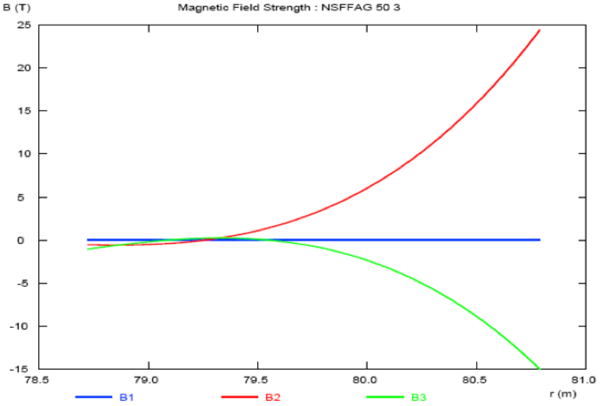

Figure 2: The nonlinear field profile with components up to 3^{rd} (octupole) order in magnets depicted in Figure 1.

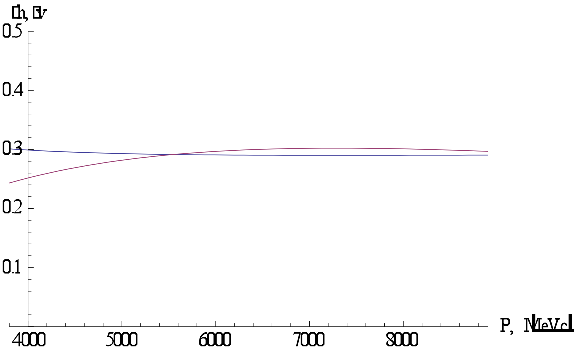

Figure 3: The tune dependence on momentum for a unit cell.

Table 1: Parameters of a Nonscaling FFAG.

Parameter	**Value**
Circumference	561m, 50 cells
Tunes (ν_x, ν_y,)	14.78, 14.8,
F,D lengths (inj-ext)	0.61-0.67, 2.52-2.22 m
Magnet strengths B, F,D(8GeV)	5.0T, -1.3T
Magnet Aperture (H,V)	50 cm, 5 cm

FFAG DESIGN AND MODELING

Powerful new methodologies in accelerator design and simulation have been pioneered using control theory and optimizers in advanced design scripts with final simulation in COSY INFINITY [9,10]. COSY INFINITY now has a full complement of sophisticated simulation tools to fully and accurately describe both conventional accelerators and the FFAG's complex electromagnetic fields. Specifically, new tools were developed for the study and analysis of synchrotron, cyclotron, and FFAG dynamics based on transfer map techniques unique to the code COSY INFINITY. With these new tools, closed orbits, transverse amplitude dependencies, and dynamic aperture are determined inclusive of full nonlinear fields and kinematics to arbitrary order. Various methods of describing complex fields and components are now supported including representation in radius-dependent Fourier modes, complex magnet edge contours, as well as the capability to interject calculated or measured 3D field data from a magnet design code or actual components, respectively.

Modelling has been initiated in COSY INFINITY and the half-cell field profile expanded in 3D polar coordinates with full fringe fields (Figure 4). Tracking is now proceeding with midplane expansion to any order. Radial dependence of the closed orbit is given in Figure 5.

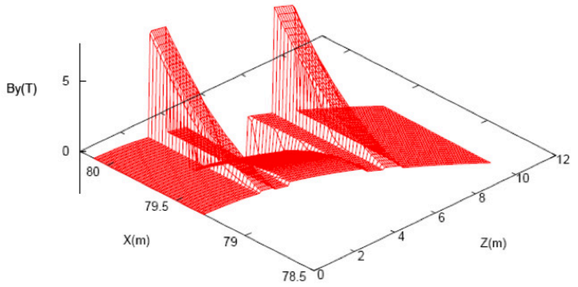

Figure 4: The 3D expansion of the field with full fringing effects generated by COSY.

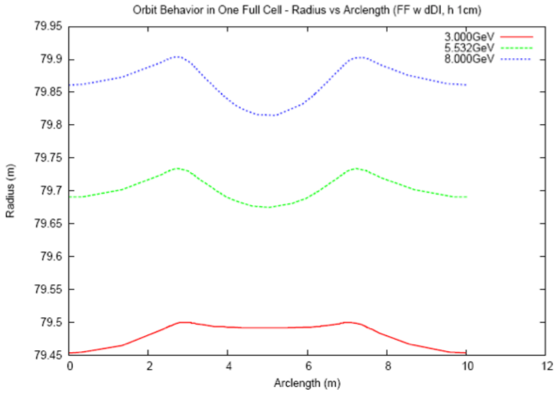

Figure 5: Radial dependence of closed orbit at injection, extraction and an intermediate energy.

SUMMARY AND FUTURE PLANS

Initial designs for a 3-8 GeV FFAG in both scaling and non-scaling versions have been presented and, potentially deliver high power protons in the multi-MW range required for Project-X using a 3-GeV cw linac as an injector. Preliminary results show that both scaling and non-scaling FFAGs could be implemented. All scenarios require further optimisation, along with tracking studies including errors and the space charge effects. Also the acceleration scenarios need to be developed, together with bunching scenarios, such as a final bunching ring in a MC scenario.

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