# A COMPACT, GeV, HIGH-INTENSITY (CW) RACETRACK FFAG*

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*Abstract*

Achieving milliamps of protons at GeV energies in a compact machine format implies both CW operation and high acceleration gradients to control losses. Above a few hundred MeV, beam loss must be well under a per cent to avoid massive shielding and unmanageable activation at high current. As relativistic energies are approached, the orbit separation between consecutive acceleration turns decreases in isochronous or CW accelerators because beam path length must scale proportional to velocity, $\beta$. To achieve the orbit separation needed for low-loss extraction, higher acceleration gradients must be deployed in relativistic machines; i.e. RF modules rather than Dee-type cavities. RF module insertion however results in a cyclotron with separated sectors and a greatly increased footprint. In Fixed Field Alternating Gradient Accelerators (FFAGs), the addition of synchrotron-like strong focusing (including reversed gradients to capture both transverse planes) promote inclusion of long, optically stable synchrotron-like straight sections and implementation of high-gradient RF, even SCRF. Further, FFAGs support constant, synchrotron-like machine tunes and tune footprints thus avoiding beam loss from resonances. The next generation of nonscaling FFAG machines not only maintain constant-tune, stable dynamics, these designs have also evolved into compact CW machines up to GeV energies for protons. The most recent innovation is an ultra-compact, 0.2 – 1 GeV FFAG racetrack design with a 3-4m by 5-6m footprint and 2-3m opposing straight sections that achieves both CW operation and low-loss extraction using SCRF. This new FFAG variant is described here. Note that minor lattice revisions would permit a CW ion therapy design capable of 430 MeV/nucleon for ions with charge to mass ratio of ~1/2 and the potential for variable energy extraction.

## INTRODUCTION

Historically, cyclotrons are the highest current, most compact accelerator technology, but only at lower energies (hundreds of MeV). Higher energies require separated sectors in the cyclotron - like the 590-MeV PSI [1] or 500-MeV TRIUMF cyclotrons [2] – in order to insert strong accelerating (rf) systems. Stronger acceleration is required to minimize beam losses and radioactivity both during acceleration and during beam extraction (fewer acceleration turns and larger separation between the beams that comprise different acceleration turns facilitate efficient extraction). However, once space is inserted between the magnetic sectors of the cyclotron, the footprint of the cyclotron grows rapidly.

High-intensity applications of relativistic proton accelerators that achieve milliamps of average current require CW operation to mitigate space charge and high acceleration gradients to limit losses to under a per cent to avoid massive shielding and unmanageable component activation. Cyclotron designs utilize Dee-shaped rf components between poles to achieve compactness, however, the accelerating gradient is low. As relativistic energies are approached, the orbit separation on consecutive acceleration turns must decrease to maintain the isochronous condition; i.e. constant revolution frequency for a fixed-frequency acceleration system. To achieve increased orbit separation, especially critical for low-loss extraction, higher acceleration gradients must be deployed; i.e. rf modules must be utilized, forcing separated sectors in a cyclotron, and an unavoidable large increase in footprint. The weak-focusing nature of traditional cyclotron fields does not permit long (several meters) straight sections without a significant scaling up of machine radius and size. However, the addition of strong focusing gradients (and corresponding strong beam envelope control) to conventional cyclotron fields – including reversed gradients to capture both transverse planes – does allow insertion of long synchrotron-like straight sections and thus efficient implementation of high-gradient, multiple-cavity rf modules, even SCRF cryomodules. Further, the nonscaling FFAG designs have evolved into a very compact racetrack shape – essentially a recirculating linear accelerator with FFAG arcs. This new generation of ultra-compact nonscaling FFAGs with constant machine tunes are described in this work, and specifically a 0.2 – 1 GeV proton FFAG with a 3-4 m by 5-6m footprint. With high gradient SCRF structures, described in these conference proceedings [3], the beam undergoes only 40 acceleration turns (1 0MV/m). Complete orbit separation is achieved at extraction for CW operation. The wide horizontal aperture SCRF pillbox design is presented in another submission [3].

## DESIGN CONCEPTS

Another key dynamics issue is resonance avoidance, accomplished with stable, constant strong-focusing machine tunes over the entire acceleration energy range. Conventional isochronous cyclotron design cannot maintain both isochronous orbits and stable tunes at relativistic energies. The next generation of nonscaling FFAGs are capable of both, exhibiting strong-focusing machines tunes, tune footprints, and space-charge tune shifts characteristic of synchrotrons. High-intensity operation and tolerance of increased space charge effects has been reported in recent preliminary simulations [4].

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There are important dynamical consequences in relativistic cyclotrons that impact machine parameters. These are discussed below without derivation.

In cyclotrons the azimuthal B field profile does not change with radius that is, the extent of the "hills and valleys" scale in direct proportion to radius. Due to the fixed azimuthal field profile, $B(\theta)$, the magnitude of the radial $B$ field must increase as $B=\gamma B_0$, to maintain isochronous orbits, with $\gamma$ the relativistic factor and $B_0$ the magnetic field at injection ($\gamma\rightarrow 1$ at nonrelativistic energies giving the conventional cyclotron).

The increasing peak B field results in a gradient term which changes the machine tune; the tune cannot be held constant in relativistic cyclotrons – it rises radially and decreases vertically. A spiral shape is introduced to increase the vertical edge crossing effect (flutter) with energy to maintain a stable vertical machine tune. Eventually the vertical tune becomes unsustainable. Tune approximations from Eq. (1) give $\nu_r \cong \gamma$ and $\nu_z^2 \cong 1-\gamma^2+F(1+2\tan^2\varepsilon)$ where F is the flutter and $\varepsilon$ the spiral angle.

$$F = \left\langle \left( \frac{B(\theta)\text{-}B_{av}}{B_{av}} \right)^2 \right\rangle \qquad (1)$$

where $\varepsilon$ defines the axis $R = R_0 e^{\theta \cot \varepsilon}$

As $\gamma$ increases, $\nu_r$ increases and $\nu_z$ decreases. The machine tune changes and crosses betatron resonances with potential for beam blowup and losses. Stable beam properties, dynamics and low-loss operation can in general not be achieved in high-energy cyclotrons unless the acceleration is strong enough to jump across resonances and separate orbits sufficiently for extraction.

The dynamics of the FFAGs, both scaling [5] and nonscaling [5] are dominated by synchrotron-like dynamics. In a FFAG all conventional focusing terms are utilized as given in the following thin-lens approximation:

$$1/f_F = k_F l + \frac{\vartheta}{\rho_F} + \frac{\eta}{\rho_F}. \qquad (2)$$

where $f_F$ and $\rho_F$ in Eq. (2) are the focal length in the horizontal plane and bend radius, respectively, $l$, the horizontally-focussing magnet half length, $k_F$ the "local" horizontally focusing gradient for an arbitrary field order, $\theta$ the sector bend angle, $\eta$ the edge crossing angle (the tangent is approximated). At high-energy, a reverse gradient component enhances the vertical tune, however the sector bend term is not available in that plane.

The synchrotron relies on the first strong-focusing gradient term, the cyclotron on the last two terms, the centripetal or weak focusing and edge focusing terms (centripetal applies to the horizontal envelope only), but the FFAG utilizes all three terms for beam envelope control and dynamical stability. This simple thin-lens expression highlights how the three machines fundamentally operate and determines ultimate flexibility in format and machine characteristics. In the FFAG, since all three terms are applied, the terms can be inter-played to achieve stable dynamics in flexible, compact lattice structures. The nonscaling FFAG optimizes the bend/reverse gradients and edge angles independently; critical for compactness and cw dynamics.

This last point is very important for nonscaling FFAGs because it allows the field, orbit location, and important machine parameters such as tune, footprint, and aperture to be approximately independent and more strongly controlled than in a cyclotron. In the nonscaling FFAG (only), the different focusing principles are combined in different and varying relative strengths through the acceleration cycle – this varying composition can be exploited to control the machine tune through the acceleration cycle without applying the field scaling law.

The design of the nonscaling FFAG is particularly powerful for a nonlinear field expansion. Including components with reverse gradients the orbital path length can be constrained such that the revolution time at each momentum scales with velocity, and simultaneously the machine tune can be controlled through edge and weak focusing effects independent of path length thereby impacting tune but not revolution frequency. Unlike the cyclotron, which relies on a predominately dipole field or fixed B-field scaling with $\gamma$, and is therefore limited in adapting path length to velocity as the energy becomes relativistic, the non-scaling FFAG can maintain isochronous orbits well into relativistic energy regimes as shown in Figure 1. Further, the nonlinear gradient has the advantage of providing increased focusing in both transverse planes as a function of energy through edge and centripetal focusing terms providing a strong constant tune in both planes while preserving considerable freedom in physical parameters. Only the nonscaling FFAG can be cw. The strong focusing attribute, implies mitigation of space-charge and stable acceleration of potentially higher currents than the cyclotron.

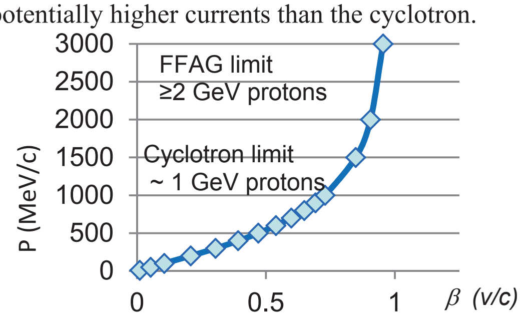


Figure 1: Momentum dependence on velocity. $\langle B_r \rangle \propto P/\beta$ for isochronous orbits that are ~geometrically similar.

## *Lattice Design*

As the demands for compactness increased, eventually all inter-component straight sections in FFAGs became too minimal for effective extraction or even injection. The racetrack configuration optimizes compactness yet provides for RF modules to be inserted in one straight and injection extraction systems in the opposite straight.

Figure 2 (left) shows the normal (blue) and reverse gradient (red) components for a periodic compact FFAG and one with two long straight insertions on opposing sides. Figure 2 (right) shows the machine tunes.

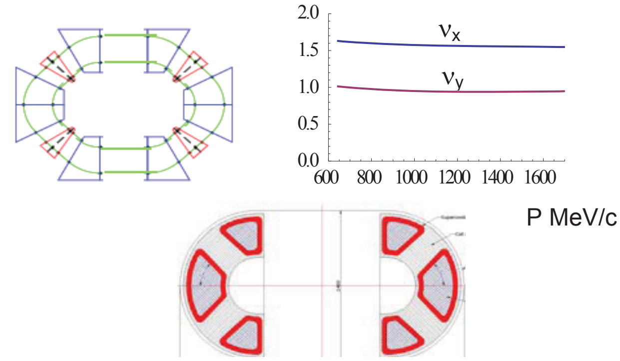


Figure 2: Racetrack layout (left) in terms of normal/reverse (blue/red) gradient components and hard-edge machine tunes (right), bottom shows magnet design.

### *Tracking*

Given the highly nonlinear field profile required for all compact, fixed magnetic field accelerators to achieve high energies (including synchrocyclotrons), efficient beam transmission is an overriding concern so high-order simulation was initiated using powerful new methodologies in fixed-field accelerator design[6]. Figure 3 depicts the tracking pictures at high-energy. Basically in this design, the geometric emittance was preserved due to the constant optics as a function of energy. When geometric emittance is preserved, the dynamical acceptance or DA actually increases and beam transmission is predicted to be near 100%. This is in contrast to the DA predicted for the 8-sector version of the Daedaleus cyclotron [7] which decreases with energy. The tracking indicates a factor of 4 increase in DA for the FFAG described in this work for a factor of 4 decrease in footprint when compared to the published tracking results for this specific Daedaleus cyclotron design [7].

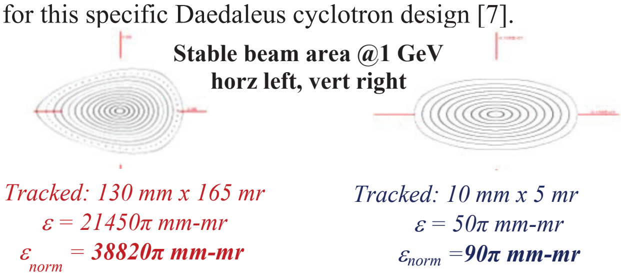


Figure 3: Tracking results using COSY INFINITY. Aperture limit is reached in vertical.

### *Magnet design*

The magnet system concept is based on calculated beam dynamics parameters and designed without an iron yoke making the system ultra-compact and much lighter. The main field in the F-magnet (Fig. 3, bottom) is formed by two NbTi Rutherford-cable trapezoidal coils separated vertically to provide space for the beam pipe and operated at 4° K (the cryostat is also designed). The relatively low D-magnet field is formed by the F-magnet return flux in the beam pipe area. Main magnet system parameters are shown in Table 1.

Table 1: Magnet Design

| Parameter | Units | Value |
|---|---|---|
| Number of magnets/coils | | 6/12 |
| Peak magnetic field coils | T | 7 |
| Magnet Beam Pipe gap | mm | 50 |
| Coil ampere-turns | MA | 3.0 |
| Magnet system height | M | ~1 |
| Total Weight | tons | ~10 |

### *Acceleration*

An ultra-compact FFAG requires a total voltage of ~10-20 MV per turn for high intensity in order to cleanly separate consecutive orbits near extraction for εnorm (95%) = 10π mm-mr (lower intensities and emittances require significantly less voltages). Continuous wave accelerating gradients of ~5-10 MV/m can only be achieved using superconducting accelerating cavities which are inserted in a cryomodule in a 2 m straight. Design of the rf is presented in this conference [3].

## SUMMARY

In summary, a 0.2 – 1 GeV FFAG racetrack design indicates a form factor that is 3-4 m wide by 5-6 m long with 2 m long opposing straight sections; one of the straight sections accommodates superconducting radio-frequency linear accelerating structures (a pillbox design) housed in a cryogenic-module. With high SCRF (also designed) this hybrid accelerator approaches the low losses of the linac and achieves clean separation of beam for extraction and supports large DA and transmission.

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