ELECTRON MODEL OF LINEAR-FIELD FFAG*

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Abstract

A fixed-field alternating-gradient accelerator (FFAG) that employs only linear-field elements ushers in a new regime in accelerator design and dynamics. The linear-field machine has the ability to compact an unprecedented range in momenta within a small component aperture. With a tune variation which results from the natural chromaticity, the beam crosses many strong, uncorrectable, betatron resonances during acceleration. Further, relativistic particles in this machine exhibit a quasi-parabolic time-of-flight that cannot be addressed with a fixed-frequency rf system. This leads to a new concept of bucketless acceleration within a rotation manifold. With a large energy jump per cell, there is possibly strong synchro-betatron coupling. A few-MeV electron model [7,9] has been proposed to demonstrate the feasibility of these untested acceleration features and to investigate them at length under a wide range of operating conditions. This paper presents a lattice optimized for a 1.3 GHz rf, initial technology choices for the machine, and describes the range of experiments needed to characterize beam dynamics along with proposed instrumentation.

INTRODUCTION

For the U.S. Neutrino Factory, FFAGs are the preferred acceleration model[1] to high energy due to their significantly reduced cost and larger acceptance, implying a factor of 4 reduction in transverse cooling and total elimination of longitudinal cooling relative to recirculating linear accelerators. These are *not* MURA-style scaling FFAGs [2], but a new breed of accelerator, using strictly linear elements, with characteristics well matched to the rapid acceleration of beams with large 6D emittances. However, they rely on untested beam dynamics which are strongly time and parameter dependent and therefore have been the subject of intensive study and simulation as documented in a series of FFAG work-shops [3]. A demonstration model is important to fully characterize the uncharted beam physics of this machine, and plans for this are the subject of this paper. The purpose of the electron model is two-fold: (i) demonstrate the frontier beam dynamics, and (ii) investigate in detail the complex parameter dependencies, of the non-scaling FFAG at a tiny fraction of the cost of the multi-GeV muon machines.

Although the new FFAG is, in one sense, a radial sector FFAG [2] without nonlinear field components, more so it is a specialized electron storage ring operable over a tremendous momentum range. Physically, the electron model will bear a strong resemblance to the KEK ATF [2]. The linear-field lattice demonstrates compaction of a very large range of momenta into remarkably narrow apertures. [Livingood's 1951 definition of momentum compaction, α= (dp/p)(dL/L), captures well the spirit of this machine for which $\alpha\to\infty$ at mid-energy.] Defining traits of this FFAG are that it operates (i) with fixed, linear magnetic fields, and (ii) with a range of momenta that is ≈1000 times larger than a synchrotron. These have two important and untested consequences.

Asynchronous acceleration

In fixed magnetic fields, the particle beam sweeps across the radial aperture during acceleration, leading to changes in orbit shape which produce a quasi-parabolic time-of-flight (ToF) variation. With a fixed frequency and rapid acceleration cycle, there is an unavoidable phase slip which makes possible *asynchronous acceleration* within a rotation manifold outside the rf bucket.

Multi-resonance crossing

The stable momentum acceptance of this machine spans ±50% in $\delta p/p$. Its uncorrected, natural (negative) chromaticity leads to the beam crossing many betatron resonance including integer and ½-integer; this has not been accomplished in any accelerator. The new FFAG gambles on crossing these resonances quickly, with manageable phase space dilution. Based on particle tracking studies, presented in 2004, Machida [4] reported that alignment and quadrupole gradient r.m.s. errors of 30 μm and 0.3% are consistent with unmeasurable emittance growth for 10-turn acceleration. These tolerances are feasible to achieve, the latter straightforward. Values for the muon machines are less demanding. The successful numerical demonstration of resonance crossing was a key milestone to proceeding with the design work. Nevertheless, verification of resonance crossing and phase space evolution in a real machine is important to bench-mark the simulations, and promote credibility in this new concept. The model will determine what level of random driving terms can be tolerated for a variety of crossing speeds, providing valuable technical specifications geared toward minimizing future component costs.

These two stated goals are the most prominent part of a broader, exhaustive study planned for the sophisticated accelerator physics that the model will demonstrate.

SPECIFICATIONS

The ring specification is driven by the desire to have relativistic gamma and the number of cells×turns both similar to the proposed 5-10 GeV muon ring [1]. The

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design entails a three-fold symmetry to cancel 1/3-integer structure resonances. The candidate host laboratory, Daresbury, is constructing a ring-like energy recovery linac prototype (ERLP) as part of a technology demonstration [5] for a fourth generation light source (4GLS) with a variable energy of 8-35 MeV. The 10-20 MeV energy range and 15.5m circumference of the electron model are well matched to the ERLP facility and its floor plan. Pre-rf studies of resonance crossing and phase space evolution can be initiated relying only on the variable injection energy using the ERLP. Table1 indicates some optimal parameters for such a facility.

Table 1. Parameters for a 10-20 MeV/c electron ring

Doublet Lattice	**Injection**	**Extraction**
#cells, cell length	42, 0.37 m	same
F quad length, gradient	6 cm, 7.2 T/m	same
CF length, gradient	7 cm, 5.3 T/m	same
Cell tunes ν_x, ν_y	0.377 / 0.314	0.12 / 0.17
Peak βx,βy (m)	0.85 / 0.68	0.57 / 0.72
ξ_x, ξ_y	-0.73 / -0.51	-0.15 / -0.22

A doublet lattice is selected for compactness and cost with no insertions. The betatron tunes are split, with horizontal greater than vertical, to reduce path-length variation [8]. Peak pole-tip fields remain below 0.2 T, making the magnet design tractable and attainable with permanent magnets. Injection and extraction will require 2 kickers each, placed one cell apart. The 20 rf cavities will be distributed evenly around the ring in every other cell using the 20 cm cell drift. Lattice properties are shown below.

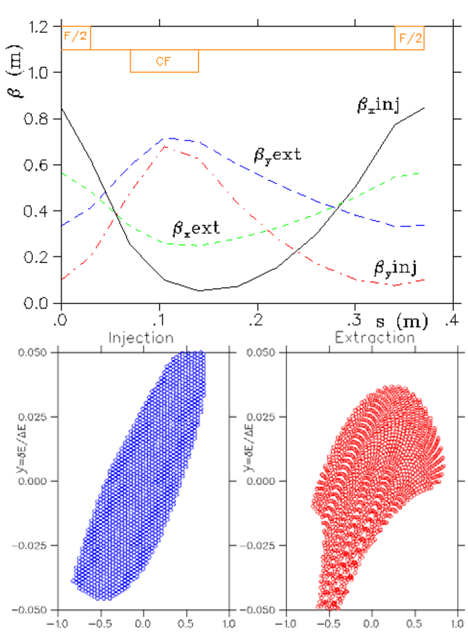

Figure 1: Lattice functions and longitudinal phase space plots for 10-20 MeV electron model.

HARDWARE

Much of the hardware needed to meet the scientific goals of the machine can be achieved by copying or modifying existing component designs at collaborating laboratories; all ring components are conventional.

RF System

The injector to ERLP uses a 1.3 GHz ELBE buncher cavity [6], and these are adopted for the FFAG model. Twenty will be required with a voltage ranging from 40-120 kV each. Initially 1.3 and 3 GHz rf were considered, but at the lower frequency the fixed ToF changes produces a smaller relative phase slip leading to more turns. A MA cavity or induction core will also be installed for slow resonance-crossing studies.

A TESLA-style linear rf distribution scheme will reduce the number of waveguides. The cavity has shunt resistance and quality factor of 1 Mohm and $1.4{\times}10^4$, respectively. A frequency variation of a few 10^{-4} will allow the fixed points to be moved up the parabolic-shaped ToF curve in order to investigate both 1- and 2-fixed point acceleration.

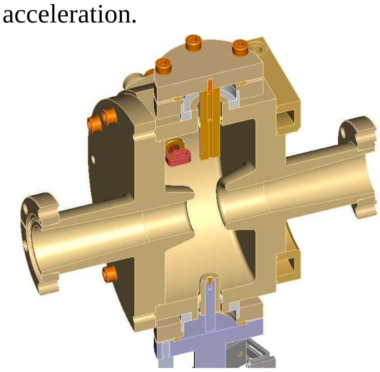

Figure 2: 1.3 GHz ELBE-style buncher cavity.

Magnets

Two magnet types are required: a horizontally focusing quadrupole (F-quad) and vertically focusing dipole (D combined function magnet). The FNAL linac-upgrade quadrupole is well suited to the model with specifications of 7 T/m gradient, a ≤ 10 cm slot length, and a ≥ 4 cm diameter good field region. The 5cm long FNAL quad has peak pole-tip field near .35T and a 5cm bore. With a BPM installed, the aperture is ≥4 cm; this is ideal for the maximum 3 cm orbit swing envisioned for the ring.

Figure 3: Fermilab 5cm long, 5cm bore quadrupole.

The combined function magnet is more challenging. Ideally, it would have independently powered dipole and quadrupole components as is preferred for complete separated function operation. However, the ≤10 cm slot constraint prohibits multiple coil installation because the limited spacing (2.5 cm at each end) cannot support the independent return paths. Increasing the gap to length aspect ratio enhances nonlinear end fields jeopardizing the linear-field dynamics of the ring. It is proposed to adopt a hybrid design with the dipole component driven by permanent magnets, and the quadrupole component powered by a modified Panofsky coil. The latter choice demonstrates relatively short ends.

Instrumentation

A system of high-resolution 4-button BPMs, one set per magnet, and turn-by-turn data acquisition forms the diagnostic backbone. These will permit capture of closed orbits, and inference of beta function and phase advances (sampled at magnet locations) versus momentum.

Altogether there are 20 straights for diagnostics in addition to BPMs internal to the quadrupoles. Promising diagnostics include optical transition radiation (OTR) foils, phase probes for beam-rf comparison, a wide-band, resistive wall-current monitor, and wire scanners. In addition the extraction line will be equipped with a pepper-pot emittance measurement rig, a dispersive region for momentum measurement, a transverse deflecting cavity and fluorescent screen for high-resolution bunch shape measurements, and an integrating current toroid or Faraday cup for transmission measurements. Full-aperture injection and extraction fast kicker magnets will able to inject or extract at any energy or turn within the range of the ring. Examples of high resolution OTRs and pepper-pots exist at both the BNL-ATF, Fermilab, Argonne wakefield test facility. The ability to inject at any energy, and kick out on any turn, allow the instrumentation to probe the entire beam history. For study of fast crossing the OTR cameras are gated turn-by-turn; for slower crossing, the OTRs are withdrawn, because of multiple scattering, but beam may still be extracted to the pepper-pot.

ACCELERATOR PHYSICS STUDIES

A key contribution to the investigation will entail the 8-35 MeV injector. Energy variability and extraction freedom will allow investigation of resonance crossing singly and severally, independent of the acceleration cycle. These aims cannot be achieved without precise and varied instrumentation to measure beam properties.

Energy variability and extraction freedom will allow us to investigate resonance crossing singly and severally. Phase space will be measured as a function of (i) tune profiles and (ii) resonance crossing speed - the latter is influenced by slow acceleration near the longitudinal fixed points. Whether the degree and evolution of emittance growth are reported accurately by our simulation codes is critical to formulation of the muon application which must respect upstream and downstream conditions on phase space. Also of interest are the longitudinal-transverse couplings generated by the closed orbit and beta function mismatch at the rf cavities.

For the longitudinal dynamics study, two key parameters will be varied: voltage and frequency (V, f). In the FFAG with 4 fixed points separating 5 manifolds, and the topology changing with both V and f, there is much to understand and verify: the serpentine channel responsible for acceleration may pinch closed for small variations in V or f, and the muon machine will operate close to these conditions. The optimum conditions for transmission, energy range, minimizing longitudinal emittance distortion, etc., need to be established experimentally to establish confidence in the feasibility of manifold acceleration. Among these conditions is the tune profile, which impacts the ToF variation.

SUMMARY AND PROSPECTS

The model serves two purposes: as demonstration machine, and research machine. It will:

- Characterize and optimize the complex parameter space of muon FFAG accelerators,
- Study resonance crossing, quantifying phase space distortion and acceptable limits for upstream and downstream (muon) systems,
- Research alignment and field errors, particularly as reflected in component cost,
- Study bucketless acceleration dynamics under conditions of multiple fixed points, and
- Validate simulation software, with regard to resonance crossing and longitudinal dynamics.

North America has taken the initiative on the concept and designs for non-scaling FFAGs, but it the U.K. which has taken the initiative to find funding for the project. Daresbury Laboratory is enthusiastic to host the electron model using their ERLP as the injector; and a consortium of British laboratories and universities applied in February 2005 to the *Basic Technology Program* of the EPSRC for funds adequate to construct a small ring without rf. A European consortium headed by the UK applied in April to the *New and Emerging Science and Technology* fund of the EU 6th Framework Program to begin the ring. Both applications are in the pre-proposal stage, and if successful will proceed to full proposals later this year.

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