NON-ISOCHRONOUS & ISOCHRONOUS, NON-SCALING FFAG DESIGNS

G.H. Rees, STFC Rutherford Appleton Laboratory, Chilton, Oxon OX11 0QX, U.K.

Abstract

Descriptions are given of some non-scaling, FFAG ring designs for the acceleration of proton or ion beams, and for the very rapid acceleration of muons to high energy. A non-isochronous design may be used for the former, and a nearly, or a fully, isochronous design for the latter. Low energy electron models are needed to study the different types. Data is given for a number of designs that have been proposed.

INTRODUCTION

Fixed Field, Alternating Gradient rings of a particular non-linear, scaling form originated in the 1950s. Lattices of combined function, gradient magnets were used, either with spiral edges, or in F(+) O D(–) O type cells, where the (±) are the bend directions. In the 1990s, interest in them returned, mainly in Japan, where a number of rings, with a D(–) o F(+) o D(–) O, triplet design, have been built.

A scaling ring is one in which beam orbits for different momenta are scaled replicas of one another. Non-scaling rings may have smaller orbit separations if the directions of bend are reversed in the D and F magnets of doublet or triplet cells. The magnetic fields fall off outwardly, so the bending radii and beam dynamics alter for each orbit.

Non-scaling, FFAG rings, with linear focusing gradients in doublet or triplet cells, were introduced [1] in the late 1990s, for the very rapid acceleration of high energy muons. The negative chromaticities give large variations of the tunes with momentum, but the crossing of integer and half integer, betatron resonances, over the ten to twenty turns of acceleration, gives little emittance growth.

Linear, non-scaling FFAGs have also been proposed for high power (MW), proton and heavy ion drivers [2], and as small, low power, rings and gantries, for use in proton or carbon ion, cancer therapy [3]. A few, beam dynamics aspects of these designs, and some practical issues, still remain to be studied.

Non-linear, non-scaling FFAGs, using cells of the form, d(–) o F(±) o D(+) o F(±) o d(–) O, with three, non-linear types of magnet for the five needed [4], were proposed in 2004. The improved control of focusing with orbit radius allows both a non-isochronous ring, of fixed cell tunes, and an isochronous ring, of a fixed vertical tune, to be realised. The name used for the symmetrical group of five magnets is “a pumplet cell”. It is possible to “match” pumplet cells which have different lengths of long straight section, and so form insertions with bends. The non-isochronous and the isochronous, pumplet rings are known as the NFFAG and the IFFAG, respectively, and when the insertions are included, as the NFFAGI and the IFFAGI.

LINEAR, NON-SCALING MUON RING

An International Scoping Study (ISS) [5] for a Neutrino Factory has selected a linear, non-scaling FFAG, for the final stage(s) of its $\mu^{\pm}$ acceleration chain, in preference to a re-circulating linac (RLA), as it may have up to three times as many cavity beam transits. The choice involves the use of a superconducting magnet ring with small orbit radii, because of $\mu^{\pm}$ lifetimes. The limited, energy ranges for the $\mu^{\pm}$ rings are chosen at 10-20, or 12.5-25, GeV.

Many identical doublet or FDFO, triplet cells are used for the FFAG magnet lattice. At most energies, F and D magnets have negative and positive bends, respectively, and the negative F bends enable high, gamma-transition (γ_t) values to be obtained. The ring is designed with $\gamma_t = \gamma$ for a γ value near to the centre of the $\mu^{\pm}$ momentum range. At other momenta, $\gamma_t \neq \gamma$, but the time-of-flight variations over the entire momentum range are small so that a fixed frequency of 201.25 MHz may be used for the distributed cavities, which give a peak rf voltage per turn of ≈ 1 GeV. A higher rf frequency is not used as the normalised, transverse and longitudinal muon beam emittances are so large (30 and 150 (π) mm rad).

The $\mu^{\pm}$ beam dynamics is unusual. Betatron tunes of the cells decrease during the acceleration cycle, while the ring tunes cross many integer resonances. The $\mu^{\pm}$ bunches are injected to give phase motion outside the long term, stable region. Non-linear, nearly isochronous motion occurs for orbits whose lengths vary quadratically with momentum, relative to the mid-range, $\gamma_t = \gamma$ orbit. The bunch centroids pass by the crest of the cavity fields, once or three times, during the “gutter” acceleration around the stable region.

Tracking simulations have been made by Machida for the full momentum range, with alignment and gradient errors included, using his s-code [6]. For random, 0.1 mm (rms h, v) magnet position errors, the rms orbit distortions increase roughly in proportion to the square root of the acceleration times, indicating random dipole, kick effects. For random gradient errors, the lattice function distortion of beam at the emittance-ellipse boundary shows similar, square-root time dependence. The probable cause is due to mismatching and is not an effect of resonance crossing.

For phase motion, the time of flight dependence for large transverse amplitudes results in a longitudinal, emittance blow-up. Remedies proposed are a raising of the rf fields (to reduce the number of turns) or by addition of a higher harmonic rf system (to flat-top the composite fields).

Other problem areas are injection and extraction. This is due to the large, beam emittances and the short, straight sections, of less than 2.5 m and with only 1.7 m available, due to the 0.4 m extents of the magnet cryostat ends.

LINEAR, NON-SCALING MW DRIVERS

Conceptual designs have been made at BNL for several proton and heavy ion, high power (0.05 up to 100 MW) drivers, and a summary, with references, is given in [2]. Linear, F(–) D(+) F(–) triplet lattices are proposed for the 1 to 11.6 GeV, proton energies and the 400 MeV/u, U238 ion energy. The beam dynamics differs from that for the $\mu^{\pm}$ ring, of the previous section, in that normalised, beam emittances are much less, space charge forces occur, the acceleration is in the stable region, and operation is far away from isochronism, with the γ-values well below γ_t. Both designs are similar, however, in that many integer betatron resonances are crossed, and the rings use many cells, with straight sections of ≈ 2.5 m.

A 4 MW, 50 Hz, 11.6 GeV proton driver for a Neutrino Factory is an example of one BNL design. It has a series chain of three, concentric rings in a common tunnel, with energy spans, 0.4 to 1.5, 1.5 to 4.45 and 4.45 to 11.6 GeV. Each ring has 136 triplet cells, with lengths of 5.934 m, 6.022 m and 6.109 m, respectively. A time of 6-10 ms is needed for acceleration using ferrite tuned cavities, and a faster option is a harmonic jump method [2], with a fixed frequency rf system. Both schemes are challenging due to the requirement for a small number of proton bunches. The 2.5 m, straight sections appear too short to achieve a very low beam loss, H^- injection system for the first ring. The fast extraction, kicker magnets are not as challenging, however, as for the $\mu^{\pm}$ ring, as the emittances of the proton beam are so much less than those for the muons.

LINEAR NON-SCALING CANCER RINGS

Tumour irradiation by proton or carbon ions is used for advanced cancer therapy. The accelerators employed for this purpose include compact, superconducting cyclotrons (with an energy degrader) and a slow-cycling synchrotron (with resonant extraction over a wide range of energies). Initiatives for other types of accelerators include a scaling FFAG, faster-cycling synchrotrons and two, small radius linear, non-scaling types of FFAG ring, one of which is outlined here [3], together with its related gantry.

Three concentric rings, each with 36 linear, non-scaling doublet cells sit in a common plane and enclosure. Ring circumferences are 34.56, 43.2 and 51.84 m (ratio 4:5:6). The two inner rings act in series to accelerate H^+ ions up to 250 MeV, and the two outer, C^{6+} up to 400 MeV/u. The F(–)D(+) cells have a total length of order 1 m, and the drifts are 0.3 and 0.1 m. Beam dynamics is similar to that for the proton and ion drivers, and rapid, harmonic jump acceleration is assumed, with 10.8 MV peak needed in the outer ring, at a frequency ≈ 1.3 GHz.

A compact, linear, non-scaling, superconducting FFAG gantry, with an FDDF type lattice cell, offers the promise of a substantial, weight reduction [3], compared with the ion gantries that are currently under development.

NON-LINEAR, NON-SCALING DRIVER

A non-linear, non-scaling and non-isochronous NFFAG is an ISS option [5] for a 50 Hz, 4 MW, 3-10 GeV, proton driver at a Neutrino Factory. The orbit circumference has to be 801.447 m, at 10 GeV, to be compatible with the associated, 20 GeV, $\mu^{\pm}$ decay rings. Insertions are not required for a ring of this size, so the magnet lattice uses only identical "pumplet" cells, of the type noted earlier. The number of cells is 66, so that the cell orbit length at 10 GeV is 12.1431 m. For an injector, a 50 Hz, 0.2 GeV, H^- linac feeds a 50 Hz, 0.2 to 3 GeV booster synchrotron, rather than an NFFAG, as it may have a more efficient, H^- injection system. Figure 1 is a layout drawing for the linac, RCS booster and NFFAG driver ring.

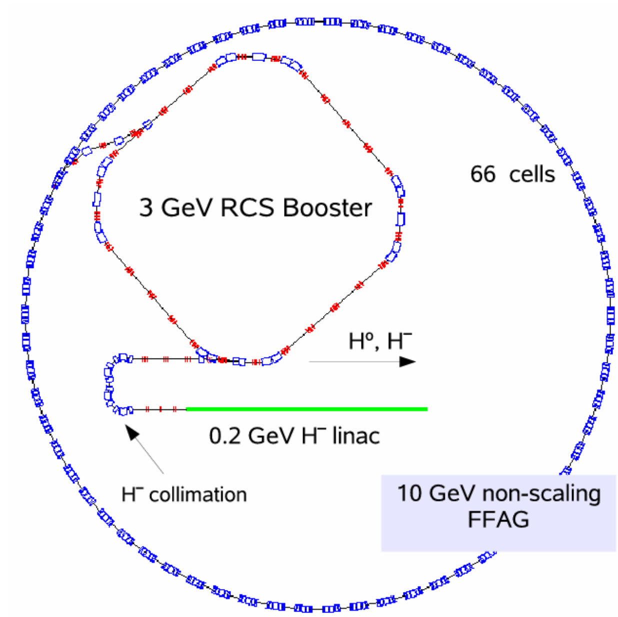

Figure1: Layout drawing of the 4 MW, NFFAG driver.

Five magnets, of three, different types are used for the dFDFdO "pumplet" cell. The non-linear d and D units are vertically focusing, parallel edged, combined function magnets, but the d have (–), and the D have (+), bending The F is a (+) bend, non-linear, horizontally focusing, combined function unit, with edges parallel to those of the d and D, as indicated in the Figure 2. There are zero entry and exit, edge angles, respectively, for the input and the output d magnets.

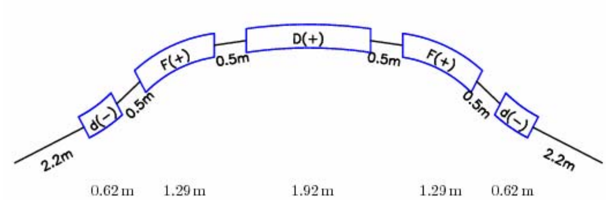

Figure 2: A single lattice cell of the 50 Hz, 4 MW, 3-10 GeV, NFFAG proton driver ring.

A modified, linear lattice code allows estimates to be made for the non-linear, field parameters needed in the cell magnets. Reference orbits are defined for the full energy range, starting at the highest energy. Successive searches are made for an adjacent orbit of lower energy, until the reference orbit at the injection energy is reached. The maximum field gradients for the ring are found at the outset, at the time of finding the parameters for the orbit of highest energy.

For each of the 20, reference closed orbits that are used, the following cell, parameter sets have to be determined: the magnetic bending radii over the cells, the bend angle for each unit, the magnet beam entry and exit angles, the length of the orbit for each cell element, the local field gradients, the separation from the two adjacent closed orbits, and the small amplitude, lattice parameters over the length of the cells.

The field gradients are made to vary linearly in between adjacent orbits, so giving local sextupolar field variations. New, bend radii are then obtained from the mean gradient between orbits and the momentum-normalized, weighted average dispersion of the initial orbit relative to the next, and vice-versa, with the weighting chosen for exact orbit closure. Data for the orbit is estimated repeatedly until the output parameters are self-consistent sets. Three, homing routines are used to determine the magnetic field profiles, one for betatron tunes, one for an exact orbit closure, and one, of limited homing range, for the special case where an isochronous orbit is identified for the lattice cell of an IFFAG ring.

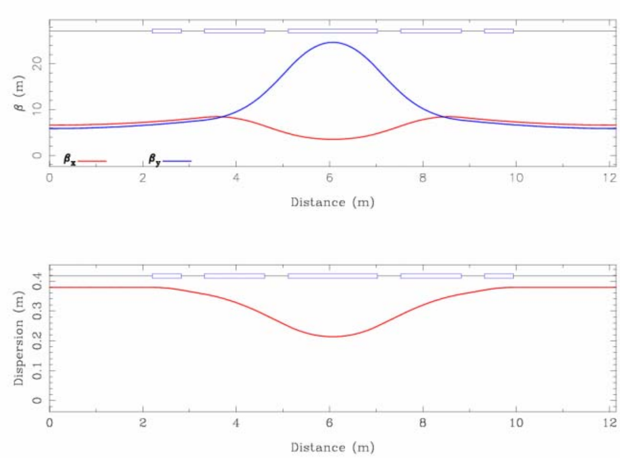

Figure 3: Small amplitude, betatron and dispersion functions for the NFFAG, 10 GeV orbit.

The small amplitude, betatron tunes per cell are set with zero chromaticities, at $\nu_h = 4/13$ and $\nu_v = 3/13$, so a group of 13 cells has integer tunes. A local cancellation of non-linear effects (to high order) thus occurs for 65, out of the 66, lattice cells. Coupling occurs for groups of 13 cells at $Q_h + Q_v = 7$, but the operating point, for the NFFAG, is at $Q_h = 20\ 4/13$ and $Q_v = 15\ 3/13$, which is far from $Q_h + Q_v$ resonance. There remains, however, variations of the betatron tunes with beam amplitude, due to the non-linear fields of the magnets.

The non-linear, non-scaling features of the ring result in γ_t varying with energy despite the constant tune values. The γ_t are imaginary at the low energies, real after mid-cycle, and decreasing at high energies. At 10 GeV, γ_t is set at ≈ 21.9 to assist the proton bunch compression that is required. A full analysis of the ring involves a processing of the non-linear, magnet lattice data obtained, followed by particle ray tracings with the Zgoubi, 6-D simulation code [7]. More studies are planned in this area.

Separations of the 3 and 10 GeV orbits are largest in the d magnets and are 330 mm, compared with maximum, beam amplitudes in the d of ≈ 15 mm, and a gap height of ≈ 65 mm. All three types of magnet (d, F and D) are room temperature units, and the D has the highest, peak field, at 1.75 T, the largest gap height at ≈ 110 mm, but the lowest 3 -10 GeV, orbit separation at ≈ 126 mm. Figure 3 shows small amplitude, lattice functions for the 10 GeV orbit.

The maximum, normalised, transverse, and longitudinal beam emittances are, respectively, 120 (π) mm mr, and 1.1 eV sec, for each of three bunches. Adiabatic, bunch compression begins in the booster, with the harmonic number, h = 3, and continues in the driver with h = 24 (8.718 to 8.944 MHz). For a compression to 3 ns rms at 10 GeV, a peak voltage of 1.3 MV per turn is required. The use of a ferrite tuned, rf system is proposed, which is distributed around the 4.4 m straight sections of the ring.

Single-pulse injection and three-pulse extraction, kicker and septum systems are needed, with extensive, primary and secondary, collimation systems, to protect against losses of the high power beam. Conventional diagnostic systems are assumed.

ISOCHRONOUS, NON-SCALING $\mu^\pm$ RING

An isochronous, non-linear, non-scaling, IFFAGI ring is another option considered [4] for a rapid acceleration of the $\mu^\pm$ beams in a Neutrino Factory. IFFAGI parameters assumed have been: an 8-20 GeV, $\mu^\pm$ energy range, and three bunch trains of μ^+, and three of μ^-, at a 50 Hz rate.

Isochronism requires that the orbit γ_t-values equal the corresponding γ for the beam energies. Design procedure is as for an NFFAG, but accuracy is improved by use of many, low energy, reference orbits (widely separated, in contrast to the equal spacing of a fixed ν_h, NFFAG). Time of flight variation with horizontal amplitude is an issue.

Pumplets are longer than doublet or triplet cells, and the radius of a superconducting IFFAGI is about twice that of a linear, non-scaling ring. Acceleration has thus to be over fewer turns for equal $\mu^\pm$ lifetimes. There are some benefits for an IFFAGI, however. The straight sections may be up to 4.8 m long, and the big ring allows twice the kicker rise times, so the extraction is much easier. Vertical, betatron tunes are nearly constant, with no integer crossing, so the vertical alignment is not as critical. Control of rf cavities is also simplified for isochronous beam acceleration.

For the insertion design, a single normal cell is matched to a single insertion cell at the reference energies, and this is achieved with the six, variable, field gradients available in two, pumplet cells. A more complex insertion is needed to match doublet or triplet cells. Design criteria include: isochronous orbits in the normal and the insertion cells, unchanged closed orbits and lattice parameters on adding the insertions, and relatively small orbit separations.

The nine conditions may be met at mid-energy, but only eight at the other energies, where a small, but acceptable, ripple for β_h (max) occurs around the ring. Matching is simplified by choosing equal bend angles for the two cells at 20 GeV, and by joining the insertion end cells to normal cells at their long straight centres, for an automatic match of the derivatives of the betatron and dispersion functions.

Four superperiods are chosen, each with ten, insertion cells and twenty, normal cells. At 20 GeV, the lengths of the orbits are 10.2 m for the insertion cells, 6.4 m for the normal cells, and 920.0 m for the ring. Acceleration over eight turns is assumed, with a 1.5 GeV, peak energy gain per turn. The number of 201.25 MHz, rf systems needed is reduced, as the 4.8 m, insertion straight sections are long enough to house four-cell cavities.

Collimation is needed over six cells, three on each side of a primary intercepting unit. Primary, loss collectors limit the normalized acceptance of the counter-rotating, μ^+ and μ^- beams to 30 (π) mm rad, and secondary units are set outwards by an extra 1.5 mm. Vertical collimation needs a constant vertical tune with energy, and units taper across the aperture, being largest at injection. Horizontal units are planned only for the inner and outermost orbits.

Initial studies of an IFFAGI, using the Zgoubi code [7], traced the beam through acceleration and found that the use of large emittances led to beam losses. More studies are now needed to identify the loss mechanisms.

NON-SCALING, ELECTRON MODELS

The four, large non-scaling rings, outlined earlier, each needs a small electron model to advance its design and to prove its viability. Two designs have linear focusing and rapid acceleration, but very different beam dynamics. The other two use special cells with non-linear magnets; one is non-isochronous and has acceleration at 50 Hz, while the other is isochronous and has its acceleration in 24.5 μs. The need for different models is thus apparent.

An electron model, of the linear, non-scaling, nearly-isochronous type, named EMMA [8], has been approved and is to be built at Daresbury Laboratory, U.K. It gives a stringent test for the $\mu^\pm$ ring it models, as the 10-20 MeV, 42 cell, 16.6 m circumference ring uses short magnets of small bending radii, which have relatively long end fields. The ring has nineteen, 1.3 GHz cavities, which provide up to 2.3 MV per turn. Design details are reported in [9].

Electron models are also under design for the two high power, proton drivers described, the linear BNL type [10], and the non-linear NFFAG design [11] at RAL. Both are considered as necessary to develop the concepts.

SUMMARY

Steady progress is being made in the understanding of the linear and the non-linear, non-scaling FFAG designs which have been proposed. Some practical issues remain to be addressed. Applications include high power proton and heavy ion drivers, medical rings and gantries, and the rapid acceleration of high energy, muon beams.

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