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MUON ACCELERATION USING FIXED FIELD, ALTERNATING GRADIENT (FFAG) RINGS

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Given their 2.2 μs lifetime, muons must be accelerated fairly rapidly for a neutrino factory or muon collider. Muon bunches tend to be large. Progress in fixed field, alternating gradient (FFAG) lattices to meet these challenges are reviewed. FFAG magnets are naturally wide; low momentum muons move from the low field side of a gradient magnet to the high field side as they gain energy. This can be exploited to do double duty and allow a large beam admittance without unduly increasing the magnetic field volume. If the amount of RF must be reduced to optimize cost, an FFAG ring can accommodate extra orbits. I describe scaling FFAGs in which the bends in each magnet are energy independent and non-scaling FFAGs in which the bends in each magnet do vary with muon energy. In all FFAG designs the sum of the bends in groups of magnets are constant; otherwise orbits would not close. Ways of keeping the accelerating beam in phase with the RF are described. Finally, a 1 MeV *proof of principle* scaling FFAG has been built at KEK and began accelerating protons in June 2000 with a 1 kHz repetition rate.

Keywords: accelerator; muon; neutrino; black hole.

1. Introduction

Scaling FFAG rings were proposed independently a half century ago by Ohkawa,[1] Symon,[2] and Kolomensky.[3] The Mid-Western Universities Research Association (MURA) built radial-sector (1957) and spiral-sector (1960) models and tested them with electrons. However, the serious development of FFAGs ceased with the ascendancy of ramping synchrotrons, which allowed smaller diameter, smaller bore rings for a given energy and magnetic field. Because the voltage needed to quickly ramp synchrotrons [4] filled with wide bunches of low energy muons is rather large, FFAGs have recently experienced a renaissance.[5,6] The FFAG design permits multiple passages of muons through both RF cavities and magnet arcs for reduced cost.

One reason FFAG rings are of interest today is because they offer economical muon acceleration for a neutrino factory [7,8] or a muon collider.[9] At a neutrino factory accelerated muons are stored in a racetrack to produce neutrino beams ($\mu^- \to e^- \overline{\nu}_e \nu_\mu$ and $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$). Neutrino oscillations have been observed.[10]

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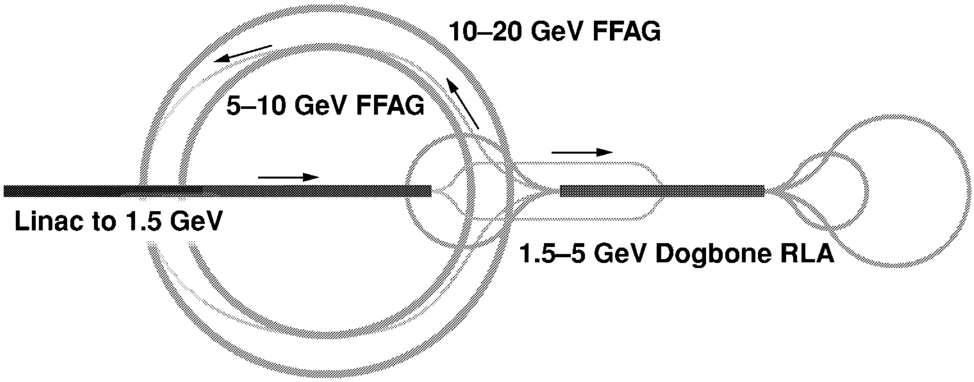

Fig. 1. Possible 20 GeV muon accelerator layout from the Ref. 8 neutrino factory design.

Further exploration at a neutrino factory could reveal CP violation in the lepton sector,[11] and will be particularly useful if the ν_e to ν_τ coupling, θ_{13}, is small.[8] A muon collider can do s-channel scans to split the H^0 and A^0 Higgs doublet.[12] Above the ILC's 800 GeV there are a large array of supersymmetric particles that might be produced[13] and, if large extra dimensions exist. mini black holes.[14] Note that the energy resolution of a muon collider is not smeared by beamstrahlung.

A cyclotron has a large volume magnetic field which is constant in time. Particle orbits move from the center to the edge of the cyclotron as they accelerate. A synchrotron has a small magnetic field volume. The B field increases with time. Particle orbit radii do not change as a particle accelerates. An FFAG ring is in between a cyclotron and a synchrotron in its design. As particles accelerate they move a small distance in gradient magnets which can accommodate higher energy orbits at slightly different radii. FFAG magnetic fields are fixed in time and their volume is larger than a synchrotron but smaller than a cyclotron.

2. A Neutrino Factory Design using Two Non-Scaling FFAG Rings

The most recent neutrino factory design[8] incorporates $5 \rightarrow 10$ and $10 \rightarrow 20$ GeV non-scaling FFAG rings. Acceleration up to 5 GeV uses a linac and a dogbone recycling linac.[8,15] A layout appears in Fig. 1 and parameters in Table 1. The 20 GeV ring is almost five times larger than a synchrotron with 5.5 T magnets. The ratio of focusing–to–bending in an FFAG ring is high. Normally, resonances are a problem in non-scaling FFAGs, but the fast muon acceleration cycle can prevent them from building up, as can highly symmetric lattice designs. Each cell uses a FDF triplet of superconducting magnets as shown in Fig. 2. Much work has gone into the lattice design to keep the beam size and hence the magnetic apertures relatively small. The idea is to control cost by reducing the magnetic field volume and by using superconducting magnets with moderate fields.

Superconducting RF (fixed 201 MHz, 10 MV/m) is used for acceleration. A

Table 1. Neutrino Factory FFAG parameters. The LHC packing fraction is higher.

	Low Energy Ring	High Energy Ring	CERN LHC
Ring Type	non-scaling FFAG	non-scaling FFAG	ramping synchrotron
Accelerated Particle	muon	muon	proton
Energy Range	5 → 10 GeV	10 → 20 GeV	0.45 → 7 TeV
Ring Circumference	400 m	500 m	27 km
Ring Radius (R)	64 m	80 m	4300 m
$B = p_{max}/.3R$	0.52 T	0.83 T	5.4 T
B_{max}	4.2 T	5.5 T	8.4 T
Magnet Packing Fraction	12%	15%	64%
RF Characteristics	10 MV/m, 201 MHz	10 MV/m, 201 MHz	200 → 400 MHz
RF Energy Extracted	16%	27%	
Total RF Voltage	480 MV	578 MV	
Initial Speed ($\beta = p/E$)	0.999777	0.999944	0.999997826
Final Speed ($\beta = p/E$)	0.999944	0.999986	0.999999991
Orbits to E_{max}	9.6	16.5	13 million
Acceleration Time	13 μS	28 μS	20 minutes
Particle Decay Loss	9%	10%	0%
$c(\beta_f - \beta_i)(\text{Time})/2$	32 cm	17 cm	380 km

niobium coated copper cavity running at 201 MHz has recently achieved a gradient of 11 MV/m and prototypes may reach 15 MV/m.[16] At 201 MHz, $\frac{1}{4}\lambda = 37$ cm, on the same order as the phase difference just due to the muons increasing in speed as shown in the last row of Table 1. Its hard to change the RF phase itself quickly. An advantage of the non-scaling FFAG is the additional control over the physical path length muons follow. Path lengths dominate speed increases in determining muon phase with respect to the RF. Fig. 3 notes the parabolic time of flight (TOF) relation that can be achieved. Muons cross the RF crest three times during the acceleration cycle. Staying closer to the crest minimizes the amount and cost of RF that is needed. In a scaling FFAG, TOF increases monotonically.

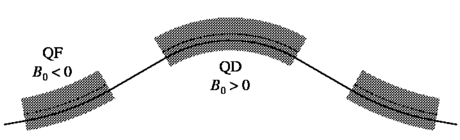

Fig. 2. Triplet Focusing–Defocusing–Focusing (FDF) lattice geometry for the superconducting magnets in the 5–10 and 10–20 GeV non-scaling FFAG neutrino factory rings.[8]

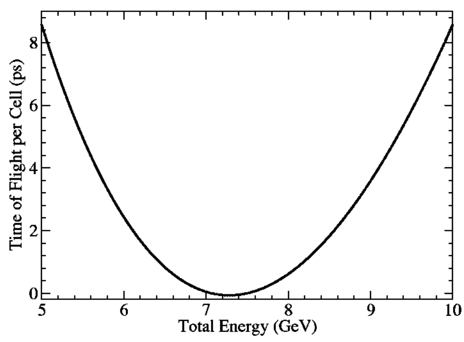

Fig. 3. Time of flight difference per magnet cell vs. energy for the 5 to 10 GeV non-scaling FFAG ring in the Ref. 8 neutrino factory design. Muons must stay in phase with the RF.

3. Scaling FFAG Rings Being Built in Japan

FFAGs are being built for muon phase rotation, radiation therapy, CT scanning, and accelerator–driven sub–critical nuclear reactor operation in Japan. A 1 MeV scaling FFAG with 8 DFD sectors has been built at KEK and has accelerated protons with a 1 kHz repetition rate.[5,17] A 150 MeV scaling FFAG with 12 DFD sectors is nearing completion. Beam has been accelerated to 150 MeV. Orbits shift from a radius of 4.4 to 5.5 m during the acceleration cycle. In these scaling FFAGs, orbit shapes and magnet focal lengths are energy independent. See Fig. 2 of Ref. 5 for a nice drawing of particle paths in scaling and non-scaling FFAGs.

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