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G.H. Rees, C. Johnstone, F. Méot

► **To cite this version:**

G.H. Rees, C. Johnstone, F. Méot. 20-50 GeV muon storage rings for a neutrino factory. European Particle Accelerator Conference (EPAC'06), Jun 2006, Edinburgh, United Kingdom. pp.WEPLS010, 2006. in2p3-00086862v1

**HAL Id: in2p3-00086862**

**<https://in2p3.hal.science/in2p3-00086862v1>**

Submitted on 20 Jul 2006 (v1), last revised 22 Sep 2006 (v2)

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# Studies of Muon Decay Rings for a Neutrino Factory.

C. Johnstone, FNAL, F. Méot, CEA&IN2P3, and G. H. Rees, RAL.

## Introduction

Muon decay rings are under study as part of an International Scoping Study (ISS) for a future Neutrino Factory. Both isosceles triangle and racetrack, shaped rings are being considered for a 20 GeV muon energy, but with upgrade potentials of 40 or 50 GeV. The rings depend on the other stages: a high power proton driver, a pion production target, a system to form and rotate trains of  $80 \mu^+$  and  $80 \mu^-$  bunches, an ionisation cooling region, a muon acceleration chain, and two neutrino detectors at distant locations.

## Decay Ring Features

The  $\mu^+$  and  $\mu^-$  bunch trains are injected into separate rings, which are in a common tunnel for the triangle rings, but in separate tunnels for the racetracks (easing the task of finding detector sites). Stored muons decay to neutrinos, which may pass from the ring straight sections to the detectors. Triangle rings have two production regions, while the racetracks have only one that is useful. The two detectors accept neutrinos from both triangle rings, but each detector is aligned to its own racetrack. Detector distances needed are 7500 km for one, and 2500 to 3500 km for the other. For these, the smallest triangle apex angle (and best production efficiency) is near  $50^\circ$ , when detectors are at opposite directions (in gnomonic projection) from vertically aligned, adjacent rings. Some inclinations of the rings to an exact vertical plane are expected for most pairs of detector sites.

## Bunch Patterns

The final patterns for each decay ring are a set of three, or five, uniformly spaced, 400 ns, trains of  $80 \mu^+$  or  $80 \mu^-$  bunches. For the triangle rings in a common tunnel, the  $\mu^+$  trains in one ring are interleaved in time with the  $\mu^-$  trains in the other. A potential proton driver has a 200 MeV,  $H^-$  linac, a 0.2-3 GeV, 50 Hz, RCS booster synchrotron and a 3-10 GeV, 50 Hz, NFFAG accelerator (similar to the one in [1]). The RCS circumference is half the length of the NFFAG injection orbit, while the proton revolution period at 10 GeV in the NFFAG,  $T_p$ , is half the muon rotation period,  $T_d$ , at 20 (40 or 50) GeV in each decay ring. The periods,  $T_p$  and  $T_d = 2T_p$ , are chosen to give revolution frequencies at sub-harmonics of 201.25 MHz, which is the muon acceleration frequency.

Sequential delays of  $n$ , RCS bunches allow uniformly spaced bunches in the NFFAG, and further sequential delays in the NFFAG, at 10 GeV, after adiabatic bunch compressions, allow a uniform filling of muon bunch trains in the decay rings. The NFFAG delays may be set at  $(p + n/5) T_d$ , for  $p$  an integer, and  $n = 1$  to 5, for the case of the five bunch trains, or set at  $(p + n/3) 2T_p$ , with  $n = 1$  to 3, for three bunch trains. By this means, the proton duration at the production target may be varied over a wide range, from a few to a few hundred microseconds. Typically, 34 to 68  $\mu s$  (2 to 4 times a  $\mu^\pm$  ring acceleration time) is considered for liquid mercury jet targets, and up to 250  $\mu s$  for solid metal targets.

## Decay Ring Specifications

In addition to the required muon bunch train patterns, there must be time gaps of  $> 100$  ns between the  $\mu^+$  and  $\mu^-$  beams in the triangle rings, to allow particle identification. The rise time of the injection, fast kicker magnets is set by the time between the  $n$  bunch trains in each ring, with  $n$  limited to five for a circumference of  $\sim 1600$  m, when each bunch train injection is estimated to need 14, fast kicker pulsers per ring. The maximum, normalised transverse beam emittances are  $30$  ( $\pi$ ) mm rad and, because of the MW beam powers, the ring apertures are set a factor 1.5 times larger than the beam envelopes, to allow the use of loss collectors. Large dynamic apertures are thus needed. For the production straights, the ratio of muon, rms divergence angles to decay neutrino, rms opening angles has to be  $< 0.14$ . A specification has yet to be set for the input, muon beam momentum spread, but attempts are being made to contain  $\Delta p/p$  to within  $\pm 2\%$  (half the range tracked).

## Lattice Designs

Both triangle and racetrack rings use bend magnets at the ends of the production straights to separate neutrinos which arise from muons at large divergence angles. These magnets complicate the lattice designs by creating dispersion in high beta regions of the matching to the arcs. Designs differ for the triangle and the racetrack lattices. The triangle rings use combined function magnets for the arcs and solenoid focusing in the production straights, whereas the racetracks adopt separated quadrupoles and dipoles for the arcs and a FODO, focusing arrangement for the straights. A figure of merit for production straight focusing is the lattice value for  $1/(\beta\gamma)_{\max}$ , which may be  $\sim 1$  for solenoids, but is  $(1-\sin \mu)/2$  for thin lens FODO cells, with  $\mu$  the half cell phase advance. For equal, muon divergence angles, the maximum beta value for solenoids is thus  $\sim$  half that for FODO cells and this helps in lowering beta values in the matching regions and obtaining a large dynamic aperture.

The circumference of each ring is 1608.8 m, giving a harmonic number,  $h$ , relative to the 201.25 MHz, muon acceleration frequency of 1080 ( $= 2^3 \times 3^3 \times 5$ ). The choice is related to the bunch train, filling scheme, and is compatible with the 10 GeV orbit of the NFFAG. The downward slope for a production straight aligned to a detector at distance,  $L$ , is given by  $\arcsin(L/2R)$ , with  $R$  the equatorial radius. For a detector at 7500 km, the downward slope is  $\sim 36^\circ$  and, for one at 3500 km,  $\sim 16^\circ$ . The resulting triangle ring then has a depth  $> 400$  m, and an apex angle of  $\sim 52^\circ$ , if vertical, and a larger apex angle, if not. A racetrack aligned to the 7500 km detector has comparable depth, due to its long production straight. Accelerator and detector sites will be identified in future and it is only then that the ring parameters may be detailed and a choice made between triangle and racetrack rings.

## Triangle Ring Details

A pair of  $52.8^\circ$  apex angle, isosceles triangle rings are under design. Their two production straights each have eight, symmetrically spaced, superconducting solenoid magnets in a 390.4 m length, for a neutrino efficiency of  $\sim 2 \times 24.3\%$ . The third straight houses beam loss collimators, radio frequency systems and tune control quadrupoles. Neutrinos from this region pass upwards to the accelerator site, as the rings are in a (near) vertical plane. The arc cells are 8.2 m in length and contain 2.9 m, focusing and defocusing, combined function magnets, separated by 1.2 m straight sections. Sextupole components are added to the fields for full chromaticity correction. There are 11 such cells at the triangle apex,

and 10 in each of the other two arcs. Cells begin and end at a defocusing magnet centre, and lattice parameters are: bend angle per cell =  $11.1^\circ$ , betatron phase shifts / cell =  $72^\circ$ ,  $\beta_{\max} = 12.67$  m and  $D_{\max} = 1.44$  m. The sextupole excitation vectors cancel over groups of five cells, so one cell near the apex is left without sextupole field components.

There are six-parameter matching sections between the arcs and the production straights, and each of these has four quadrupoles, a dipole and a gradient magnet. The total length, including the production straight end magnet, is 35.0 m. At the arc end,  $D_{\min}$  is 0.845 m, and  $D$  is kept low while  $\beta$ -values are large until, after 35.0 m,  $D$  is brought to zero. At the solenoid focusing waists, the  $\beta$ -value is set at 94.3 m, and this increases in the matching section to 101.4 m horizontally, and to 123.8 m, vertically. The chosen solenoid focusing provides a ratio of 0.1 for the rms,  $\mu$  to  $\nu$ , divergence angles.

The section opposite the triangle apex is mirror symmetric about its centre point. There is a central section of FODO cells, which may be adjusted for betatron tune control, and on each side of which are matching sections to the adjacent arcs. In the long, zero dispersion, central FODO region, there are two quadrupole types and, in each adjacent section, there are five more for betatron matching, followed by a further six and a gradient magnet, for six parameter matching to the neighbouring arc.

Due to  $e^\pm$  losses after  $\mu^\pm$  decays, the warm bores of superconducting, arc magnets are clad with lead to absorb the  $e^\pm$  power. Direct  $\mu^\pm$  wall loss also leads to magnet heating. Hence, both rings will have loss collimators, located in four of the central, FODO cells noted in the last section. There will be horizontal and vertical primary collimators, and secondary collectors downstream, after betatron phase shifts of  $20^\circ$ ,  $90^\circ$  and  $160^\circ$ . Beam activation may be high, so use of room temperature quads, with radiation hard windings, is planned.

Bunch trains are injected into the upstream ends of the production straights nearest to the surface. There is an injection septum magnet just downstream of a first solenoid and 24 m of fast kicker magnets between the second and third solenoids. The estimated number of 5 kA, 50 kV, fast pulse systems to power the kickers is 14, with 2 spares, for each ring.

The lattice is modified and the rings re-aligned when upgrading from 20 to 40 or 50 GeV. Some matching elements are changed and repositioned, and solenoid focusing is reduced, with  $\beta = 160.3$  m at the beam waists, restricting the  $\mu$  to  $\nu$ , rms angle ratio to 0.12.

Muon tracking simulations, using the Zgoubi code, are described in [2] for a ring with a smaller apex angle. The basic optical properties of the triangle decay rings are established on the basis of accurate ray tracing methods. Tracking a linear machine shows very weak coupling and well-behaved transverse phase space motions for a  $\pm 4\%$  range of  $\Delta p/p$ . A 1,000-turn tracking of a chromaticity corrected, error free ring, without corrections of the orbits, shows 63% survival for 60 ( $\pi$ ) mm rad, normalised emittances, over the same  $\Delta p/p$  range, both twice the values envisaged. The effect of errors is next to be studied.

References

- [1] G H Rees, FFAG Studies for Neutrino Factory Accelerators, Nuclear Physics B (NuFact 05, Proceedings Supplement) 155 (2006), p 301-304.

[2] G Rees and F Méot, NuFact muon storage ring: study of a triangle design based on solenoid focusing straights, CEA DAPNIA-06-04, LPSC-06-38, May, 2006.