20 – 50 GEV MUON STORAGE RINGS FOR A NEUTRINO FACTORY *

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Abstract

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. Both rings are designed with long straights to optimize directional muon decay. The neutrinos from muon decay pass to one or two distant detectors; the racetrack ring has one very long production straight aligned with one detector while the triangular ring has two straights which can be aligned with two detectors. Decay ring specifications and lattice studies are the primary topic of this paper. Injection, collimation, and the RF system are covered in a second contribution to these proceedings.

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. Ring characteristics depend on upstream stages: a high power proton driver, a pion production target, a system to form and rotate trains of 80 μ^+ and 80 μ^- bunches, an ionisation cooling region, a muon acceleration chain, and, finally, two neutrino detectors at distant locations.

The μ^+ and μ^- bunch trains are injected into separate rings, which are in a common tunnel for the triangular rings. Both species can be injected into the racetrack under counter-rotating conditions if both straights are used for neutrino production. (This scheme works as long as the bunch trains remain separated in time from opposite-sign bunches that are decaying in the opposing straight.) Stored muons that decay in the long straight sections form a well-collimated, parallel neutrino beam directed towards the detector sites. If chosen appropriately, two detectors can accept neutrinos from both of the triangular rings, while the racetrack can only service one far detector site. For a racetrack, each detector would have a dedicated ring in a separate tunnel (easing the task of matching desirable detector sites with appropriate baselines).

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DECAY RING SPECIFICATIONS

Physics issues dictate that the detector baselines needed are 7500 km and 2500 to 3500 km, respectively. For this choice, the smallest triangle apex angle (and best production efficiency) is near 50˚, constraining the detector locations to be in opposite directions (in gnomonic projection) from vertically aligned, adjacent rings, as in Figure 1. Some incline of the rings from a pure vertical-plane alignment is required for most pairs of detector sites. In the racetrack case (Figure 2), two rings in independent tunnels imply different vertical declinations directed to the two respective detectors. (Both rings would have a common injection point and injected bunches could alternate between the two rings.)

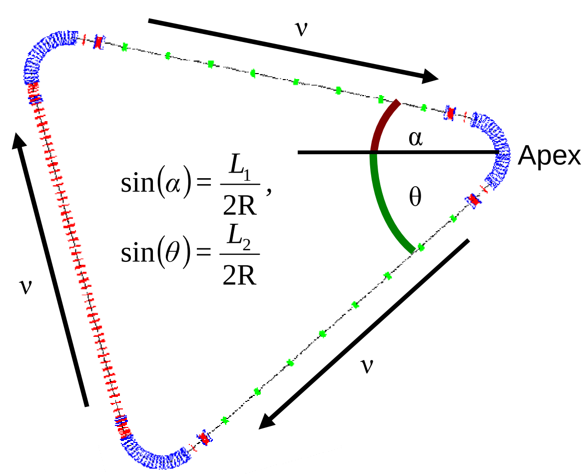

Figure 1: Vertical plane layout for the isosceles triangle ring. L_1 and L_2 are the detector baselines, and R is the equatorial radius.

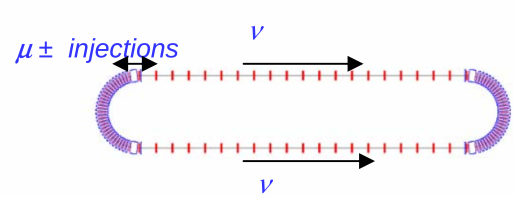

Figure 2: Plan layout for the for the racetrack.

The geometry of the triangle ring is dictated by the choice of detector sites, however, the circumference in both types of rings is determined by the length, spacing and number of bunch trains injected and matching to the muon acceleration rf and bunch revolution timing of upstream systems as documented in the second contribution to these proceedings. The final patterns for each decay ring consist of a set of three, or five, uniformly spaced, 400 ns, trains containing 80 μ^+ or 80 μ^- bunches. (Increasing the number of muon bunches relaxes design problems associated with high intensity in upstream systems and increasing the storage ring circumference increases the production efficiency notably up to a point. A further increase in circumference — which must remain an integer times revolution period of the protron driver — buys little improvement in production efficiency so the optimum appears to be 5 bunches, with 3 bunches as an alternative option.) For the triangle rings in a common tunnel, the μ^+ trains in one ring are interleaved in time with the μ^- trains in the other. In order for the detectors to resolve the individual trains, 100 ns must be maintained between the interleaved bunches. The interval between bunch trains in a ring is therefore 600 ns, which allows a 300 ns injection kicker rise and 300 ns fall time. In the case of two racetrack rings with non-interleaved bunches, this is the time interval between bunches due to the injection kicker. For 5 bunch injection, the circumference of the ring is therefore ~1600 m and correspondingly less for fewer bunches.

In the case of the two racetrack rings, different numbers of bunches can be divided and injected between the two respective rings allowing a circumference variation (the 3500 km ring, for example, can be significantly longer for the same vertical tunnel depth than the far baseline ring.)

The design is further complicated by the large transverse muon emittances (30π mm-rad) coupled to small divergence requirements in the production straight. Due to the MW beam powers, the ring apertures are increased by a factor of 2.25 times the beam envelopes to allow the use of loss collectors. Exceptionally large dynamic apertures are thus a design requirement. Component apertures in the production straights are particularly large in order to accommodate the large emittance in combination with the experimental constraint that the ratio of the muon divergence to the decay neutrino opening angle is required to be <0.14. A background-sweep dipole must be incorporated at the ends of the production straights to eliminate any neutrinos with large opening angles (arising from parent muons with large divergence angles) which generate background in the detectors. (These magnets complicate the lattice designs by creating dispersion in high beta regions of the matching to the arcs.)A specification has yet to be set by the experiments for the allowable muon beam momentum spread, but practical concerns limit deltap/p to within ± 2-4%. The lower value is generally considered the limit to retain bunched beam structure with a reasonable rf system, which is a requirement of the interleaved schemes.

Sextupole components are added to the arc magnetic fields in both cases for full chromaticity correction. In the triangle there are 11 arc cells at the triangle apex, and 10 in each of the other two arcs. The sextupole excitation vectors cancel over groups of five cells, so one cell near the apex is left without sextupole field components. All racetrack arc cells contain chromatic correction sextupoles

Table 1: Decay Ring design Specifications

Energy	20 → 40 or 50 GeV
Declination ∠s	~16° , 36° (3500, 7500 km)
ε_n (full)	30 π mm-rad
Ring acceptance	67.5 π mm-rad
Momentum Acceptance	2 – 4% (RF – no RF)
Peak magnetic field	≤7T
Bunch train length, spacing	400 ns, 100ns
rms div. in decay straight	0.1/γ – 0.2/γ

LATTICE DESIGNS

An isosceles triangle ring with an apex angle of 52.8° is presently under design in parallel with an equivalent circumference racetrack ring. The overriding design goal is to maximize muon decay in the production straight or the ratio of production straight to circumference. If, after the accelerator and detector sites are chosen, the triangular ring is no longer vertically oriented, then a larger apex angle is required and the lengths of all the straights change accordingly. A final ring design cannot be specified until accelerator and detector sites are identified.

Although the arcs differ in the triangle and racetrack lattices (Table 2), this fact represents primarily an effort to optimize. The same arc design can be employed in both cases and this also holds for the production straights.

Table 2: Arc Designs

Arcs	Triangle	Racetrack
Magnets (SC)	Combined function	Separate function
Arc cell length	8.2 m	9.8
#cells	31	30
β_{max}	12.7 m	16.1 m
ν_x / ν_y	72°	86° / 87°
magnet spacing	1.2 m	0.75 m
Bend/cell	11.0°	10.3°
D_x	1.44 m	1.25 m

Table 3 indicates production straight parameters and Table 4 is an overall comparison of the two designs. Solenoids were used for the triangle production straight because the lattice value for 1/(βγ)max, may be ~1 for solenoids, but is (1-sin μ)/2 for thin lens FODO cells, with μ the half cell phase advance. For equal, muon divergence angles, the maximum beta value for solenoids is thus ~ half that for FODO cells and this helps in lowering beta values in the matching regions and obtaining a large dynamic aperture. Finally, the third straight of the triangle ring 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. This section, opposite the triangle apex, is mirror symmetric about its centre. The central section of FODO cells, may be adjusted for betatron tune control, and on each side are sections for six-parameter matching to the neighbouring arc.

Table 3: Production Straight

Prod Straight	Triangle (for 52.8° apex ∠)	racetrack
Cell Length	49.8	50.0 m
β_{max}	94.3 m	153 m
rms divergence	$0.1/\gamma$	$0.1/\gamma \rightarrow 0.2/\gamma$
Components	SC solenoids	NC quadrupoles
Bore	36.6 cm	46.6 cm
Strength	4.3 → 6.4 T	0.9 →2.2 kG
Length	4.8	1.5 m

Table 4: Design comparison for equal circumferences

General	Triangle (for 52.8° apex ∠)	racetrack
Circumference	1609	1609
Prod straight	2 x 398.5	614 m
Efficiency/ring	2 x 24.8%	38.2%
Depth	>400m	>400m

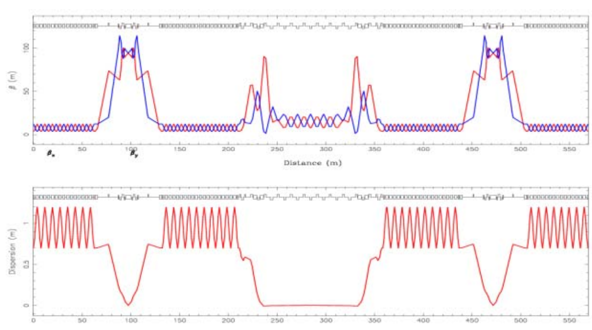

Figure 4: Optical functions for triangle lattice (long production straights are not shown).

In the triangle, there are six-parameter matching sections, ~35 m long, between the arcs and the production straights, and each of these has four quadrupoles, a dipole and a gradient magnet. A similar matching section is implemented in the racetrack. Lattice functions are shown in Figures 4 and 5 for the two designs. Bunch trains are injected into the upstream ends of the production straights nearest to the surface. The lattice is modified and the rings re-aligned when upgrading from 20 to 40 or 50 GeV for the triangle The racetrack is simply operated at higher current with identical optical functions..

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 ± 4 % range of deltap/p. Similar results were obtained for the racetrack which was tracked in reference[2] .Tracking muons in a chromaticity corrected, error free ring, without orbit corrections, see Figure 6, shows 63% survival for 60 (π) mm-rad, normalised emittances, over the ± 4 % deltap/p range (two times the values envisaged). The effect of errors is to be studied next.

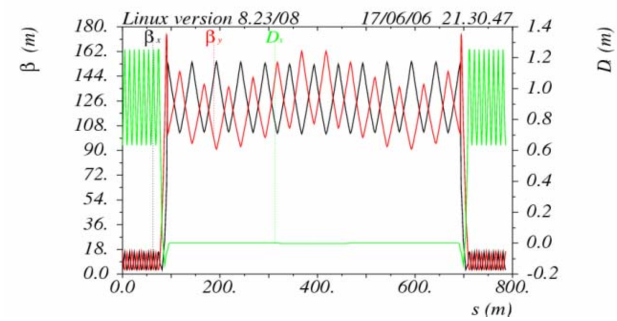

Figure 5: Optical functions: horizontal (black) and vertical (red) and dispersion (green) for ½ the racetrack design. The production straight is shown in the center.

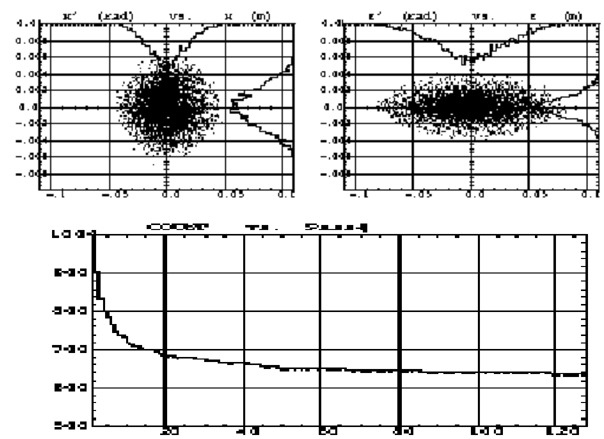

Figure 6: Tracking results for the triangle ring: horizontal phase space (top, left), vertical (top, right), and transmission (bottom).

REFERENCES

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