MUON STORAGE RINGS FOR A NEUTRINO FACTORY

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Abstract

The goal of a Neutrino Factory is to generate intense beams of neutrinos from muon decay for particle physics studies, in particular CP violation in the Standard Model, the mass hierarchy, and the neutrino mixing angle θ_{13}. Intense muon beams are created and accelerated in a system of particle accelerators to energies of 20–50 GeV. They are then allowed to decay in dedicated storage rings with long straight sections aligned on suitably chosen far detectors. A variety of ring geometries are possible, and their design and construction present demanding challenges for accelerator R&D, covering not only beam optics but touching on geological and engineering aspects of constructing almost vertical storage rings several hundred metres below the Earth's surface. The basic ideas are described in this paper and are demonstrated by three possible models developed in recent years.

THE NEUTRINO FACTORY

The International Scoping Study laid down the baseline for a Neutrino Factory aimed at generating an average of 10^{21} neutrino events per year [1]. A 4 MW beam from a proton driver impinges on a pion production target, which looks likely to be based on a liquid mercury jet. The pions are captured in a solenoid channel. They decay to muons, which are phase rotated and formed into trains of 80 interleaved μ^+ and 80 μ^- microbunches at 201.25 MHz. The transverse emittance is reduced via ionisation cooling in order to make the bunch trains ready for the next set of accelerators. Since muons have a half-life of 2.2 μs in their rest-frame, relativistic time dilation is used and acceleration has to be rapid. The preferred scheme is a series of recirculating linear accelerators (dogbones) followed by one or possibly two fixed-field alternating gradient accelerators (FFAGs), depending on the final muon energy. A top energy of 25 GeV is proposed for the most pressing physics needs, though neutrino factory designs make allowance for future upgrades to about 50 GeV. A schematic drawing of a possible scenario is shown in Figure 1.

MUON STORAGE RINGS

Once accelerated, the muon bunch trains are stored in dedicated rings where the particles decay according to

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu, \qquad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu.$$

The rings have long straight sections to direct the neutrino beams at detectors at roughly 4000 and 7500 km distances.

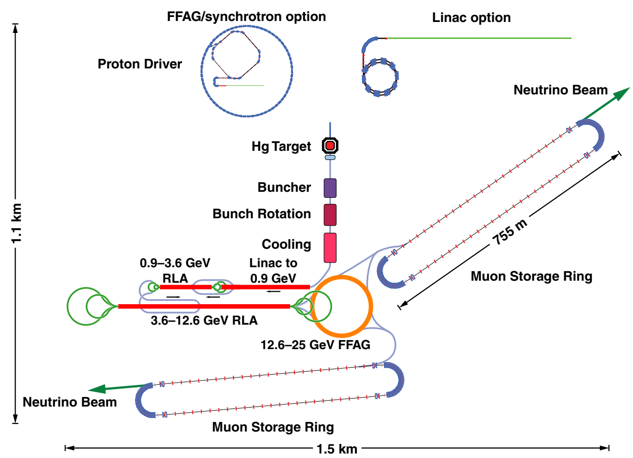

Figure 1: IDS baseline scenario for a Neutrino Factory

Three options have been developed: a racetrack lattice, an isosceles triangle shape and a bow-tie layout. In theory the racetrack (included in Figure 1) can handle both sign muons but can point at only one detector. The isosceles triangle and bow-tie rings can point at two separate detectors but will hold muons of only one sign. Additionally, the bow-tie ring preserves the muon polarisation, which may interfere with the accuracy of the beam instrumentation.

Important parameters to be considered in the design of the decay rings are:

- the efficiency, defined as the ratio of the total length of neutrino production straights to the circumference.
- the depth of the tunnels, which has geological and cost implications.
- the ratio, χ, of the muon rms divergence angle to the rms opening angles of the decay neutrinos; this has been set at $\chi \leqslant 0.14$ for normalised rms transverse beam emittances of $\sim 4.8\,\pi$ mm.rad.
- the megawatt levels of muon beam power, which demand efficient ring collimation systems.

To alleviate problems such as heating and shock in the NF target and beam loading in the muon accelerators, the number of proton bunches (and therefore the number of muon bunch trains) in a pulse should not exceed three. A proton driver meeting the requirements has been designed with a booster circumference of 401 m and a main ring of 802 m, and a compatible size for the decay rings is then 1608.8 m. The bunch trains have a duration of 397.5 ns and are equally spaced with gaps of 1391 ns. It is then possible to interleave the μ^+ and μ^- bunches in time, providing a gap between neutrino and anti-neutrino bursts of at least 100 ns at the detectors.

Racetrack Design

The layout of the racetrack ring is shown in Figure 2. The basic design consists of achromatic arcs, matching sections between arcs and straights and long quadrupole production straights. At the ends of each straight are bending magnets giving a combined angle of 1.8° to separate off neutrinos from muons with large divergence angles. These generate dispersion in the main arcs, which comprise 15 FODO cells, each of length 8.8 m, of superconducting dipole and quadrupole magnets. The arc bending angle is 176.4°, and the bending field in the dipoles is 4.28 T.

The design shown in Figure 2 has one production straight only, 599.4 m long, giving an efficiency of 37.25%. The second straight is used for collimation, rf systems and tune control. If the ring were to be adapted to take counter-rotating bunches of μ^+ and μ^-, additional dispersion-free sections would need to be created for this equipment, to the slight detriment of the production straights. Two rings in separate tunnels are necessary to point at the mid-range and long-range detectors at 4000 km and 7500 km respectively (as in Figure 1). They would be directed at respective angles of approximately 18° and 36° into the ground, giving tunnel depths of 233 m and 444 m.

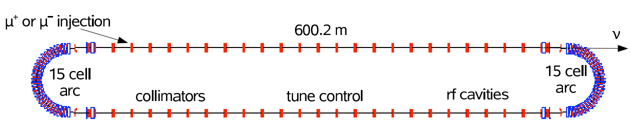

Figure 2: Layout of racetrack ring

Betatron and dispersion functions are shown in Figure 3. The matching sections match from a peak beta of 14.2 m in the arcs to a value of 153.0 m in the straights. The angle ratio $\chi = 0.12$ is within the value of 0.14 required. However, since χ scales as $\sqrt{\gamma}$, the limit would be exceeded at 40-50 GeV, which means the same ring may not be suitable for an energy upgrade.

Triangular Design

In contrast to the racetrack lattice, an isosceles triangle can have two production straights pointing at different detectors. The lengths of the baselines dictate an apex angle of $\gtrsim 50^\circ$, and the example of 52.8° shown in Figure 4 can serve several combinations of detector locations (q.v.). The direction of the upper straight is fixed by the mid-range detector, and the ring can then be rotated about this line until a suitable long range detector site is found. The production straights are 398.5 m long, giving an efficiency of $2 \times 24.8\%$, and a maximum depth of 493 m. Two triangular rings could be built in the same tunnel, one for μ^+ and the other for μ^-.

The arcs are made up of superconducting combined-function magnets in cells of 8.2 m length. Eleven cells

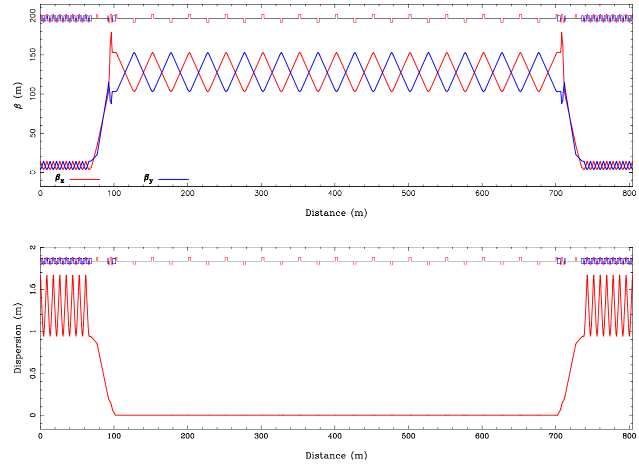

Figure 3: Optical functions for the racetrack ring

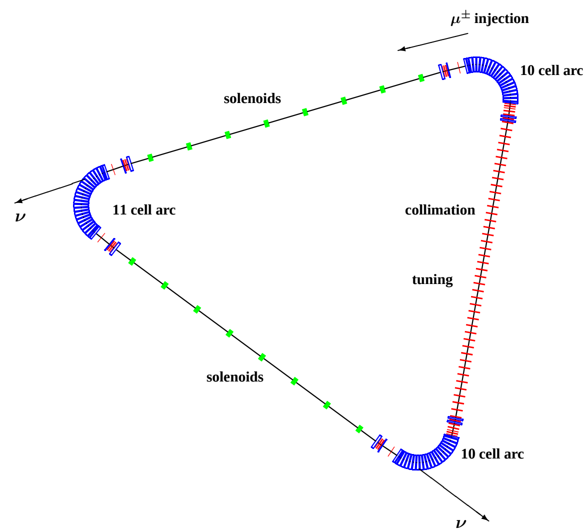

Figure 4: Layout of isosceles triangle ring

form the triangle apex and there are ten cells in each of the other arcs. The total bend angle in the arcs is 344.1°, leaving 15.9° to deal with large angle muons in the straights. The production straights use eight 4.0 T superconducting solenoids, which allow much smaller betatron functions than quadrupoles for the same muon divergence angles. In the example shown, a β of 12.7 m in the arcs is matched to a value of 94.3 m in the straights. Details of the ring optical functions are given in Figure 5, in which the lattice arrangement has the production straights to either side of the central collimation/tuning/rf straight. The ratio of muon rms divergence angle to the rms opening angles of the decay neutrinos, χ, is about 0.12 for an energy of 25 GeV, and could be maintained for upgrades to higher energy.

Bow-tie Design

The triangular design has advantages over the racetrack lattice through the ability to serve two detectors with one ring, plus better efficiency, but suffers from the depth at which the tunnel penetrates into the ground. A third design,

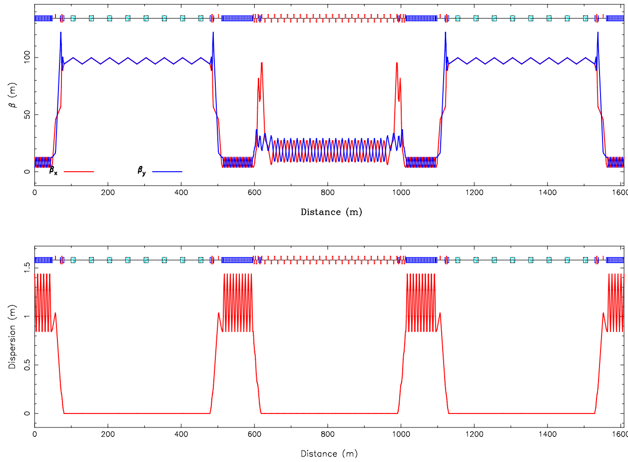

Figure 5: Optical functions of the isosceles ring

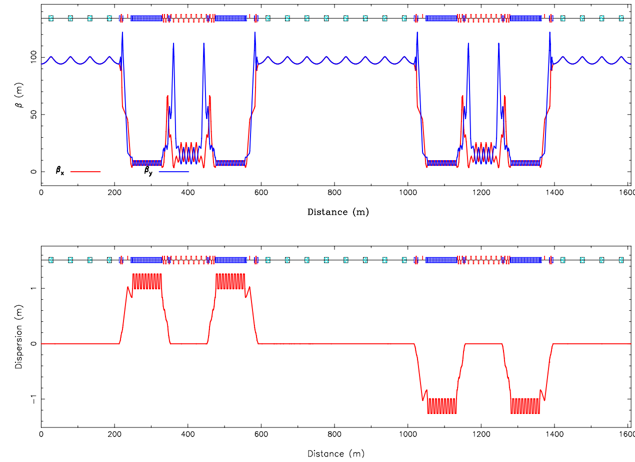

Figure 7: Optical functions of the bow-tie ring

the bow-tie lattice (Figure 6) goes some way to overcoming this. The ring has a crossing angle of 52.8° and production straights of 469 m, giving an efficiency of 2×29.2. The design closely follows that of the triangle ring, with the same features of matching between large β-values in the straights and much smaller values in the arcs. The optical functions are shown in Figure 7, where the change in sign of the dispersion in the arc regions can be compared with Figure 5. There are advantages over other designs in the higher neutrino production efficiency, the use of fewer quadrupoles and the reduced tunnel depth of 312 m. In addition, the straights directing unusable neutrinos to the accelerator site are reduced. There are however more bending cells and the muon polarisation is retained. The latter may be overcome by tuning the lattice to an intrinsic depolarising resonance while preserving the optics in the production straights [2].

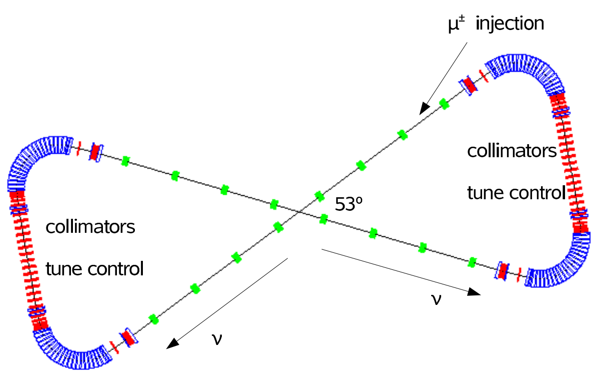

Figure 6: Layout of bow-tie ring

Further details of earlier versions of these rings can be found in [3].

DETECTOR SITES

The racetrack lattice has the greatest flexibility in that, provided there are detectors at the right distances from the site, it can be pointed in any direction. For example, a facility at Fermilab could feed detectors at Gran Sasso (7400 km) and Norsaq (3500 km). However, two separate tunnels would be needed, at a substantial depth, with a total of four transfer lines, in order to handle both μ^+ and μ^- in the same ring. Depending on the NF site, the triangle or bow-tie may prove more suitable geometries because of their greater neutrino production efficiency, the use of only one tunnel and a reduced number of transfer lines. Sited at RAL, for instance, the facility could direct neutrinos to INO, Pykara (7630 km) and Gaspe, near Montreal (4280 km), using an apex angle of 59°. The plane of such a ring would be at 21° to the vertical, giving depths of 458 m and 290 m for the triangle and bow-tie respectively. Another combination at RAL could be Baksan, Russia (3375 km) and the Waste Inspection Pilot Plant (WIPP) in New Mexico (7513 km) with a 60° apex angle, at 30.6° to the vertical and similar tunnel depths.

With predicted tunnel depths of this magnitude, a geological survey of the sub-terrain of any proposed Neutrino Factory site is essential. The alternative is to use a ring with shorter production straights, with a corresponding reduction in efficiency. There would also need to be changes to the proton driver design to maintain a uniform muon bunch layout. With fewer neutrino events reaching the detectors, facility operation might have to be extended for a year or two to obtain sufficient statistics, with consequential increases in total running costs.

REFERENCES

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