BEAM DYNAMICS STUDIES FOR A NEUTRINO FACTORY DECAY RING

M. Apollonio*, M. Aslaninejad, J. Pasternak,
Blackett Laboratory, Imperial College, London, UK

Abstract

The Race Track design for the Decay Ring of a Neutrino Factory is studied with the MAD-X code. Optimisation of the working point, study of resonances and of dynamic aperture for several off-momentum cases are presented. An introduction to the problem of beam losses is given.

INTRODUCTION

In a Neutrino Factory complex [1] neutrinos are generated in storage rings with long straight sections pointing towards far detectors. Several possible designs for these Decay Rings have been proposed each with specific advantages and drawbacks. For example the triangle design can reach two opposite detectors with a high production efficiency (40% more than the Race Track configuration) but requires two side-by-side rings in a vertical plane, therefore constraining the possible detector locations. The Race Track design, albeit less performing, allows a greater flexibility and has been chosen as the baseline case in the framework of the International Design Study. This paper represents an initial study of the machine properties of these storage rings; the original optics has been produced by C. Prior [2] and subsequently adapted in the framework of the MAD-X code [3]. MAD-X allows an easy calculation of the Twiss parameters, determination of the working point and particle tracking used to infer the dynamic aperture of the machine. The structure of the ring is illustrated

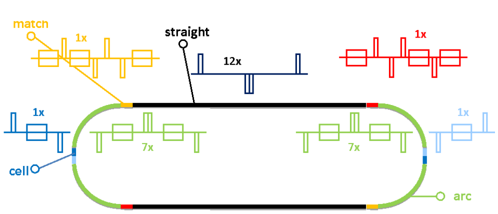

Figure 1: Schematic diagram of the Race Track Decay Ring with its main regions: (black) decay straights, (green/blue/cyan) arc sections, (red/yellow) matching sections. The small diagrams show the structure of the linear optics cells.

in Fig. 1 which shows the three main elements of the optics: straight sections, arcs and matching sections. The total length of this machine is 1608.8 m (600.2 m for each of the straight sections) with a central momentum of 25 GeV/c.

* m.apollonio@imperial.ac.uk

OPTICAL PARAMETERS AND WORKING POINT

The Decay Ring Twiss parameters from MAD-X calculations are shown in Fig. 2: it can be seen how the beta functions are kept low in the arcs to reduce the size of the beam and increase transmission, while their values are increased in the straight sections to reduce beam divergence and make it negligible with respect to the one originating from muon decays. The merging of these two opposite behaviours is guaranteed by the matching sections. Fig. 3 illustrates the phase advance along the ring: the working point is found to be (Q_x=8.5229,Q_y=8.2127).

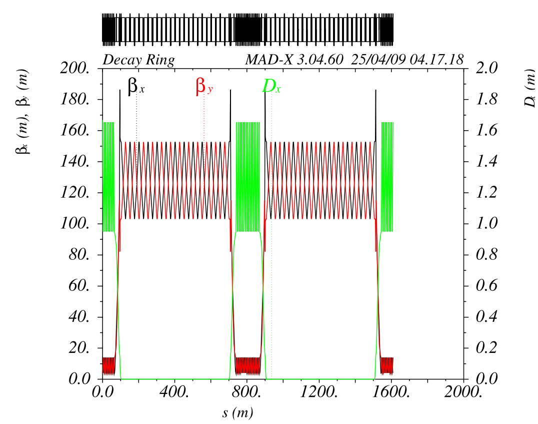

Figure 2: β_x (black) and β_y (red) functions for the decay rings. Their values are deliberately chosen high in the straight sections to reduce the divergence of the beam (see text). Dispersion in the arcs is also shown (green plot).

It should be stressed how a $\pm$ 10% change in momentum causes the working point to move sensibly in the (Q_x,Q_y) plane crossing resonances which could be detrimental for the stability of the beam. To reduce this effect one can introduce non-linear elements, like sextupoles in the dispersive arcs, and tune them to make the chromaticity plots flat. Chromaticity correction is motivated by the need for large momentum acceptance, which is not yet fully known due to longitudinal emittance blow up in FFAG presently under study [4]. A visual summary of these results is shown in Fig. 4 where resonance diagrams and chromaticity plots are displayed.

PARTICLE TRACKING AND DYNAMIC APERTURE

Introduction of non-linear elements along the ring is advocated to mitigate resonance crossing effects, potentially catastrophic for a storage ring. However two things

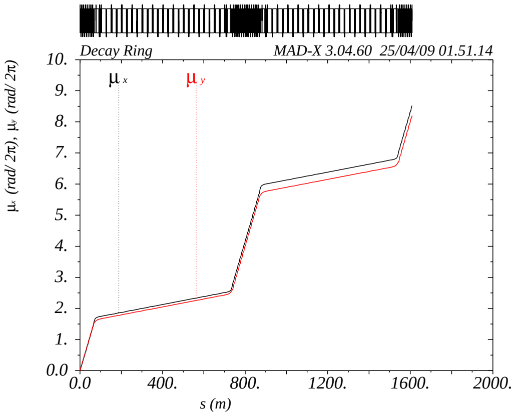

Figure 3: Phase advance over a period in the Decay Ring with a fast increase in the arcs due the small beta functions and a slow increase in the straights where $\beta_{x,y}$ are large.

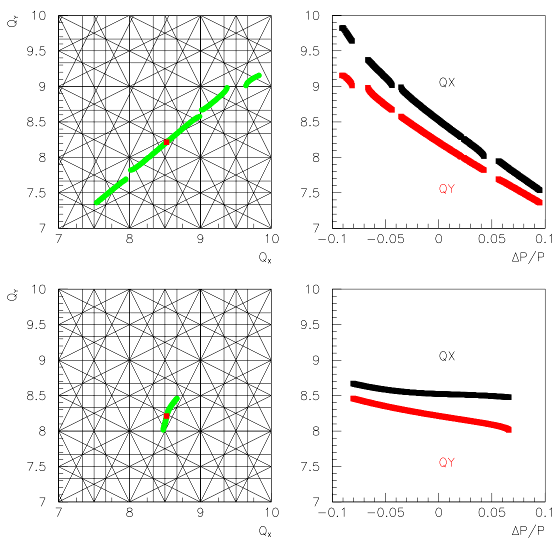

Figure 4: Upper section: linear optics configuration. (Left) tune excursion with crossing of resonances as a function of momentum displacement (green line): the red dot shows the working point. The natural chromaticity of the beam is shown on the right for both the transverse planes. Lower section: the effect of sextupoles is shown. Chromaticity is strongly reduced (right) and also the crossing of potentially dangerous resonances.

should be stressed in the case of a muon ring: (a) at 25 GeV/c muons circulate on average less than 100 times in the 1608.8 m long ring before decaying, (b) the sextupoles introduced in the optics create coupling between the transverse planes and reduce the dynamic aperture of the beam. Concerning point (a) the natural question arises whether it is important to avoid resonance crossing, given the relatively short beam lifetime required. The second aspect has been investigated to produce a more quantitative answer. The study has been carried on using the module *thintrack* of MAD-X and tracking particles checking whether they survive after a large number of turns. Prior to tracking, lattice magnets are sliced into 50 thin elements and the structure is re-matched to produce the same working point conditions. Muon decays are not present in this simulation. After some trials we decided that a particle is stably confined in the lattice if it is not lost after 500 turns. The physical aperture of the ring is chosen arbitrarily high (x=y=1 m) in order to focus on the dynamical aspects of beam transport only. Muons are started in the middle point of an arc with initial phase space coordinates given by the formula $(x_{i=1,N}, y_j, x'{=}0, y'{=}0)_{j=1,M}$. If a muon is lost before 500 turns the corresponding (x, y) values are recorded. Fig. 5 shows how increasing the initial x (and therefore the associated amplitude) results in a loss of the muon. We notice how the elliptical shape of the Poincaré plots is fairly well preserved and also how particle losses happen in a rather sudden way. With the introduction of non-linear elements

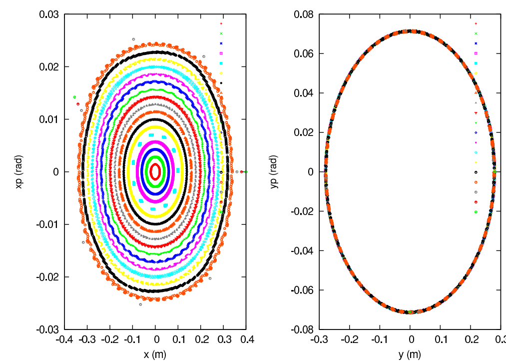

Figure 5: A scan in the (x, x') phase space is shown with a fixed initial value (y=28 cm, y'=0), for the linear optics ring. The left plot is a Poincaré map for the (x, x') section, showing a behaviour very close to elliptical curves even for large beam radii. The evolution of the other transverse coordinates (y, y') is totally decoupled, as can be inferred by the sharp ellipse in the right plot.

phase space plots are highly distorted from the original ellipses, and $x - y$ correlation is visible in the blurred trajectories in both planes (Fig. 6). A summary of the dynamic aperture calculations is shown in Fig. 7.

DECAY LOSSES

One aspect of Decay Ring operations is related to particle losses along the structure. Muons decaying into neutrinos also generate lower energy electrons which are unlikely to be confined within the ring. Concerns about safety and radiation levels are of paramount importance when dealing with nominal rates of 10^{21} muon decays per year. A realistic model of the Race Track ring is therefore the first step to assess this issue. The G4Beamline [5] code has been used to reproduce the Decay Ring geometry whose rendering is given in Fig. 8. Muons can be tracked and left decaying in the ring while secondaries are collected in sensitive planes for further evaluations.

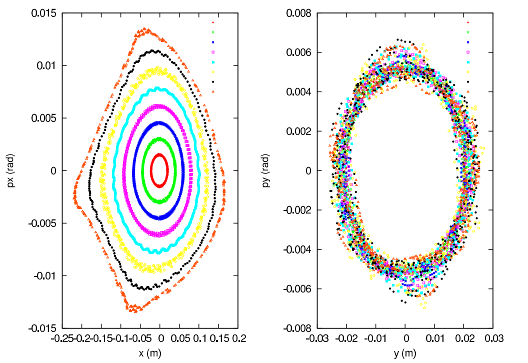

Figure 6: The meaning of the plots is the same as in Fig. 5 but the ring is now equipped with sextupoles to correct for chromaticity effetcs (see text). This results in highly non-elliptical trajectories (Poincaré plot on the left) and coupling between x and y planes, as can be inferred from the blurred trajectories.

CONCLUSIONS AND FUTURE WORK

A preliminary study of the Race Track Decay Ring for the Neutrino Factory has shown some of its features: working point, chromaticity, possible resonance crossing for off-momentum configurations and compensation with sextupoles. The question whether we need chromaticity corrections is still open and should be addressed in terms of the real effect of resonances over a relatively small number of turns. First tracking studies show how dynamic aperture is reduced when using sextupoles, while remaining surprisingly high and well above the nominal acceptance even for off-momentum cases. We believe this needs further investigation with the inclusion of misalignments, field imperfections and fringe fields. Also the use of other tracking codes is envisaged to confirm these results.

We started considering the issue of losses from beam decays and identified a method to investigate this problem which is based on the code G4Beamline: a version of the Race Track ring within this framework has been produced that needs to be tuned and analysed.

REFERENCES

[1] J. S. Berg *et al.* "International Scoping Study of a future Neutrino Factory and super-beam facility, 3 September 2008, RAL-TR-2007-23.

[2] C. Prior, "Muon Storage Rings for a Neutrino Factory", these proceedings, poster session WE6PFP099.

[3] F. Schmidt, H. Grote, MAD-X "User's Guide", http://mad.web.cern.ch/mad/madx_manual.pdf.

[4] J. S. Berg, S. Machida, "FFAG Designs for the International Design Study for the Neutrino Factory", these proceedings, poster session, TU1GRC04.

[5] T. Roberts "A Swiss Army Knife for Geant4, optimized for simulating beamlines", in http://www.muonsinc.com/tiki-index.php.

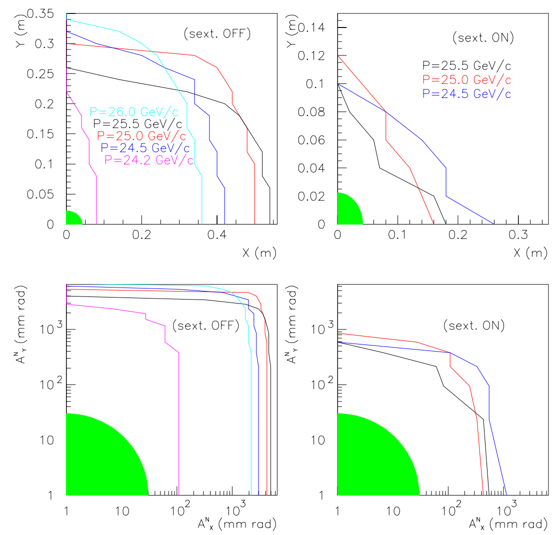

Figure 7: Dynamic Aperture for the Decay Ring. Left column: linear optics. Right column: sextupoles introduced in the lattice. (Top) contour plots defining the maximal radius for a particle injected in the middle point of an arc before being lost in the lattice. In off-momentum cases this radius is generally reduced. The green area represents the beam size corresponding to the nominal acceptance (30 mm rad). Points on the contour plots (R_x, R_y) are used to define the normalized amplitudes in the two transverse planes (A_x^N,A_y^N), where $(A_i^N = \frac{P}{m_\mu} R_i^2/\beta_i)_{i=x,y}$ (bottom). In this case the green area denotes the 30 mm rad fiducial acceptance.

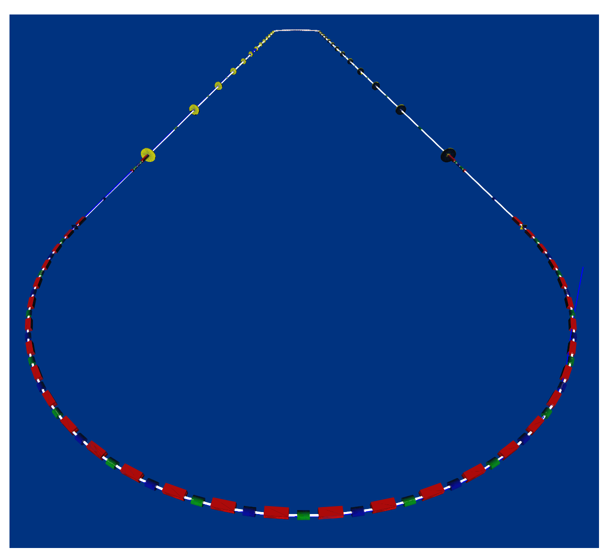

Figure 8: A perspective view of the Race Track Decay Ring in G4Beamline. Color convention: (red) dipoles, (blue) focussing quadrupoles, (green) defocussing quadrupoles, (yellow) virtual detectors for tracking studies.