MUON DECAY RING STUDY

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Abstract

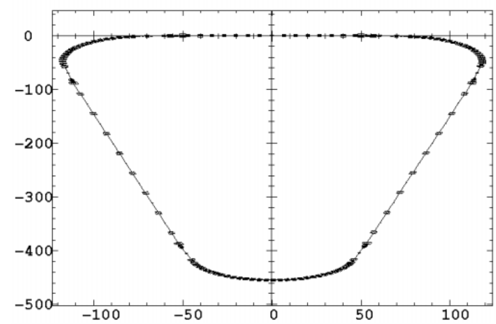
Two designs considered by the International Scoping Study (ISS) for the final stage of the neutrino factory are the triangle and bow-tie muon decay rings. Unlike the racetrack design, these geometries enable two detectors to be targeted from one storage ring. A beam dynamics study of both rings is carried out using the Zgoubi tracking code. In particular the operating point in tune space is optimised. Results of muon spin tracking are presented.

INTRODUCTION

From the point of view of neutrino production, the design of the muon decay ring must take account of the number of detectors that can be targeted, the opening angles of the decay neutrinos, the ratio of the production straight to the total circumference and the preservation of muon polarisation. The current ISS design [1] calls for two decay rings to store both μ^+ and μ^- bunches (at 20 GeV) and to serve two detectors. The racetrack design is favoured since two rings can be built in separate tunnels. The triangle and bow-tie rings need to be built side-by-side. However, if suitable detector sites are found, the triangle and bow-tie rings would be favoured over the racetrack due superior neutrino production efficiencies. In order to target two detectors, the triangle and bow-tie will have to built at an angle close to the vertical plane.

In the case of the triangle ring, two 300.8 m production straights and a 1170 m circumference give a neutrino production efficiency of 51.4% (in the racetrack design the figure is 37.3%). Eight solenoids, each 4 m, are included in each production straight. They are used instead of FODO cells since, for equal muon divergence angles, the maximum β value for solenoids is about half that found in FODO cells. This reduces the beam size in the production straights. FODO focusing cells are used in the arc section of the ring. A matching section ensures that dispersion in the arc is reduced to zero in the production straight. The third side of the triangle, which is not used for neutrino production, contain quadrupoles whose gradients can be adjusted for tune control of the ring.

The bow-tie is similar in composition to the triangle ring. In this case, two 425.2 m production straights and a 1608.8 m circumference give a 52.9% neutrino production efficiency. Since the net bend in the bow-tie is zero, the turn-by-turn muon polarisation is preserved. This is a disadvantage of the bow-tie, since the depolarisation of the muons allow a measurement of energy spread to be made



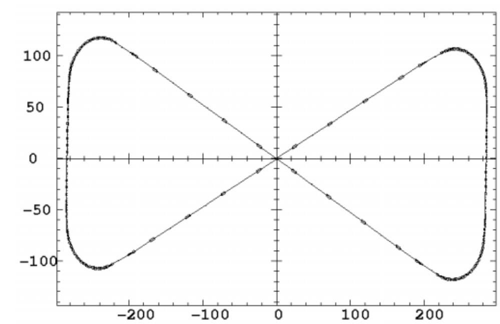


Figure 1: Triangle and bow-tie decay rings. The scale is in meters.

[2]. The geometry of the bow-tie and triangle rings are shown in Fig. 1.

BEAM DYNAMICS

The high accuracy of the integration method in the Zgoubi tracking code allows efficient multi-turn tracking in the muon storage ring. When setting up the lattice, dipole and combined function magnets are first translated and rotated in order to match cell tune specifications and fix the closed orbit. Due to coupling in the solenolds, a non-zero but negligible closed orbit remains, shown in Fig. 2 for the bow-tie.

The muon decay ring is required to have a relatively large transverse admittance, 3π cm rad in each transverse plane, and a $\frac{\delta p}{p}$ admittance of 3%. It is necessary to establish an operating point in betatron tune space where these requirements are met. Quadrupoles in the tuning section of both rings can be adjusted to scan the tune space. Multiturn tracking in the rings, at various amplitudes, allows the the dynamic aperture to be found.

Some of this work been done in the triangle ring [3], this paper will concentrate on the bow-tie. A preliminary

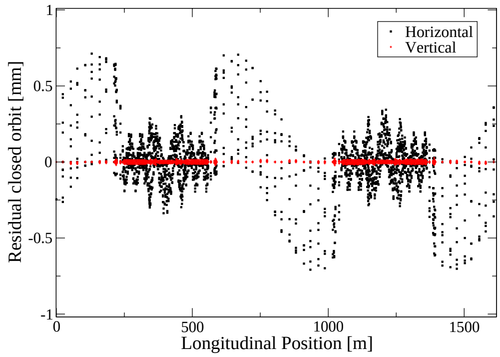


Figure 2: Horizontal and vertical residual closed orbit in the bow-tie ring calculated over ten turns. The origin is at the center of the production straight. Note the vertical scale is in the range ± 1 mm.

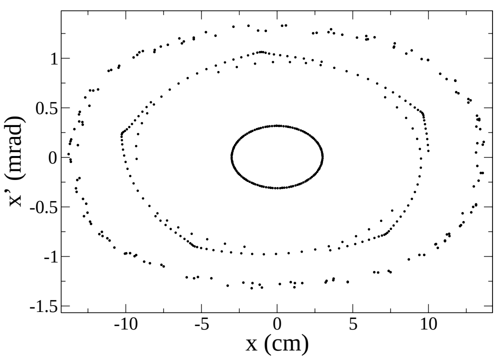


Figure 3: Horizontal phase space of muons with equal emittance in the horizontal and vertical planes. The outer curve represents a 3.3 Pi cm normalised emittance.

scan of the tune space has been done. Single particles are tracked for 155 turns, thats double the muon lifetime at 20 GeV (in the triangle ring the equivalent number is 215 turns). The maximum dynamic aperture, found at horizontal and vertical tunes (14.38,12.78), is 3.3 Pi cm normalised in both planes. It is found that the dynamic aperture is limited by the resonance associated with fractional tune 0.5 in

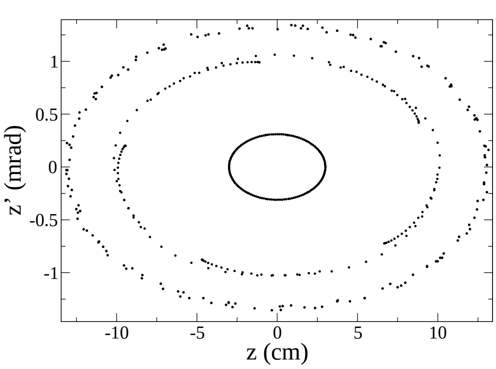


Figure 4: Vertical phase space of muons with equal emittance in the horizontal and vertical planes. The outer curve represents a 3.3 Pi cm normalised emittance.

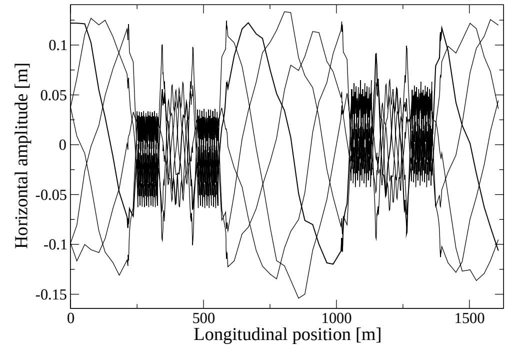


Figure 5: Horizontal beam envelope given by five particles with normalised emittance 3 Pi cm.

the horizontal plane.Phase space plots in the middle of the production straight (where $\beta_x = \beta_y = 94.2$ m) are shown in Fig. 3 and Fig. 4. The beam envelope in the horizontal plane for five muons with emittance 3 Pi cm is shown in figure 5. More comprehensive tracking studies are required to optimise the dynamic aperture in the bow-tie decay ring.

SPIN POLARISATION

The polarisation of the muon bunch in the decay ring is of interest from the point of view of neutrino production and of energy spread measurements. It is expected that the natural longitudinal polarisation of -27% (opposite to the direction of motion) produced by pion decay will be preserved in the cooling and acceleration stages until arrival at the decay ring [2]. For simplicity in this preliminary study, the muons are assumed to be fully polarised in the longitudinal direction initially. The motion of the spin **S** is governed by the Thomas-BMT equation

$$\frac{d\mathbf{S}}{dt} = \frac{q}{m}\mathbf{S} \times \mathbf{\Omega} \tag{1}$$

where

$$\mathbf{\Omega} = (1 + \gamma G)\,\mathbf{B} + G(1 - \gamma)\mathbf{B}_{\parallel} \tag{2}$$

where q, m, γ and G are respectively the charge, mass, Lorentz relativistic factor and anomalous magnet moment of the particle. $\mathbf{B}_{\parallel}$ is the component of the magnetic field $\mathbf{B}$ parallel to the velocity of the particle. It follows that the spin tune, i.e. the number of spin precessions completed in one turn, is given by,

$$\nu_s = \gamma G \tag{3}$$

For muons at 20GeV, the spin tune is 0.2219. However, in the bow-tie ring the spin precession in one half is cancelled out in the other so that the spin tune is zero. Spin tracking in Zgoubi confirms that the polarisation in the bow-tie is preserved at all particle amplitudes and momenta to within 10^{-6} when tracking 155 turns. The expected spin tune in the triangle ring is in good agreement with Zgoubi turn-by-turn tracking results (Fig. 6) though a negligible difference builds up with turn number. (It has already been shown, for different magnet types, that spin tracking calculations in Zgoubi compare well with theory [4].)

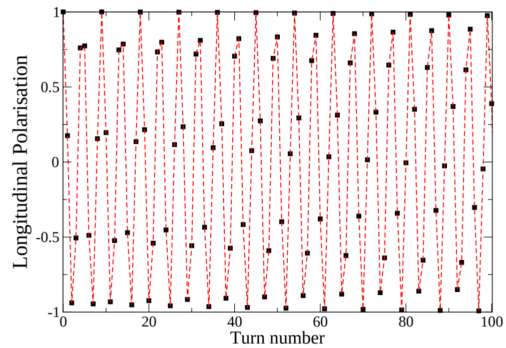


Figure 6: Longitudinal component of polarisation for muons tracked in the triangle ring (black squares) compared with spin tune tune prediction (red dashed).

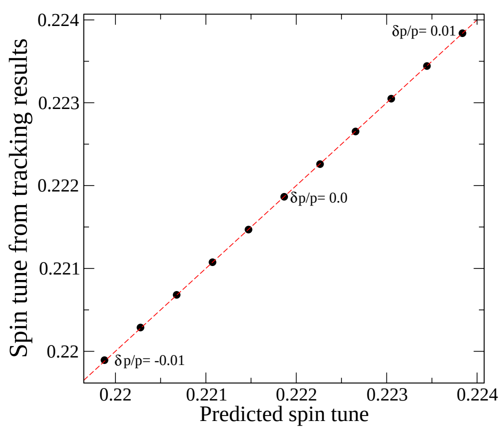


Figure 7: Predicted spin tune at momenta in the range $\frac{\delta p}{p} = \pm 0.01$ with stepsize $\frac{\delta p}{p} = 0.002$ compared with Zgoubi tracking result (circles). The dashed line represents equality.

In the triangle ring it was found that the turn-by-turn spin precession varies with momentum and with muon transverse emittance. The variation of spin tune with momentum from the Zgoubi tracking results is compared with that predicted by Eqn. 3 in the momentum range $\frac{\delta p}{p} = \pm 0.01$ in Fig. 7. The difference between theory and tracking result is of the order 10^{-6}. The Zgoubi tracking results also show a variation with beam emittance (Fig. 8). Due to the differential spin precession between particles of different momentum, there is a degradation in polarisation [5]. To obtain this result with Zgoubi, ten muons uniformly distributed in the momentum range and starting on the closed orbit were tracked for 215 turns. It is clear in Fig. 9 that a higher momentum spread results in a faster rate of spin depolarisation. A muon polarisation diagnostic would allow the rate of depolarisaion and so the energy spread of the muon bunch to be measured [2].

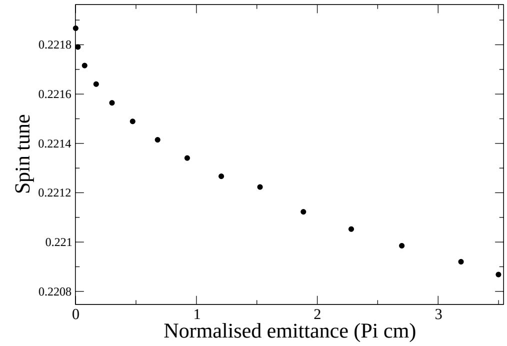


Figure 8: The variation of spin tune with transverse emittance from Zgoubi tracking results. The muons have equal emittance in the horizontal and vertical planes and are at reference momentum.

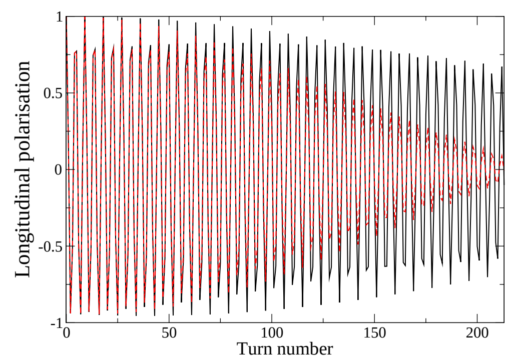


Figure 9: Depolarisation due to momentum spread of 0.5% (black solid) and 1.0% (red dash).

CONCLUSIONS

This paper describes a preliminary analysis of beam dynamics and spin tracking in the bow-tie and triangle muon decay rings. An operating point in tune space that maximises dynamic aperture in both transverse planes (3.3 Pi cm normalised emittance) has been selected for the bow-tie ring. It has also been shown that spin tracking in Zgoubi in both rings results in turn-by-turn spin precession with expected spin tune and, in case of the triangle ring, depolarisation with energy spread. In future work, the effect of a more realistic energy distribution on the depolarisation rate should be studied.

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