STUDIES OF 10 GeV DECAY RING DESIGN FOR THE INTERNATIONAL DESIGN STUDY OF THE NEUTRINO FACTORY

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Abstract

Owing to the discovery of large θ_{13} [1], the final muon storage energy in the baseline solution of the International Design Study for the Neutrino Factory (IDS-NF) has been set at 10 GeV. A new racetrack design has been produced for the decay ring to meet this requirement. The details of lattice design and the beam dynamics calculations are discussed. The feasibility of the injection system for both positive and negative muons into the ring is explored in detail.

INTRODUCTION

The final stage of the IDS-NF design for a neutrino factory is a racetrack storage ring in which six muon bunches of each sign counter-rotate. Each of the bunches is about 250 ns in duration and injected pulses arrive at the storage ring separated by 120 μs. The neutrinos that are created from muon decays in one of the long production straights of the racetrack are sent towards far and near detectors. There should be a gap of at least 100 ns between neutrino signals arriving at the detectors. The measured value of θ_{13} dictates that the far detector should be located about 2000 km away and so the ring should be tilted out of the horizontal plane by about 10°.

The muon storage ring design, up to now, consisted only of the production straights where the betatron function is high (to ensure the beam divergence is less than $\frac{0.1}{\gamma}$), densely packed arcs in which the betatron function is small to reduce beam size and matching sections in between. A 1006 m ring was designed, just large enough to accommodate the muon bunches including the effects of debunching. The neutrino production efficiency η_p, defined as the ratio of production straight length to ring circumference, was $35.8\% \times 2$.

INJECTION CONSIDERATIONS

In the earlier design, it was envisaged that the beam would be injected in the long straights of the production section. Each muon sign would be injected simultaneously using a septum-kicker-septum configuration with the elements located in consecutive drifts.

However, injection in this section is challenging owing to the low phase advance per cell and large transverse β

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leading to high kicker peak fields (0.08 T) and aperture (0.44 m × 0.34 m), respectively. The maximum rise/fall time required of the kicker magnets is 0.8 μs given by

$$\tau_{rise/fall} = \frac{C}{cn_b} - t_b \tag{1}$$

where C is the circumference of the ring ($\approx$ 1km), n_b is the number of bunch pairs stored and t_b is the bunch duration [2]. While a previous study showed that the peak field can be achieved, meeting both the rise/fall time and the aperture requirements in the same kicker will be challenging [3].

In order to relax the kicker requirements, a dedicated insertion section is proposed. Simultaneous injection of both muon signs is preferred from the point of view of the rise/fall time allowed. However, it excludes placing the insertion in the middle of the arc, since each muon bunches of each sign would then arrive at the end of a production straight simultaneously. In fact, injection must be at least a distance L_{ex} on either side of the arc centre where L_{ex} is given by

$$L_{ex} = \frac{c}{2}(t_b^{ini} + n_\tau \eta T_0 \delta + t_{gap}) \tag{2}$$

where t_b^{ini} is the initial bunch duration (250 ns), t_{gap} is the desired gap between neutrino signals to be maintained for n_τ mean decay times, δ is the fractional total momentum spread, η is the phase slip and T_0 is the revolution time. Assuming that η is 5×10^{-3} and it is a requirement to maintain a 100 ns gap for 4 mean decay times, then L_{ex} is 83.7 m. Placing an insertion in the production straight is also excluded since it would result in an unacceptable increase in beam divergence. Therefore, the insertion can only be placed between the arc and the matching section to the production straight.

INSERTION SECTION

The zero dispersion insertion is made up of four FDF triplet cells with 3.7 m long drifts in which to place injection magnets. As shown in Fig. 1, a symmetric arrangement of septa and kicker magnets about a central empty drift allows injection of both muon signs from opposing directions. The horizontal phase advance per cell is set close to $\pi/2$ to maximise the displacement at each septum owing to kickers located one and three cells away. The peak

Figure 1: Insertion section schematic. The black rectangle represent triplet magnets while the red and blue rectangles represent kicker magnets and septa, respectively. The empty long drift is shown as a white rectangle.

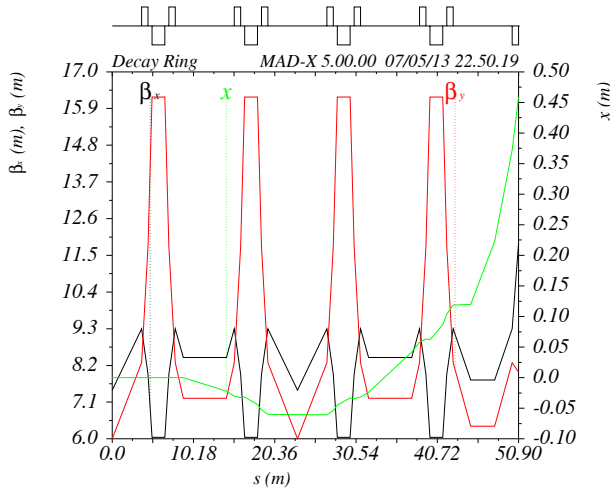fields of both kicker magnets must be equal in magnitude to allow simultaneous injection.

Figure 2: Trajectory of injected beam centroid (green) from right to left through a septum (blue rectangle) and two kickers (red rectangles). The optics are also shown.

Table 1: Injection Settings

	Angle (mrad)	Length (m)	Field (T)	Rise/Fall Time (μs)
Septum	67.5	3.0	0.75	-
Kicker	8.1	5.4	0.05	1.37

Injection settings are listed in Table 1. The injected beam reaches the closed orbit after passing through two opposite polarity kicker magnets. The trajectory of the opposite sign muon bunch will be antisymmetric reflected about the centre of the empty drift. This means that injection will be from the outside of the ring for one muon sign and from the inside of the ring for the other. Apart from the kicker rise/fall time, previous studies indicates that these parameters are realisable [3].

MATCHING THE INSERTION SECTION

A dispersion suppressor section is needed between the arc and the insertion section. The suppression is done by following eleven normal arc cells with three in which the bend angle is reduced by $\frac{2}{3}$. The total number of cells must be increased by two to conserve the total bend (176.4°) in
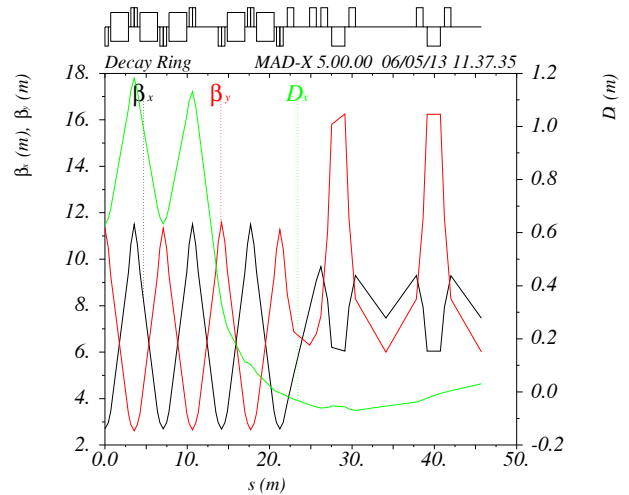

Figure 3: Matching from arc to insertion. The dispersion suppressor covers the first 21.64 m, followed by the 7.49 m optics matching section and then the first insertion cell.
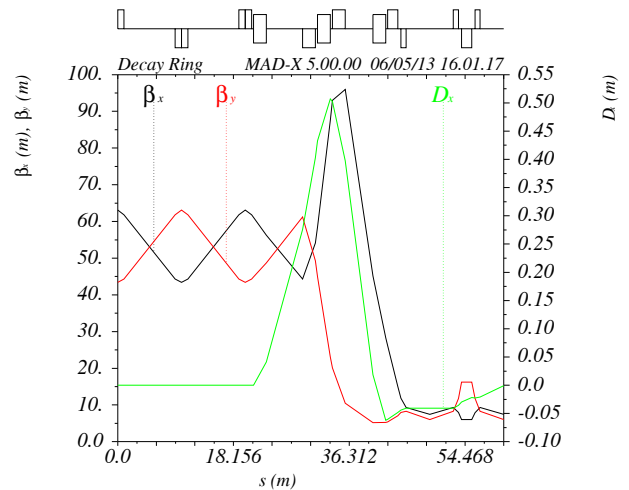

Figure 4: Matching from production straight to insertion. A production straight cell covers the first 20 m, followed by the 27.62 m matching section and then the first insertion cell.

the arc. Note, since this total bend is less than π the insertion does not point in the direction of the detectors. Following the dispersion suppressor, an optics matching section comprising four quadrupoles is added. The dispersion suppressor and matching section are shown in Fig. 4. The small non-zero dispersion that remains in the insertion will have a negligible impact on injection.

Between the insertion and the production section, a matching section is required. This comprises four quadrupoles and three dipole magnets. As in previous designs, the bends are arranged to ensure that in the transition from high to low beam divergence, none of the decay neutrinos are directed at the detectors. They also serve to remove decay electrons and stray muons.

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LOWER ARC

To maintain left-right symmetry an insertion must be included at either end of the upper arc. However, insertions are not needed in the lower half of the ring and excluding them helps to increase the production efficiency. Since the insertion contributes to the width of the upper half, the lower arc must be increased in length. To reduce the number of distinct elements in the ring, this is done by increasing the drift lengths. As in the upper half, a matching section is required between the production straight and the arc. An iterative procedure is adopted in order to both match the optics and obtain the desired width with convergence achieved in a few steps. The arc gradients are increased by 2.8% in order move the working point away from integer.

RING SUMMARY

The principal ring parameters are listed in Table 2 and the optics and geometry are shown in Figs. 5 and 6 respectively. Owing to the inclusion of the insertion and associated dispersion suppressor and matching sections, the length of each production straight is increased by 200 m to ensure that η_p is equivalent to the earlier insertion-free design. The available kicker rise/fall time, taking into account debunching up to the point of injection of the final bunch, is approximately 1.37 μs. The phase slip is low enough to ensure that virtually all the muons will have decayed before debunching significantly reduces the gap between neutrino signals sent to the detectors. Solving for n_τ in Eq. 2, and assuming the total momentum spread is given by $\delta = 0.05$, shows the beam can circulate for ten mean decay times before the neutrino signal gap drops below 100 ns.
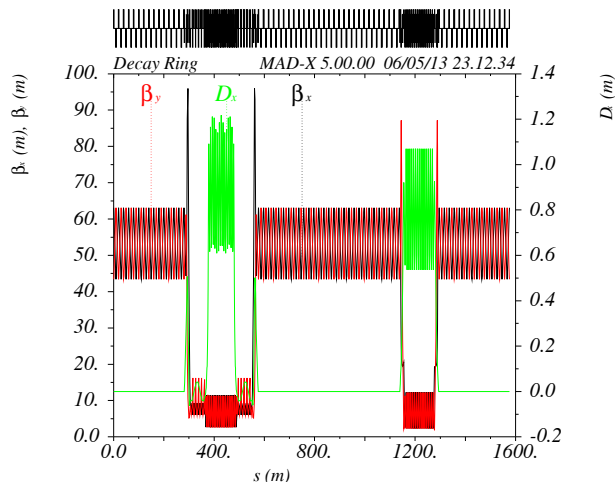

Figure 5: Ring optics. The upper half is on the left, starting in the middle of a production straight.
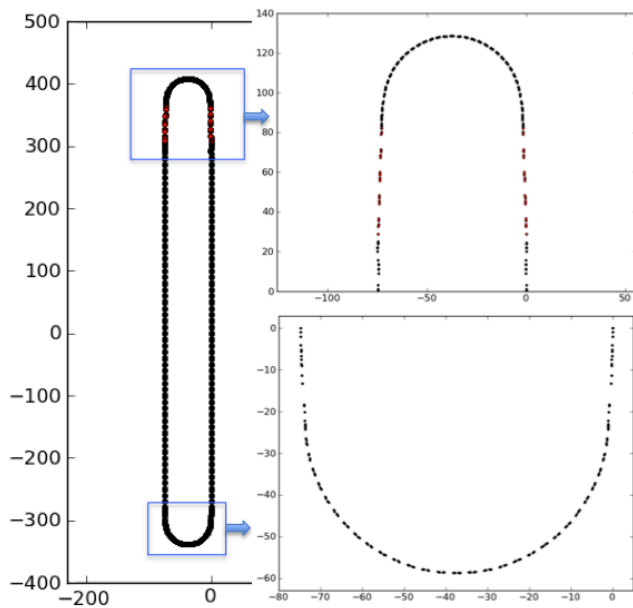

Figure 6: Storage ring geometry. The entire ring is on the left while the subfigures on the right show zoomed images of the areas highlight by blue boxes. The red dots represent the injection insertion.

Table 2: Ring Parameters

		Unit
Upper arc (incl. disp supp)	120.4	m
Lower arc	112.0	m
Insertion	46.4×2	m
Production straight	560×2	m
Circumference	1575.8	m
Width of ring	74.77	m
Length of ring	747.249	m
Production efficiency η_p	$35.56\% \times 2$	
Total tune (H,V)	14.25, 14.88	
Phase slip η	2.8×10^{-3}	
Turns per mean lifetime	39.6	

CONCLUSIONS

Designing a feasible injection system for the storage ring has led to the addition of a dedicated insertion and consequently a substantial increase in circumference. This increase is largely driven by the need to maintain production efficiency.

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