STATUS OF THE DECAY RING DESIGN FOR THE IDS NEUTRINO FACTORY

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Abstract

In the International Design Study for the Neutrino Factory (IDS-NF) a racetrack design has been adopted for the decay ring. The injection system into the decay ring is described. The feasibility of injecting both positive and negative muons into the ring is explored from the point of view of injection timing. Considerations for the design of a decay ring for a 10 GeV neutrino factory are included.

INTRODUCTION

In the light of the recent measurement of large θ_{13} [1], the energy to which muons should be accelerated in a neutrino factory has been reduced from 25 GeV to 10 GeV - necessitating a new storage ring design. Just one storage ring is now required to serve a single far detector about 2000 km away. Some possible laboratory and detector pairs are shown in Table 1. As before, the new racetrack lattice will need to fulfil a number of key criteria - including a high neutrino production efficiency η_p (where η_p is the fraction of neutrinos aimed at the detectors), reasonable dipole fields in the arcs, maintenance of sufficient separation of muon bunches during the store and a realistic means of injection.

The 25 GeV ring is extensively described in [2]. Aspects of the engineering have been considered, for example how the magnets will be installed and the location of cryogenic plant, and much of this work will be applicable in the reduced energy ring. A costing of the 25 GeV ring has also been made. This work is reported at this conference in [3].

Table 1: A selection of laboratory and detector site pairs that come close to the updated IDS-NF specifications.

Lab	Detector	Distance (km)	Tilt (degrees)
CERN	Oulu, Finland	2287	10.34
FNAL	Homestake, SD	1286	5.80
FNAL	Gaspe, Montreal	1996	9.01
RAL	Oulu, Finland	2075	9.37

10 GeV LATTICE DESIGN

A racetrack lattice is favoured for the 10 GeV decay ring. The ring will be filled with six muon bunches - three counter-rotating bunches of each polarity. Each bunch is 250 ns in duration and is separated from the others in the train by 120 μs. The decay ring should store these bunches for several mean decay times and keep debunching in check so that the intense bursts of neutrinos that are produced are separated by at least 100 ns. Some of the considerations that will inform an eventual design follow.

Production Straight

The production straight consists of quadrupoles arranged in a FODO lattice. The beam divergence should be restricted to less than 10% of the natural decay cone angle $(1/\gamma)$ to ensure a focussed neutrino beam. Assuming a normalised rms emittance of 4.8π mm, the betatron function in the ring required to meet this condition at 10 GeV is 45.4 m. The reduction in the required β with decreasing relativistic γ mean that the magnet apertures in the production straight do not change significantly. A preliminary set of lattice parameters are presented in Table 2 and the resulting β-functions shown in Fig. 1.

Table 2: Preliminary production straight parameters.

Drift length	8.0 m
QF/QD length	1.0 m
QF/QD gradient	0.68 T/m
Beam envelope in QF/QD	0.141 m

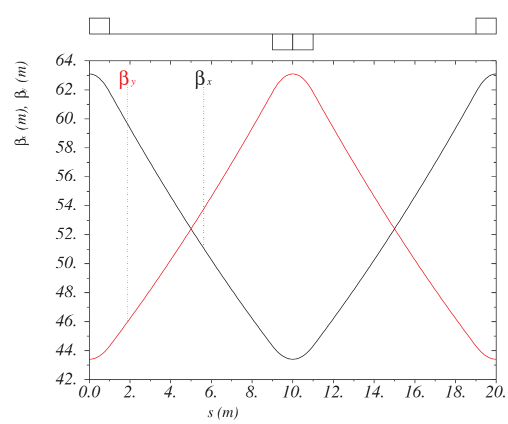

Figure 1: Optics in one production straight cell.

Arc and Matching Sections

In the 25 GeV design, each arc consists of 15 tightly packed FODO cells with a dipole between each consecutive quadrupole. A low β-function is required in the arc to minimise apertures. Due to technology and cost considerations, it is desirable to restrict the dipole field to $\approx$ 4 T.

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Fewer dipoles, and hence fewer arc cells, may be necessary at 10 GeV which would lead to an increase in η_p. However, reducing the number of bends tends to increase the phase slip and so lead to a more rapid debunching (see later section).

The optics for a preliminary 10 GeV design is shown in Fig. 2. To match the optics and dispersion in the arc to that in the production straight a dedicated section is needed, as can be seen in the figure. The matching section at 10 GeV may be shorter than at 25 GeV due to the reduced β-function in the production straights. The overall design of the ring has yet to be optimised for phase slip and injection. It is likely that the design process will lead to a substantial increase in the circumference.

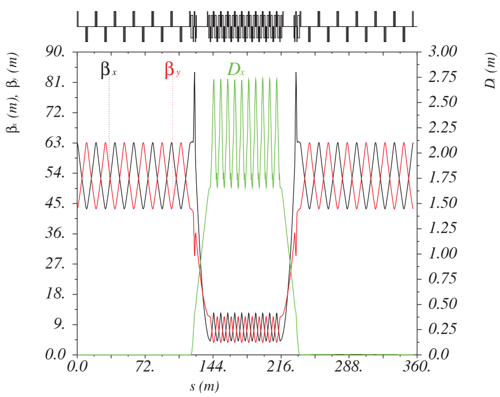

Figure 2: Optics over half a ring for a preliminary 10 GeV design. The horizontal axis extends from the centre of one production straight to the other. The midpoint corresponds to the centre of an arc.

INJECTION

Injection Timing

The six muon bunches in the ring must be correctly synchronised to ensure that bursts of neutrinos are sent to the detectors at evenly spaced intervals. It is of interest to work out at which locations bunches of opposite polarity cross one another as this will be a factor in the choice of injection points. It is obvious that a crossing point cannot be located at the centre of the arc since then bunches will arrive at their production point simultaneously. By an argument of symmetry, it can be seen that when all six bunches are equally distributed around the ring, two bunches of both signs must be located at the arc centres to ensure the correct timing. Therefore, there must be a crossing point at the centre of each production straight and another set $\pm$ L/6 on either side, where L is the ring circumference (i.e. they will all lie in the production straight if $\eta_p \geq 2/3$).

The injection kickers should be located to allow for the rise and fall time between bunches. In Fig. 3 the six points in the ring where the bunches cross one another can be seen. The bunches alternate between two sets of three crossing points in a time interval $\frac{L}{6c}$. Two injection schemes can sensibly be considered.

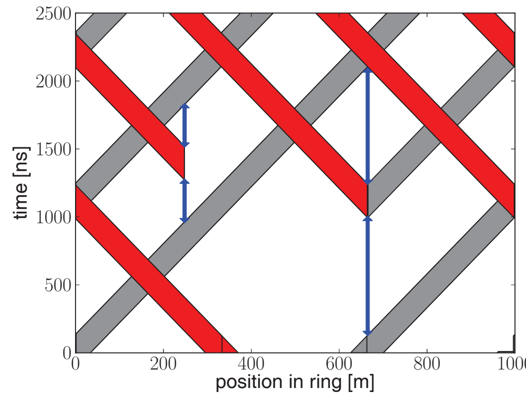

Figure 3: Illustration of the two injection schemes. The grey and red bands represent muon bunches of opposite sign counter-rotating in the ring. The horizontal axis shows the position in the ring with the origin at the end of one of the production straights. The horizontal axis covers the circumference which is arbitrarily chosen. As bunches reach either end of the horizontal range, they wrap around to the other side. The bunch size is given by the thickness of the band but ignores debunching. The blue arrows on the left depict injection scheme 1 and those on the right show injection scheme 2. The length of the arrows before and after the bunch injection give the available kicker rise and fall time, respectively.

Injection Scheme 1 In the first scheme, a separate injection system for each muon polarity is included, one in each production straight, with the kicker halfway between two meeting points. A delay of length $\frac{L}{6}$ is needed between the arrival of bunches of opposite polarities at their respective injection points. For the final bunch the available rise time, given by the time from a circulating bunch passing the kicker to the arrival of the injected bunch, is $\frac{L}{6c} - t_b$ (where t_b is the bunch length and assuming a thin lens kicker). Note, t_b will increase as the beam circulates due to debunching. The available fall time is equal to the rise time as long as the kicker is exactly halfway between meeting points.

Injection Scheme 2 In the second scheme, muon bunches of both polarities are injected simultaneously into a single kicker. The kicker needs to be located at one of the crossing points (presumably at the upper end of the production straight) in order to ensure the circulating bunches will be in synchronisation. Since the bunches are counter-rotating they must be injected into the kicker from opposite directions. While the design of the transfer line from the final acceleration stage may be complicated by this requirement, the advantage of this scheme is the increase in available kicker rise/fall time to $\frac{L}{3c} - t_b$. The two injection schemes are illustrated in Fig. 3.

Kicker and Septum Settings

It is proposed to make use of the long drifts in the production line for injection. The injection scheme assumes an injection septum and kicker in neighbouring long drifts. The injection must ensure a 2 cm separation between the injected and circulating beam at the septum exit and stay clear of any magnet hardware. It is also desirable to limit the kicker peak field to 0.1 T and and the septum to less than 2 T.

Table 3: Injection settings at 12.6 GeV.

	Angle (mrad)	Length (m)	Field (T)
Septum	90.0	3.0	1.3
Kicker	10.7	5.0	0.09

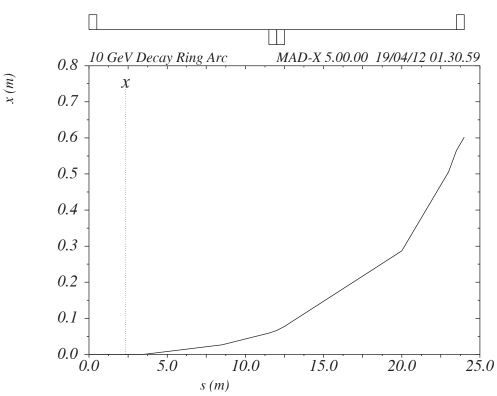

Figure 4: Injection at 12.6 GeV.

Injection settings for a 12.6 GeV lattice, with a 11 m drift, are given in Table 3 with the resulting injection trajectory shown in Fig. 4. Injection is from right to left in the figure. Injection at 10 GeV is more challenging due to the shorter drifts in the production straight. The drifts may need to be lengthened to ease injection but care must be taken not to allow an excessively large oscillation of the β-function.

DEBUNCHING

After n_τ mean decay times τ, the amount of debunching in the absence of rf is given by

$$\Delta s = n_\tau c \tau \eta_s \frac{dp}{p} \quad (1)$$

where η_s is the phase slip. In order to maintain a minimum separation ΔT between neutrino signals, the minimum circumference C_{min} is given by

$$C_{min} = n_b c \left(\Delta T + n_\tau \tau \eta_s \frac{dp}{p} + t_b \right) \quad (2)$$

where n_b is the number of bunches in the ring. Assuming the phase slip $\eta_s = 0.005$ (as it is in the 25 GeV lattice), a 2% rms momentum spread, using the mean decay time at 10 GeV and setting $n_\tau = 4$, then the minimum required circumference is 1279.8 m. The phase slip of the 10 GeV lattice will need be carefully considered. A rf bunching cavity may need to be included.

INSERTION

Due to the lack of available space in the lattice, apart from in the production straights where the large beam size can be an impediment, it may be desirable to include an insertion at the halfway point in an arc. An insertion could be used to provide space for injection hardware or for a bunching cavity. Including an insertion will lead to a reduction in η_p without a compensating increase in the production straight length. An insertion with dispersion suppression has been implemented for the preliminary 10 GeV design (Fig. 5).

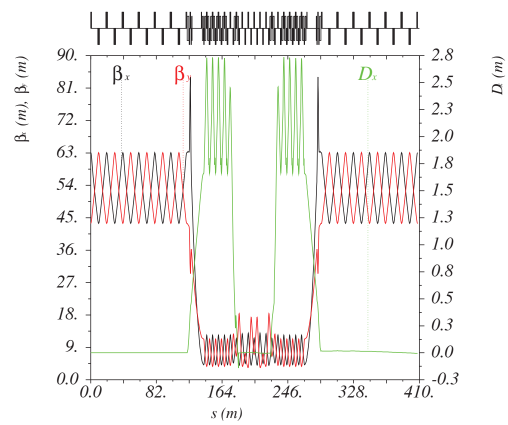

Figure 5: Optics for a preliminary 10 GeV design with an insertion at the centre of the arc and a dispersion suppressor on either side. The suppression of the dispersion can be seen by comparison with Fig. 2.

CONCLUSION

This paper reports some of the aspects to be considered when putting together a design for the decay ring. Devising an injection scheme with realisable kicker transient times and peak fields is one of the key design challenges.

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