THE INTERNATIONAL DESIGN STUDY FOR THE NEUTRINO FACTORY

K. Long and J. Pozimski, Imperial College London, Exhibition Road, London, SW7 2AZ, UK
J.S. Berg, Brookhaven National Laboratory, P.O. Box 5000, Upton, NY 11973-5000, USA
on behalf of the IDS-NF collaboration

Abstract

The International Design Study for the Neutrino Factory (the IDS-NF) has recently completed the Interim Design Report (IDR) for the facility as a step on the way to the Reference Design Report (RDR). The IDR has two functions: it marks the point in the IDS-NF at which the emphasis turns to the engineering studies required to deliver the RDR and it documents the present baseline design for the facility which will provide 10^{21} muon decays per year from 10 GeV stored muon beams. The facility will serve one neutrino detector situated at a source-detector distance of between 1500 km and 2500 km. The conceptual design of the accelerator facility will be described and its performance will be summarized.

INTRODUCTION

The phenomenon of neutrino oscillations, arguably the most significant advance in particle physics over the past decade, has been established through measurements on neutrinos and anti-neutrinos produced in the sun, by cosmic-ray interactions, in nuclear reactors, and using beams produced by high-energy particle accelerators [1]. In consequence, we know that the Standard Model is incomplete and must be extended to include neutrino mass, mixing among the three neutrino flavours and therefore lepton-flavour non-conservation. These observations have profound implications for the ultimate theory of particle interactions and for the description of the structure and evolution of the Universe.

In the Neutrino Factory, beams of (anti-)electron and (anti-)muon-neutrinos are produced from the decay of muons circulating in a storage ring. As the ratio of the mass of the muon to that of the electron is large, the neutrinos carry away a substantial fraction of the energy of the parent muon, hence, high neutrino energies can readily be achieved. Charged-current interactions induced by "golden channel", $\nu_e \rightarrow \nu_\mu$, oscillations produce muons of charge opposite to those produced by the anti-muon neutrinos in the beam and thus a magnetized detector is required. The additional capability to investigate the "silver" ($\nu_e \rightarrow \nu_\tau$) and "platinum" ($\nu_\mu \rightarrow \nu_e$) channels makes the Neutrino Factory the ideal place to look for oscillation phenomena that are outside the standard, three-neutrino-mixing paradigm. It is thus the ideal facility to serve the precision era of neutrino oscillation measurements [2].

Recently, the Daya Bay and RENO experiments reported measurements of the small mixing angle θ_{13} [3,4]. The measured value, close to the upper end of the previously allowed range, has permitted the IDS-NF collaboration to adopt a stored muon energy of 10 GeV as the baseline for the facility (see Figure 1). A single detector placed between 1500 km and 2500 km from the source then gives optimum sensitivity for the discovery of CP-invariance violation and the determination of the mass hierarchy [2]. The baseline accelerator facility provides a total of 10^{21} muon decays per year. The Neutrino Factory has superior discovery reach for CP-invariance violation and can measure the oscillation parameters with a precision that is significantly better than realistic alternative facilities.

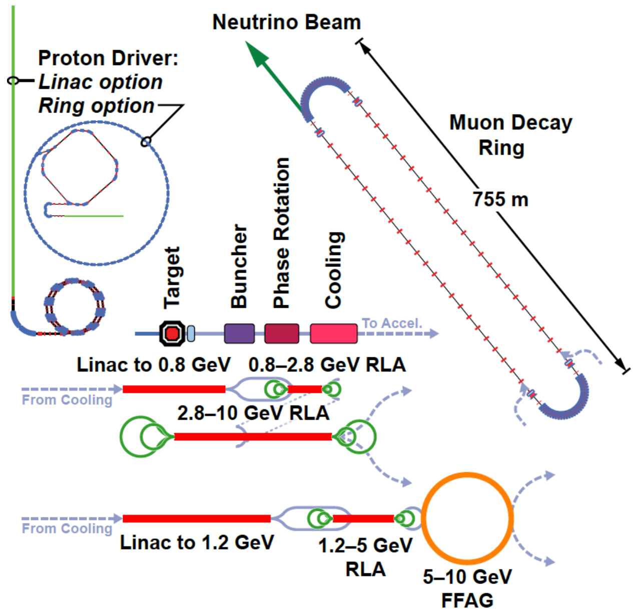

Figure 1: The accelerator facilities for the neutrino factory [2]. Compared to previous baselines the final muon energy has been reduced to 10 GeV following the Daya Bay and RENO results. Two different muon accelerator scenarios both derived from the previous baseline are under investigation to determine the most cost effective solution.

ACCELERATOR COMPLEX

A schematic diagram of the Neutrino Factory accelerator facility is shown in Figure 1. Muons are produced by the interaction of high-energy protons with a target resulting in the production of pions which decay to muons. Pions and muons of both signs are captured and focused in a high-field solenoid channel designed to maximize the number of muons transported to the muon storage ring. The captured muons have a large energy spread and a large transverse emittance, both of which need to be reduced so that the beam can be accelerated efficiently. In the muon front end, the buncher and phase rotation sections reduce the energy spread. Then the transverse emittance is reduced using ionization cooling. A sequence of accelerator systems is used to accelerate the beam to its final energy. The first stage of acceleration is performed using a linac because the large transverse emittance and energy spread, and the variation of velocity with energy make it impractical to recirculate the low-energy beam through the cavities. The linac is followed by one or two recirculating linear accelerators, in each of which the beam makes multiple passes through the accelerating structures. In the case of the one RLA scenario the final stage of acceleration is performed using a linear non-scaling fixed field alternating gradient accelerator, which allows many more passes through the cavities. Finally, the beam is injected into one racetrack-shaped decay ring the straight sections of which are pointed at one detector at a distance of 1500-2500 km. The reduction in muon energy by a factor of 2.5 compared to the previous baseline design reduces the number of accelerator systems and reduces the engineering challenges of the decay rings, both with significant impact on the total cost for the facility. The question whether two RLA's or one RLA and one FFAG are the most cost effective solution will be the subject of further investigations.

PROTON DRIVER

At the start of the accelerator chain, a proton driver capable of delivering an average power of 4 MW is required. Several boundary conditions define the proton beam parameters necessary to produce the desired number of muons in the storage ring. The proton-beam energy must be in the multi-GeV range in order to maximise pion production. In addition, the Neutrino Factory requires a particular time structure consisting of 3 very short bunches separated by 120 μs. The short bunch length of 1–3 ns rms is dictated by the efficiency of the muon-beam capture and the bunch separation is constrained by beam loading in the downstream muon accelerator and the recovery time of the mercury-jet target. In order to achieve such short bunches, a dedicated bunch-compression scenario needs to be designed carefully in order to deal with very strong space-charge forces. Several proton driver schemes fulfilling these requirements have been proposed and site-specific proton drivers for CERN, FNAL and RAL have been presented in the IDS-NF IDR [2]. The CERN solution is based upon the SPL and the FNAL solution on Project X. Each of these scenarios employs a high power linac followed by an accumulator and a compressor ring. The RAL solution is based on an ISIS upgrade and will use RCSs for acceleration and bunch compression.

TARGET

A liquid-mercury-jet target has been chosen as the baseline. The target must operate in a high magnetic field to maximize the capture of the pions that are emitted with a large transverse momentum. Extensive studies of the target have been performed to find the optimal proton-beam energy and target-station geometry [5,6]. Recent work showed that, for the IDR design, the heat load expected in the superconducting coils would exceed technical limitations and an improved layout was produced [7]. Since then the physics design of the target station has been altered to accommodate the engineering requirements (see Figure 2).

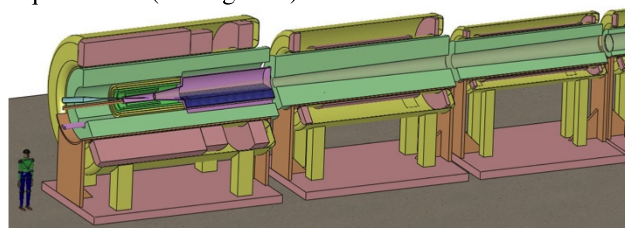

Figure 2: New layout of Neutrino Factory target station and capture solenoid. Due to engineering requirements the details of the layout of the superconducting coils have been changed to allow for room between the modules for maintenance. As the magnetic field profiles stayed unchanged so will the muon yield.

MUON FRONT END

The muon front end is designed to optimise the number of muons that can be transmitted through the downstream accelerator complex. Two major changes have been made to the baseline muon front-end setup shown in Figure 3. A chicane has been added between the pion decay channel with longitudinal drift and the adiabatic buncher, phase-rotation system, and ionization-cooling channel. The chicane consists of a solenoidal transport channel with a beryllium absorber at the end of it. The chicane will remove unwanted secondary particles (mainly protons) from the beam to avoid activation downstream in the muon accelerator. Particle dynamics studies showed a good suppression of low and high momentum protons [8]. Further work towards the RDR will concentrate on the development of an engineering design of the chicane with emphasis on the particle absorbers.

One further change in the baseline was a revision of the lattice for the buncher, phase rotator and cooling sections in response to engineering requirements as illustrated for the buncher section in Figure 4.

Experimental studies have shown that in a magnetic field, the maximum gradient of room-temperature RF cavities is significantly reduced. Since the experimental work is still in progress, it is currently unknown to what extent the RF gradients will be limited by the magnetic fields. Various studies with different lattice layouts, the use of pressurized gas-filled RF cavities and cavity surface treatment have demonstrated competitive performance to the baseline cooling lattice at significantly reduced breakdown risk [9,10,11].

ISBN 978-3-95450-115-1

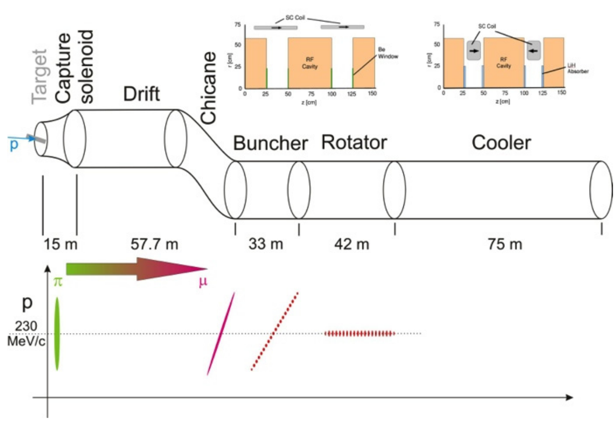

Figure 3: Schematic overview of the muon front end including the newly added chicane. The lattice design of Buncher, Rotator and Cooler are shown in the top row, while the bottom row shows the development of the particle burst within the front end.

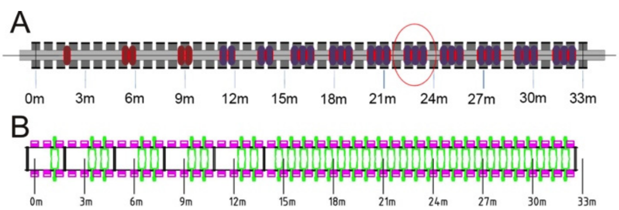

Figure 4: Changes to the buncher section due to engineering constrains. **A** shows the physics lattice design with one critical position marked. The highly modular engineering lattice adopted as baseline avoiding this problem is shown in **B**.

Engineering constraints have also forced some modifications to the cooling lattice. We will study the performance impact of these changes and may make further design changes to mitigate any resulting performance reductions. We will study some different lattice options for the cooling channel, in particular a bucked coil configuration and a lattice where the solenoids have additional iron shielding, which will reduce the magnetic fields at the cavities. We will assess their performance relative to the baseline cooling channel and make a decision as to whether we should change our baseline cooling lattice.

MUON ACCELERATION

The Neutrino Factory accelerator facility will accelerate muons to 10 GeV. This will be achieved in three stages (see Figure 1) following the cooling section. The chain of accelerators is optimized in cost by maximizing the efficiency at each stage. Due to the change in the baseline muon energy two possible setups, differing mainly in the final acceleration stage, are under investigation. A solenoid focused linac first accelerates the beam to a total energy of either 0.8 GeV or 1.2 GeV [12]. Then a dog-bone re-circulating linear accelerator (RLA) with FODO cells accelerates the beam to 2.8 GeV (or 5 GeV). The linac and RLA lattices have been revised to improve the transverse acceptance and simplify the design of the switch yards. The final acceleration is performed using either another RLA (2.8 – 10 GeV) accelerating in 4 passes or a fixed field alternating gradient (FFAG) accelerator (5-10 GeV) in around 6.5 turns. Magnets in the injection and extraction sections will need to be somewhat larger than the main ring magnets to take into account the beam oscillation in these regions. Preliminary simulations of the 25 GeV ring indicated that the resulting symmetry breaking has a tolerable effect on the orbits [2,13]. All accelerating cavities are 201.25 MHz superconducting cavities, the design of which is described in [2].

STORAGE RING

The Neutrino Factory design specifies one racetrack-shaped storage ring pointed toward a detector 1500–2500 km away. The design of the 10 GeV storage ring has been developed from the 25 GeV ring that was included in the previous baseline. In the future, tracking studies will address the machine's dynamic aperture including errors. The decay ring is 1600 m in circumference and accommodates the equally-spaced, 250 ns long bunch trains with time intervals of at least 100 ns between the neutrino bursts. The production straights for the race-track design are 240 m long, giving an efficiency of 33.7%.

ACKNOWLEDGMENTS

This paper describes the work performed by all members of the International Design Study of the Neutrino Factory. More details can be found in the references and at https://www.ids-nf.org/.

REFERENCES

[1] C. Amsler et al, Physics Letters B, 667, 1 (2008).
[2] S. Choubey et al, the IDS-NF collaboration, arXiv:1112.2853 (2011).
[3] F.P. An, et al, the Daya Bay Collaboration, Phys.Rev.Lett. 108, 171803 (2012).
[4] J.K Ahn et al, the RENO collaboration arXiv:1204.0626 (2012).
[5] J. Back et al, IPAC-2011-MOPZ008 (2011).
[6] X.Ding, et al, Phys. Rev. ST Accel.Beams, 14, 111002 (2011).
[7] R. J. Weggel et al., PAC-2011-TUP265 (2011).
[8] P. Snopok et al, FERMILAB-CONF-11-047-APC (2011).
[9] A. Alekou et al, IPAC-2010-3458-3460, IPAC-2010-WEPE051 (2010).
[10] M. BastaniNejad et al, "FERMILAB-CONF-09-205-AD-APC (2009).
[11] A. Alekou et al, IPAC-2010-3455-3457, IPAC-2010-WEPE050 (2010).
[12] A. Kurup et al, IPAC-2011-MOPZ009, JLAB-ACP-11-1419 (2011).
[13] J. S. Berg et al., IPAC-2011-MOPZ007 (IPAC 2011).