# THE INTERNATIONAL DESIGN STUDY FOR THE NEUTRINO FACTORY

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*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 25 GeV stored muon beams. The facility will serve two neutrino detectors; one situated at a source-detector distance of between 2500—5000 km, the second at 7000—8000 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 electron and (anti-) muon-neutrinos are produced from the decay of muons circulating in a storage ring. As the muon charge-to-mass ratio is large, the neutrinos carry away a substantial fraction of the energy of the parent muon, hence, high neutrino energies can readily be achieved. Time-dilation is beneficial, allowing sufficient time to produce a pure, collimated beam. Charged-current interactions induced by "golden channel", $\nu_e \to \nu_\mu$, 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" ($\nu_e \to \nu_\tau$) and "platinum" ($\nu_\mu \to \nu_e$) 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.

The baseline specification for the Neutrino Factory, developed within the International Design Study for the Neutrino Factory (the IDS-NF), has been optimized for the discovery of CP-invariance violation, the determination of the mass hierarchy, and the determination of $\theta_{13}$ [2]. The optimum requires two distant detectors. One at the "magic baseline", 7000–8000 km, the second at a source-detector distance in the range 2500–5000 km. The sensitivity to non-standard interactions improves as the stored-muon energy is increased, reaching a plateau at around ~25 GeV [3]. A baseline stored muon energy of 25 GeV has therefore been adopted. The baseline accelerator facility provides a total of $10^{21}$ muon decays per year split between the two distant neutrino detectors.

The discovery reach of the Neutrino Factory is significantly better than realistic alternative facilities, particularly for small values of the last unknown "mixing angle", $\theta_{13}$. Recent results hint that $\theta_{13}$ may be large, i.e. close to the present upper bound [4]. In this case, a re-optimization of the baseline Neutrino Factory will still yield superior performance.

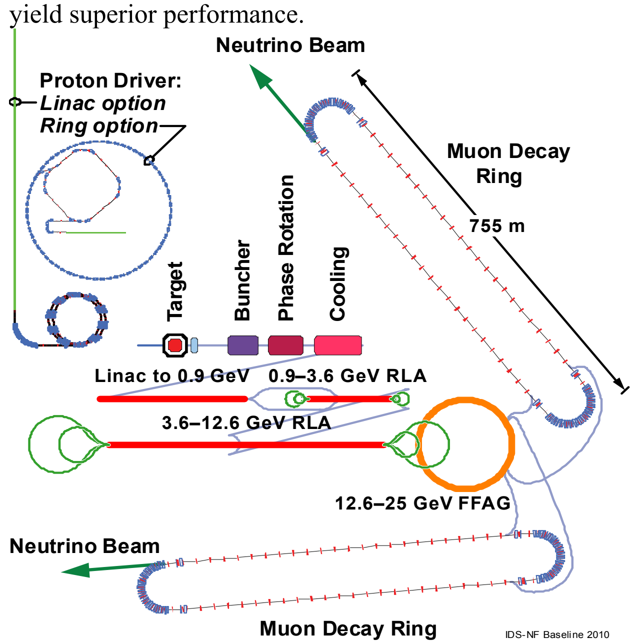


Figure 1: The accelerator facilities for the neutrino factory [5].

## ACCELERATOR COMPLEX

A schematic diagram of the Neutrino Factory accelerator facility is shown in figure 1 [5]. 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. This is accomplished in the muon front end using a buncher and a phase rotation section. In the muon front end the transverse emittance of the bunch train is then reduced using ionization cooling. A sequence of accelerator systems is used to accelerate the beam to the final energy. The first stage of acceleration is performed using a linac because the large transverse emittance and the variation of velocity with energy makes it impractical to recirculate the low-energy beam through the cavities. The linac is followed by two recirculating linear accelerators, in each of which the beam makes multiple passes through the accelerating structures. 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 two racetrack-shaped decay rings the straight sections of which are pointed at the two distant detectors. The rings have very long straight sections to ensure that a large fraction of the muons are moving toward the detector when they decay.

## 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 rings of the Neutrino Factory. The proton-beam energy must be in the multi-GeV range in order to maximise the 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 [5]. 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

Since a solid target is likely to be damaged by a proton beam of the intensity that is required, 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 [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 (see figure 2) [7].

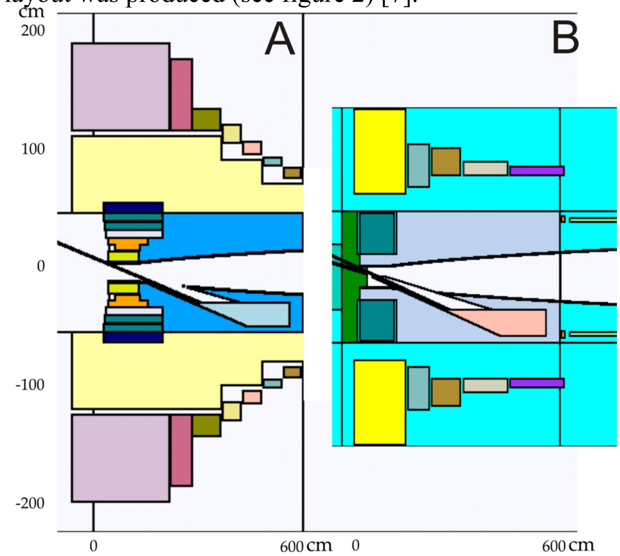


Figure 2: IDS-NF target geometry (B), and new improved target geometry (A). The inner radius of the solenoids has increased from 65 cm to 120 cm, and additional shielding has been added in region between the inner warm and outer superconducting coils.

## MUON FRONT END

The muon front-end consists of a pion decay channel and longitudinal drift, followed by an adiabatic buncher, phase-rotation system, and ionization-cooling channel. It is designed to optimise the number of muons that can be transmitted through the downstream accelerator complex.

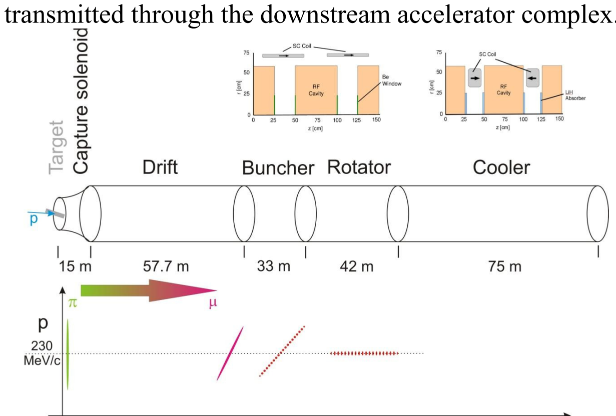


Figure 3: Schematic overview of the muon front end. The lattice design of the Buncher, Rotator and Cooler are shown in the top row, while the bottom row shows the development of the particle burst within the front end.

Experimental studies have found 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 been performed and show encouraging results [8,9,10]. Since the publication of the IDR a chicane consisting of solenoids has been added to the layout between the decay channel and the buncher section. This chicane will remove unwanted secondary particles (mainly protons) from the beam to avoid activation downstream in the muon accelerator. Particle dynamics studies show a good suppression of low and high momentum protons [11].

## MUON ACCELERATION

The IDS-NF will accelerate muons to 25 GeV. This is done in four of stages (see figure 1) to optimize the system cost by maximizing the efficiency at each stage. A solenoid focused linac first accelerates the beam to 0.9 GeV total energy. Then, two dog-bone re-circulating linear accelerators (RLAs) with FODO cells accelerate the beam to 12.6 GeV. The lattices for accelerating to 12.6 GeV have been designed, including transition lines. Magnet error tolerances are reasonable. Magnet design has begun and tracking studies have started using more realistic magnet end fields [12]. The final stage is a fixed field alternating gradient (FFAG) accelerator, taking the beam to 25 GeV total energy within 11.8 turns. Based on the need for space for injection and extraction magnets, and other hardware, lattice designs presented earlier have been updated [5]. Multiple cell types were under consideration, but a triplet lattice with 3 m drift lengths and two-cell RF cavities was chosen Injection and extraction will be the most challenging aspect of the FFAG. 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 indicate that the resulting symmetry breaking has a tolerable effect on the orbits [13]. All accelerating cavities are 201.25 MHz superconducting cavities, the design of which is described in [5].

## STORAGE RING

The IDS-NF design specifies two racetrack-shaped storage rings pointed toward detectors 2500–5000 km and 7000–8000 km away respectively. The simultaneous use of both baselines allows degeneracies among the parameters used to described neutrino oscillations to be resolved and generally improves the sensitivity of the machine [5]. A design has been produced for a storage ring and tracking studies have confirmed that the machine's dynamic aperture is more than sufficient for the beam [14]. The decay ring of 1.6 km in circumference can accommodate the equally-spaced, 250 ns long bunch trains and can allow time intervals of at least 100 ns between the neutrino bursts. The production straights for the race-track design are 600.2 m long, giving an efficiency of 37.5% and the tunnel depths for the far detector ring of this size is 444 m. Simulations showed that, assuming the predicted energy spread of the muons, the bunches in the bunch train will not merge sooner than twice the lifetime of the muons, therefore no RF has to be installed in the decay ring. To reduce the systematic uncertainty in the neutrino flux, beam diagnostics is required in the storage ring [5,15]. An efficient collimation, as well as a beam injection system needs still to be developed.

## 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, (1008).
[2] S. Choubey et al, the IDS-NF collaboration, https://www.ids-nf.org/wiki/FrontPage/Documentation?action=AttachFile&do=get&target=IDS-NF-020-v1.0.pdf.
[3] J. Kopp, M. Lindner, and T. Ota, Phys. Rev. D 76 (2007) 013001, arXiv:0702269 [hep-ph].
[4] K. Abe et al, T2K Collaboration, Phys. Rev. Lett. 107, 041801, (2011); P. Adamson et al, MINOS Collaboration, Submitted to: Phys.Rev.Lett. arXiv:1108.0015 [hep-ex] (2011).
[5] The IDS-NF collaboration, IDS-NF-020 (2011). https://www.ids-nf.org/
[6] The IDS-NF collaboration, IDS-NF-017 (2010). https://www.ids-nf.org/
[7] J. Back "Particle Production Simulations for the Neutrino Factory Target", IPAC2011
[8] C. Rogers et al. "Muon cooling performance in various Neutrino Factory cooling cell configurations using g4mice", IPAC2010
[9] M. Bastani Nejad *et al.*, "RF breakdown of metallic surfaces in hydrogen", PAC2009
[10] A. Alekou, "Alternative muon front-end for the international design study (IDS)", IPAC 2010
[11] P. Snopok et al, "Front End Energy Deposition Studies and Mitigation Strategies for IDS-NF", IPAC 2011
[12] A. Kurup, "The Muon Linac for the International Design Study for the Neutrino Factory"; IPAC2011
[13] J. Pasternak, "Effect of Chromaticity Correction, Field Errors and Magnet Misalignments on the Beam Dynamics in the Muon FFAG for the Neutrino Factory", IPAC2011
[14] M. Apollonio,"Beam dynamics studies for a Neutrino Factory decay ring"; PAC2009
[15] M. Apollonio, "Muon polarimeter in a Neutrino Factory decay ring" IPAC2010.