

## Final Results from the IDS-NF Study

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**Soler, F.J.P.**<sup>\*†</sup>

*School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, United Kingdom.*

*E-mail:* [paul.soler@glasgow.ac.uk](mailto:paul.soler@glasgow.ac.uk)

Neutrino Factories are facilities that produce neutrino beams with well-defined flavour content and energy spectra, from the decay of intense, high-energy, stored muons, to search for CP violation in the neutrino sector. The International Design Study for the Neutrino Factory (the IDS-NF) is providing a Reference Design Report (RDR) for such facilities, optimised for the high values of  $\theta_{13}$ . The accelerator facility will deliver  $10^{21}$  muon decays per year from 10 GeV stored muon beams. The straight sections of the storage ring point to a 100 kton Magnetised Iron Neutrino Detector (MIND) at a distance of  $\sim 2000$  km from the source. The accuracy in the value of  $\delta_{CP}$  that a Neutrino Factory can achieve is between  $4^\circ$  and  $5^\circ$  and the  $\delta_{CP}$  coverage is between 85% and 90%, both of which are unrivalled by other future facilities.

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<sup>\*</sup>Speaker.

<sup>†</sup>On behalf of the IDS-NF Collaboration.

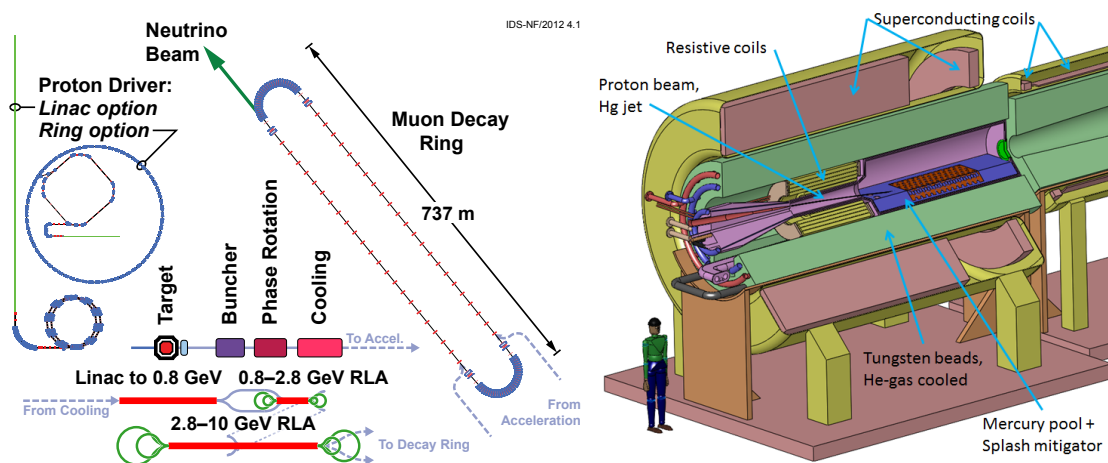
## 1. Introduction

The Neutrino Factory is an accelerator that produces intense neutrino beams from the decay of muons in flight in a storage ring [1]. This allows to determine the absolute flux and spectrum of neutrinos with smaller systematic errors than at alternate facilities. The International Design Study for a Neutrino Factory (IDS-NF) is the latest of a series of design studies specifying the accelerator, diagnostic and detector systems that make up the facility, their schedule and cost, and the overall physics performance. An Interim Design Report (IDR) [2] and a report for the EUROnu project have already been published [3, 4].

Neutrino oscillations in matter can be extracted from the appearance of  $\nu_\mu$  ( $\bar{\nu}_\mu$ ) in a far detector for a stored  $\mu^+$  ( $\mu^-$ ) beam (the golden channel) [5]. The recent discovery that  $\theta_{13}$  is non-zero [6, 7, 8, 9, 10], and global fits from all the available data [11, 12] suggest that the discovery of CP violation in the neutrino sector and the determination of the CP violating phase  $\delta_{CP}$  can be realised in future experiments.

## 2. Neutrino Factory Accelerator

The Neutrino Factory baseline described in the IDR [2] was optimised for small values of  $\theta_{13}$ . For large values of  $\theta_{13}$ , the facility has now been re-optimised to have one 100 kton Magnetised Iron Neutrino Detector (MIND) at approximately 2000 km. A schematic of the accelerator facility can be found in Figure 1. It includes a proton driver that can deliver a beam between 5 and 15 GeV; a target, capture and decay station that can handle 4 MW proton power; a bunching and phase rotation section to reduce the energy spread of the beam; an ionisation cooling section to reduce the transverse emittance of the muon beam; a series of nested accelerators that can accelerate the muon beam from 120 MeV up to 10 GeV; and a muon storage ring with long straight sections that can store the beam for about 1000 turns.



**Figure 1:** Left: Schematic drawing of the IDS-NF accelerator complex. Right: Neutrino Factory target.

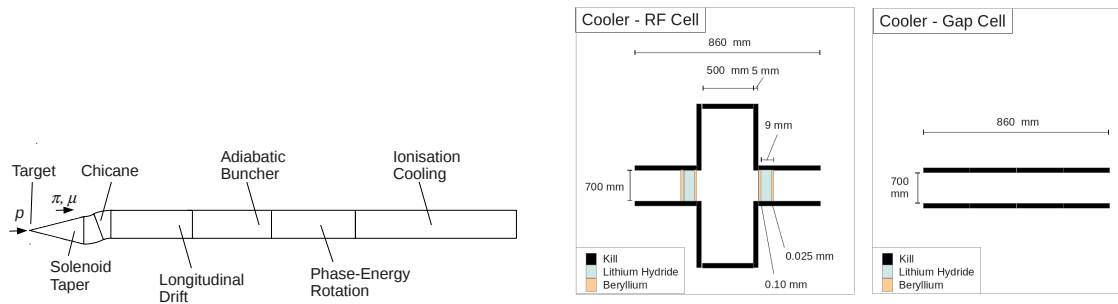
## 2.1 Proton Driver and Target

The proton driver includes a pulsed proton beam with average beam power of 4 MW, a repetition rate of 50 Hz, with three bunches per train in 240  $\mu$ s, 1-3 ns proton bunch length and energy between 5 and 15 GeV (with a preferred proton energy around 8 GeV). The beam radius should be 1.2 mm (RMS), with a geometric emittance less than 5  $\mu$ m and a  $\beta^*$  at the target of greater than 30 cm. One possible example of a proton driver is the Proton Improvement Plan (PIP) at Fermilab, which includes a staged linear accelerator facility, with a first 200 kW LINAC at 0.8 GeV (PIPII), followed by a 1 MW facility at 3 GeV (PIPIII) and a final stage delivering between 2 MW and 4 MW at 8 GeV [13, 14]. Other possible proton drivers include the SPL at CERN or a Fixed Field Alternating Gradient (FFAG) at a green field site [15]. The baseline target [16] consists of a liquid mercury jet inside a 20 T capture solenoid field (Figure 1, Right). The MERIT experiment [17] has provided a proof-of-principle of the mercury jet target. Increased radiation shielding surrounding the target had to be included to protect the target solenoid. The full target station will be described in the Reference Design Report of the International design Study for a Neutrino Factory.

## 2.2 Muon Front End

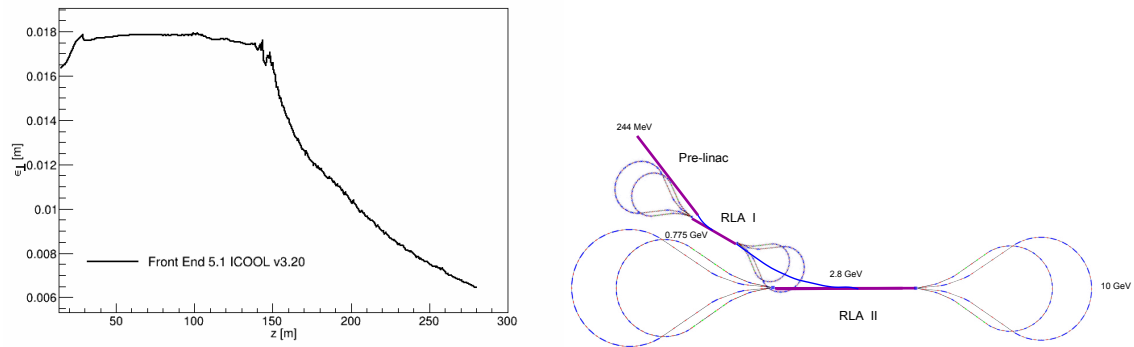
The Neutrino Factory muon front end consists of a pion decay solenoid taper, a chicane to remove proton contamination, a longitudinal drift section, followed by an adiabatic buncher, phase-energy rotation system, and ionisation cooling channel (Figure 2). Updates to the front-end described in reference [18] are presented in this section. Downstream of the target solenoid, the magnetic field is adiabatically reduced from 20 T to 1.5 T over a distance of 15.0 m. A chicane at 19.0 m, consisting of a 5.0 m outward bend of 12.5° followed by a 5.0 m reverse bend, designed to remove particles with momentum above 500 MeV/c and a 0.1 m long beryllium plug to range out low energy protons. The pions then drift longitudinally over 40.9 m inside a 1.5 T solenoidal field and decay to the daughter muons. The drift channel is followed by a 33 m buncher section that uses 44 RF cavities of 0.5 m width at 0.75 m intervals, with decreasing frequency (358.9 to 235.4 MHz) and increasing gradient up to 11.9 MV/m to form the muon beam into a train of bunches. Then there is a 36 m phase-energy rotating section that decelerates the leading high-energy bunches and accelerates the late low energy bunches, so that each bunch has the same mean energy. It consists of 48 cells of 0.75 length including normal conducting RF cavities, with frequencies reducing from 231.5 to 202.1 MHz, with a constant gradient of 13 MV/m, and superconducting coils delivering a 1.5 T focusing field.

The muons then pass the ionisation cooling channel, comprising repeated cells of absorbers, which reduce both transverse and longitudinal momentum, and RF cavities, which reaccelerate the longitudinal momentum, thereby reducing the transverse emittance. The cooling channel design consists of a sequence of 28 identical supercells, each of which comprises 5 cooling cells of 0.86 m length followed by an empty gap cell to provide space for bellows, diagnostics and other services (Figure 2, Right). Each cooling cell contains one 0.5 m long 201.25 MHz RF cavity, with two 9 mm thick LiH absorber discs and strong focusing solenoid coils with opposite polarity (maximum field of 2.8 T providing transverse focusing with  $\beta_{\perp} = 0.8$  m) at the ends of each cavity. The cooling channel is expected to reduce the RMS transverse normalised emittance from  $\varepsilon_N \sim 0.018$  m to  $\varepsilon_N \sim 0.0065$  m (Figure 3, Left), increasing the muon yield by a factor of 2.2 to 0.066  $\mu$ /proton.



**Figure 2:** Left: Neutrino Factory front-end. Right: Baseline design of RF muon cooling lattice cell with the empty gap cell.

The Muon Ionisation Cooling Experiment (MICE) will test one cooling channel cell using liquid hydrogen and LiH absorbers [19, 20].



**Figure 3:** Left: Cooling performance of the muon front-end. Right: Accelerator system for the 10 GeV Neutrino Factory.

### 2.3 Acceleration System and Decay Ring

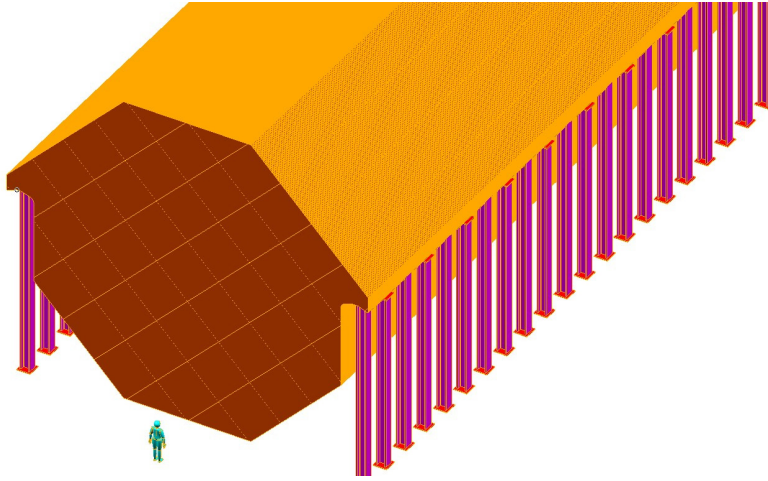
The acceleration proceeds in three stages: a 146 m LINAC that accelerates from 244 MeV to 775 MeV, a first Recirculating Linear Accelerator (RLA) of 79 m length that accelerates up to 2.8 GeV, and a second 264 m RLA up to 10.0 GeV (Figure 3, Right).

There is one decay ring based on a racetrack design, with two 562 m long decay straights. The upper and lower arcs are 121 m and 113 m long respectively, with an added 46 m long insertion section, and matching sections that are 105 m in total. The total circumference is 1556 m with a total length from end to end of 737 m. Three positive and three negative muon bunch trains (250 ns long at injection) circulate in opposite directions along the storage ring, with a minimum separation between consecutive  $\mu^+$  and  $\mu^-$  bunch trains of 100 ns. The decay straights point to a far detector at a distance between 2000 and 2500 km ( $10^\circ$  slope). Muons are stored in the decay rings for about 1000 turns, with a muon beam divergence of  $0.1/\gamma$ .

### 3. Neutrino Factory Detector

#### 3.1 MIND Detector Concept

The appearance of “wrong-sign” muons at a Magnetised Iron Neutrino Detector (MIND) is the main signature for the  $\nu_\mu$  appearance “golden channel”. MIND consists of large octagonal iron plates of dimensions  $14\text{ m} \times 14\text{ m} \times 3\text{ cm}$ , followed by two planes of scintillator bars (one in  $x$  and the other in  $y$ ) 1 cm thick (see Figure 4), with a toroidal magnetic field between 1.0 and 2.2 T [21]. The field is created by a Superconducting Transmission Line (STL) of diameter 7.8 cm, within a 10 cm bore, carrying 100 kA of excitation current. The modules repeat themselves to form a detector 140 m long, with 100 kton fiducial mass, placed at a distance between 2000 and 2500 km, which yields the best performance for the discovery of CP violation at large  $\theta_{13}$  [22]. The far detector is complemented by two near detectors (one at the end of each of the decay ring straights) to determine the neutrino flux, measure neutrino cross sections and to search for non-standard interactions [23].

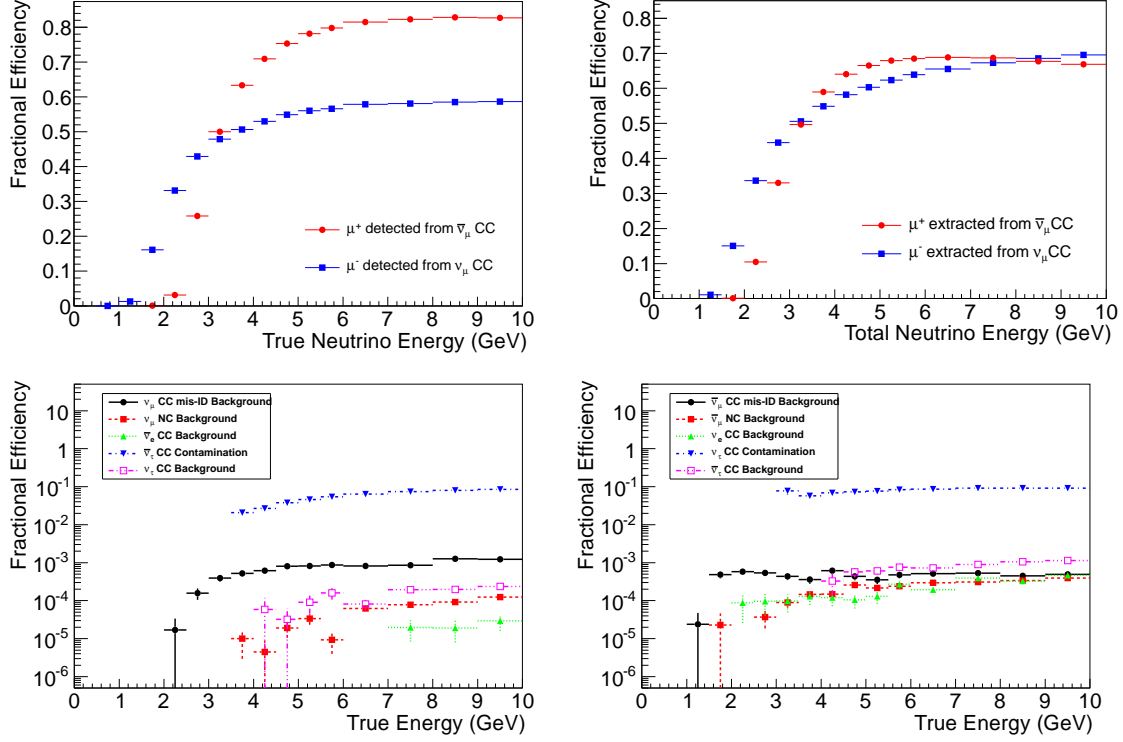


**Figure 4:** Left: Schematic drawing of MIND.

#### 3.2 MIND Simulation, Reconstruction and Analysis

The GENIE neutrino event generator [24] was used to create neutrino interactions in MIND, which was simulated using the GEANT4 package [25]. The simulation includes a wide range of neutrino interactions, including deep inelastic scattering, quasi-elastic scattering, and pion production channels. Muon tracks resulting from the neutrino interaction events were identified and fit using a Kalman filter supplied using the RecPack software package [26]. A selection process is applied to the output of the Kalman fit using a number of criteria, such as the quality of the reconstructed track, the number of hits used in the analysis, the mean energy deposition, the variation in the energy of the track and the transverse energy of the muon. These criteria are input into a multi-variate analysis using the TMVA package [27]. A Boosted Decision Tree algorithm that maximises the variable  $S/\sqrt{S+B}$  was shown to be the most effective at selecting the signal ( $S$ ) over the background ( $B$ ), under both  $\mu^+$  and  $\mu^-$  focussing for MIND. The signal efficiencies for a  $\mu^+$

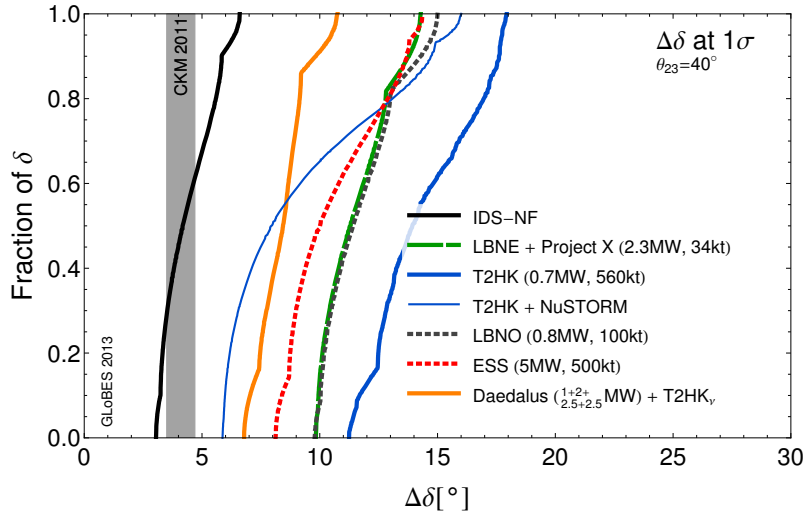
from  $\bar{\nu}_\mu$  charged current (CC) interactions and a  $\mu^-$  from  $\nu_\mu$  CC interactions, with  $\mu^+$  focussing in the detector, are shown in Figure 5 (top, left) and for  $\mu^-$  focussing are shown in Figure 5 (top, right). The neutrino oscillation backgrounds for stored  $\mu^-$  and  $\mu^+$  beams, with a  $\mu^+$  focussing detector, are shown in Figure 5 (bottom left) and 5 (bottom right), and are all below  $10^{-3}$  (similar results are obtained for a detector that focusses  $\mu^-$ ), except for the  $\nu_\tau$  oscillation signals, which are  $\sim 2\%$ .



**Figure 5:** Top left: Charged current detection efficiency as a function of neutrino energy for a detector that focusses  $\mu^+$ . Top right: Charged current detection efficiency as a function of neutrino energy for a detector that focusses  $\mu^-$ . Bottom left: Fraction of background events left for a stored  $\mu^-$  beam with a detector that focusses  $\mu^+$ . Bottom right: Fraction of background events left for a stored  $\mu^+$  beam with a detector that focusses  $\mu^+$ .

#### 4. Neutrino Factory Performance

Analyses of the performance of MIND at a Neutrino Factory have been carried out previously [21, 22, 28]. In this paper we show the sensitivity calculated with the GLOBES package [29] to perform the neutrino oscillation fits, for the multi-variate analysis described above. The accuracy achieved in the measurement of  $\delta_{CP}$  for  $\theta_{13} = 9^\circ$  for a 100 kt MIND detector exposed to a neutrino beam resulting from  $5 \times 10^{21}$  muon decays of both charges is shown in Figure 6. Both  $\mu^+$  and  $\mu^-$  focussing detector fields are considered, assuming the anticipated systematic uncertainty of 1% in the signal and 20% in the background [28, 30]. The Neutrino Factory outperforms all other facilities, with an accuracy in  $\Delta\delta_{CP}$  between  $4^\circ$  and  $5^\circ$  and a  $\delta_{CP}$  coverage between 85% and 90%.



**Figure 6:** Expected precision for a measurement of the CP violating phase at a Neutrino Factory compared to alternate neutrino oscillation facilities as a function of the fraction of possible values of  $\delta$  for which a given precision can be reached at  $1\sigma$ .

## 5. Conclusion

The International Design Study for a Neutrino Factory (IDS-NF) will deliver the Reference Design Report in 2015. The present baseline design was re-evaluated to take into account the recent measurements of  $\theta_{13}$ . The optimum performance of a Neutrino Factory delivers  $10^{21}$  muon decays per year from a 10 GeV stored muon beam, with a 100 kton Magnetised Iron Neutrino Detector (MIND) at a distance of  $\sim 2000$  km from the source. The full design of the facility has been achieved, including all the accelerator and detector systems and their performance. The accuracy in the value of  $\delta_{CP}$ , between  $4^\circ$  and  $5^\circ$ , and the  $\delta_{CP}$  coverage between 85% and 90% that a Neutrino Factory can achieve are unrivalled by any other possible future facilities.

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