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Neutrino oscillation physics with a Neutrino Factory

F.J.P. Soler∗†
School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, UK.
E-mail: paul.soler@glasgow.ac.uk

We illustrate that the baseline Neutrino Factory configuration being developed within the International Design Study for the Neutrino Factory (the IDS-NF) is optimized for standard oscillation-physics measurements and for searches for new physics. For small values of θ_{13} ($\sin^2 2\theta_{13} < 10^{-2}$) a Neutrino Factory with two storage rings in which 25 GeV muons decay, pointing to two neutrino detectors, one situated at a distance between 2500 to 5000 km, the second between 7000 and 8000 km is optimal. If the value of θ_{13} is found to be large ($\sin^2 2\theta_{13} > 10^{-2}$), a Neutrino Factory in which 10 GeV muons are stored in a single ring provides the best sensitivity for the discovery of CP violation in the neutrino sector, the determination of the neutrino mass hierarchy and the measurement of θ_{13}.

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∗Speaker.
†On behalf of the IDS-NF Collaboration.

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1. Introduction

The Neutrino Factory is a new type of accelerator facility in which a neutrino beam is created from the decay of muons in flight in a storage ring. The expected absolute flux and spectrum of neutrinos can be calculated with smaller systematic errors than at alternate facilities. Neutrino oscillations can be studied from the decay of both μ^+ and μ^- thereby improving sensitivity to CP violation. Neutrino oscillations in matter can be extracted from the appearance of ν_μ in far detectors (the golden channel) [1]:

$$P_{\nu_e\nu_\mu(\overline{\nu}_e\overline{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\mp}\right)^2 \sin\left(\frac{B_\mp L}{2}\right) + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right) \quad (1.1)$$

$$+J\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_\mp}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{B_\mp L}{2}\right)\cos\left(\pm\delta_{CP} - \frac{\Delta_{13}L}{2}\right) \quad (1.2)$$

where $\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}$, $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$, $J \equiv c_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$ is the Jarlskog determinant and $B_\mp \equiv |A \mp \Delta_{13}|$, with $A = \sqrt{2}G_F n_e$ the matter parameter and n_e the electron number density. When $\frac{AL}{2} = \pi$ (named the magic baseline), in which $L \approx 7500$ km assuming the density of the earth, a clean determination of θ_{13} can be extracted.

Global fits to neutrino oscillation results provide accurate values of θ_{12}, θ_{23}, Δm_{12}^2 and Δm_{31}^2 [2]. More recently, there have been hints that θ_{13} is non-zero [3, 4], which combined with a reappraisal of reactor neutrino fluxes, provides tantalising evidence at the 3σ level that θ_{13} is large: $\sin^2\theta_{13} = 0.021 \pm 0.007$ [5]. However, this evidence needs to be confirmed in the next generation of neutrino experiments. The discovery of CP violation and the origin of symmetries in the neutrino sector are crucial in elucidating the origin of the baryon asymmetry of the universe and the physics of flavour. Experimentally, this can be achieved by determining the neutrino mass hierarchy (the sign of Δm_{31}^2), whether $\theta_{23} = \pi/4$ or whether it is below or above $\pi/4$ and determining whether the CP violating phase δ_{CP} is different from zero.

The goals of the International Design Study for a Neutrino Factory (IDS-NF) are to provide a Reference Design Report (RDR) for a Neutrino Factory and associated detectors by 2013. The specification of each of the accelerator, diagnostic and detector systems that make up the facility, their schedule and cost, and the physics performance of the Neutrino Factory will be delivered in the RDR. An Interim Design Report (IDR) [6] was recently published, co-sponsored by the MAP programme in the USA [7] and the EUROnu programme in Europe [8]

2. Neutrino Factory Accelerator and Detector Baseline

The Neutrino Factory baseline was described in the IDR [6]. A schematic of the accelerator facility can be found in Figure 1, and is described in [9] in these proceedings. The detector baseline consists of two Magnetised Iron Neutrino Detectors (MIND). One detector of 100 kton is at a distance between 2500 and 5000 km, and the other of 50 kton is between 7000 and 8000 km. The appearance of “wrong-sign" muons is the main signature for the ν_μ appearance “golden channel". MIND consists of large octagonal iron plates of dimensions 14 m $\times$ 14 m $\times$ 3 cm, followed by two planes of scintillator bars each 1 cm thick (see Figure 2), with a toroidal magnetic field between 1.0 and 2.2 T (see [10] in these proceedings for further details).

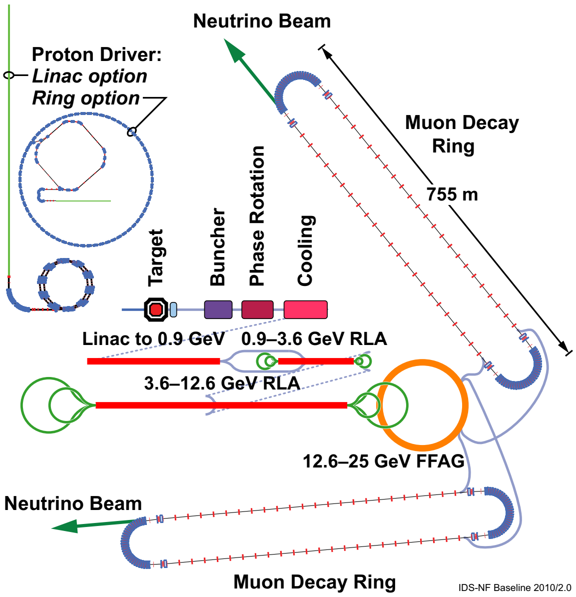

Figure 1: Schematic drawing of the IDS-NF accelerator complex.

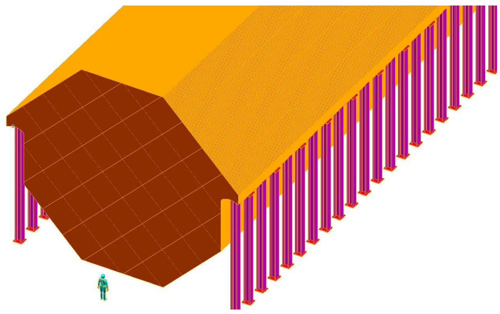

Figure 2: Schematic drawing of MIND.

3. Neutrino Factory Performance

A simplified detector was used for the simulation and analysis. This detector used a square cross section 15 m $\times$ 15 m immersed in a uniform dipole magnetic field of 1 T oriented in the positive y direction. The event generators NUANCE and LEPTO were used in combination with GEANT4 to simulate the neutrino deep inelastic, quasi-elastic and pion production interactions. Events were reconstructred by a Kalman filter and a comprehensive analysis to select the oscillation signal, while eliminating the overwhelming background, was achieved (see references [6, 10, 11] for further details).

At large values of θ_{13} ($\sin^2 2\theta_{13} > 10^{-2}$) the Neutrino Factory is optimum when the muon energy is 10 GeV, and for a single baseline with one 100 kton MIND at a distance of 2000 km (Figure 3 and MIND LE in Figure 4). The Neutrino Factory with two baselines and 25 GeV (IDS-NF 2.0 in Figure 4) is optimal for $\sin^2 2\theta_{13} < 10^{-2}$. These results are compared with other possible facilities, such as LBNE, with and without Project X, the CERN SPL with the MEMPHYS detector in Fréjus, a Beta Beam with $\gamma = 100$ and MEMPHYS (BB100), a combination of Beta beam and SPL and not building new facilities beyond T2K and NOvA (2025). The Neutrino Factory outperforms all other facilities for all values of θ_{13}.

4. Conclusions

The International Design Study for a Neutrino Factory published its Interim Design Report in March 2011. The IDS-NF is on target to produce a Reference Design Report, including performance and costs, by 2013. The main concepts for the accelerator systems and the detectors have been defined, the performance has been optimised for both small and large values of θ_{13}. The Neutrino Factory outperforms all other facilities in CP discovery coverage.

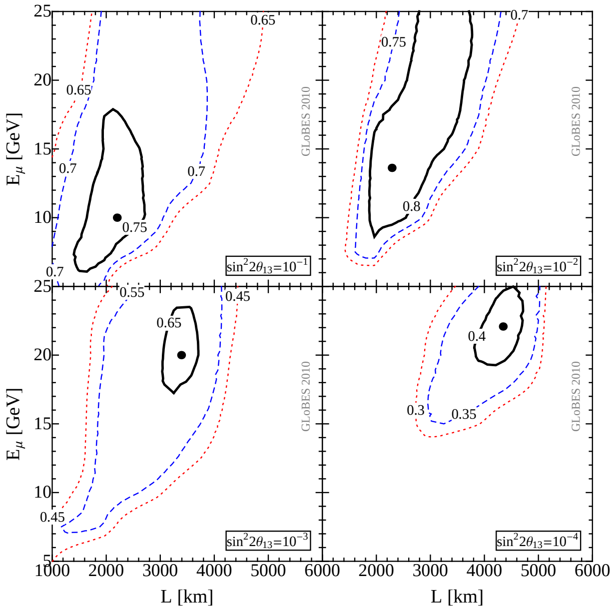

Figure 3: Fraction of δ_{CP} for which CP violations will be discovered (3σ CL) as a function of distance L(km) and muon energy for the single baseline Neutrino Factory.

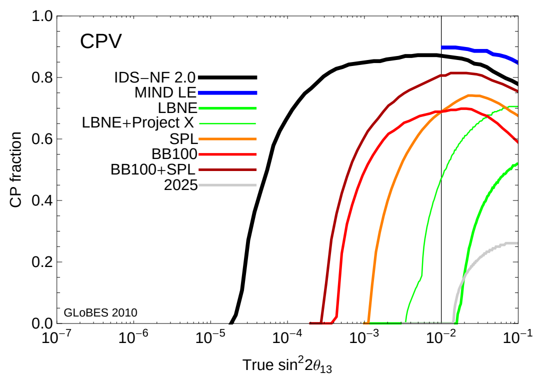

Figure 4: Performance of future neutrino facilities for CP violation.

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