Status of a MIND type Neutrino Factory Far Detector

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Abstract. A realistic simulation and analysis of a Magnetized Iron Neutrino Detector (MIND) has been developed for the purpose of understanding the potential sensitivity of such a facility. The status of the MIND simulation and reconstruction as discussed in the interim design report is reviewed here. Priorities for producing a more realistic simulation for a reference design report will be discussed, as will be the steps that have already been taken towards an improved simulation.

1. Introduction

A magnetized iron neutrino detector (MIND) has been proposed as a far detector for a neutrino factory[1]. The detector has a high mass with a simple method of producing a magnetic field for the purpose of charge identification. The purpose of the far detector, in association with a near detector system, is to measure θ_{13} and δ_{CP} through the measurement of "Golden channel" neutrino oscillations, $\nu_e(\bar{\nu}_e) \rightarrow \nu_\mu(\bar{\nu}_\mu)$ [2]. A MIND detector will measure this by identifying the production of muons with the opposite sign of the neutrino source beam. A realistic simulation of a MIND-type detector is required for the optimization of golden channel measurements at the neutrino factory.

2. Conceptual design of a Neutrino Factory MIND

The proposed MIND is composed of alternating iron and scintillator planes. Each scintillator plane consists of twinned arrays of scintillator bars, 1 cm thick and 3 cm wide, arranged to measure the x and y position of an incident particle. The planes are to be built on an octagonal cross-section, 14 m$\times$14 m, with projections on either side of the iron plates to support the detector.

The stresses and distortions of an iron plane have been studied using a finite element simulation. Because the iron cannot be fabricated in a solid sheet, the iron plates will be constructed of iron strips, 2 m in width and 1.5 cm thick, in two perpendicular layers to provide strength and rigidity. The total thickness of an iron plate is 3 cm. The simulation shows the maximum deformation in any direction is less than 2 mm with vertical deformations on the support projections less than 0.2 mm.

The iron plate provides the magnetic field for the detector using a superconducting transmission line [3] (STL) running along the detector's axis of symmetry as a current source.

An STL can carry the 100 kA required to generate the 1 Tesla average magnetic field within a 7.8 cm diameter contained by a 10 cm bore. The magnetic field inside the iron has been simulated showing field deformations because of the octagonal geometry and the gaps between the iron strips used in the fabrication of the plates, as shown in Fig.1. It is thought that these sudden changes in the field direction and intensity will affect scattering in the muon tracks, which will require study in the full detector simulation.

To extract the required physics, a two baseline experiment using two different MINDs has been proposed. A 100 kTon MIND at a distance of 4000 km in coordination with a 50 kTon MIND at a distance of 7500 km is one example. For a cuboid geometry the detectors must be 125 m and 62.5 meters long, respectively. With 429 scintillator bars per plane, there will be 4.28×10^6 readout channels for the 100 kTon detector and 2.14×10^6 channels for the 50 kTon detector. To achieve the same mass using an octagonal geometry the detectors must be 150 m and 75 m long respectively with a proportional increase in the number of scintillator channels.

3. Simulation

A simplified detector was used for the simulation detailed in the neutrino factory interim design report (IDR) [1]. This detector used a square cross section and was immersed in a uniform magnetic field oriented in the +y-direction. GEANT 4 [4] was used to provide the material interactions of charged species while a combination of NUANCE [5] and LEPTO [6] were used to generate the neutrino interactions in the detector. The simulation included 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 fitter supplied using the RecPack software package [7]. A selection process is applied to the output that Kalman fit using a number of criteria such as the length of the track, the number of hits used in the analysis, the quality of the reconstructed track, the amount and direction of bending of the track, and the likelihood that the track is the result of a charge current event. The effect of these cuts on sets of μ flavoured neutrino charge current events is shown in Fig.2.

The simulated response of the detector in the 25 GeV/c μ beam is used to synthesise a sensitivity of the detector to the measurement of $\sin^2 2\theta_{13}$ and δ_{CP}. The fluxes and oscillation probabilities at a far detector based on the initial beam state was calculated using the Neutrino Tool Suite (NuTS) [8]. For the purpose of this study 2.5×10^{20} μ^+ and μ^- decays are assumed to occur in the storage ring per year as the true relative muon yields are not known and changes

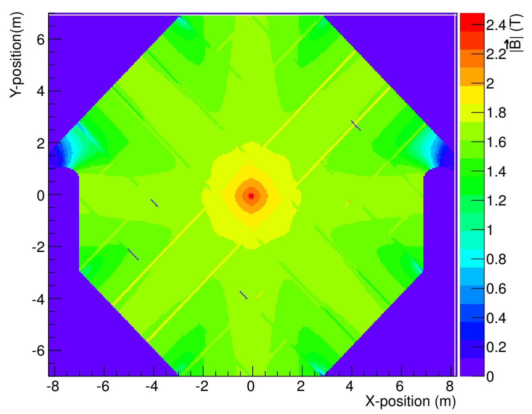

Figure 1. Magnetic field map simulated in the realistic geometry of the iron plate.

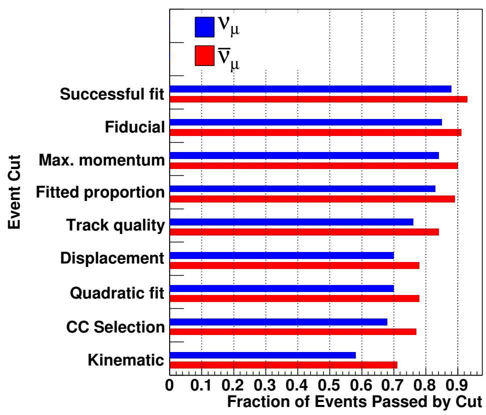

Figure 2. Fraction of events left after the application of the listed cuts applied to isolate charge current events.

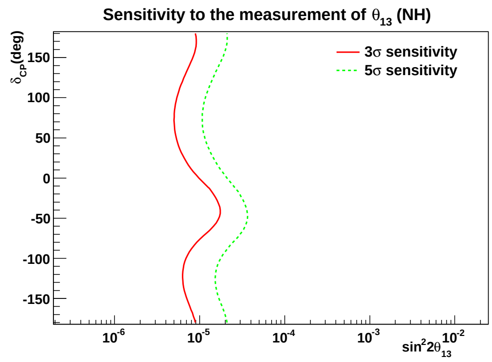

Figure 3. Sensitivity of the neutrino factory to measurement of $\sin^2 2\theta_{13}$ for given the shown values of δ_{CP}.

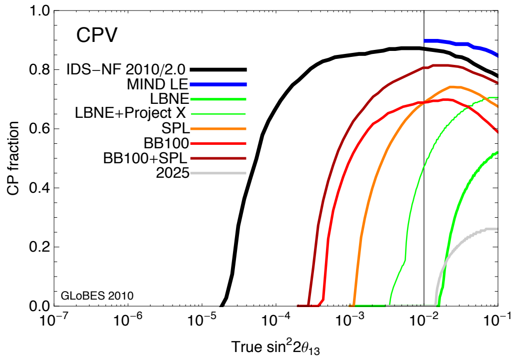

Figure 4. Sensitivity of the neutrino factory to measurement of δ_{CP} given the shown values of $\sin^2 2\theta_{13}$.

in the relative yields do not change the physics results. Assuming a two detector experiment described above, both $\sin^2 2\theta_{13}$ and δ_{CP} are fit simultaneously by minimizing

$$\chi^2 = \sum_j \left\{ 2 \times \sum_e^{E_\mu} \left(A_j x_j N^e_{+,j}(\theta_{13}, \delta_{CP}) - n^e_{+,j} + n^e_{+,j} \log \left(\frac{n^e_{+,j}}{A_j x_j N^e_{+,j}(\theta_{13}, \delta_{CP})} \right) \right. \right.$$
$$\left. \left. + A_j N^e_{-,j}(\theta_{13}, \delta_{CP}) - n^e_{-,j} + n^e_{-,j} \log \left(\frac{n^e_{-,j}}{A_j N^e_{-,j}(\theta_{13}, \delta_{CP})} \right) \right) + \frac{(A_j - 1)^2}{\sigma_A} + \frac{(x_j - 1)^2}{\sigma_x} \right\} \quad (1)$$

where $n^e_{i,j}$ is the "data" for an energy bin e and detector baseline $j \in \{4000, 7500\}$ for μ signals with charge, i, and $N^e_{i,j}$ is the prediction for the same bin. Two systematic uncertainties are explicitly included in the fit. An uncertainty in the number of interactions, A_j, was assessed as $\sigma_A = 0.05$ owing to errors in the fiducial mass of the detectors. The known differences in interactions between neutrinos and anti-neutrinos, x_j, are limited by near detector measurements as $\sigma_x = 0.01$.

The sensitivity of these experiments to θ_{13} was defined as the set of points in $(\theta_{13}, \delta_{CP})$ where, $\chi^2(\theta_{13} = 0) - \chi^2_{min} \geq n^2$. The bands of sensitivity to $\sin^2 2\theta_{13}$ corresponding to $n = 3$ and $n = 5$ are shown in Fig. 3. The fraction of δ_{CP} accessible to a MIND detector at a neutrino factory compared to other experiments, as calculated from GLoBES [9], is shown in Fig. 4.

4. Toward a realistic simulation

The IDR MIND simulation does not represent the intended final geometry, so it is imperative to move to a more realistic model using an octagonal cross-section and corresponding magnetic field. This work has begun and requires the optimization of the analysis to this new geometry. A hadronic reconstruction for the MIND analysis is planned as is the introduction of the muon momentum reconstruction using the muon range. A major systematic study of the background introduced by cosmic rays is planned which will have an impact on choosing the detector site, specifically the depth required to achieve the experimental goals.

The first step towards a realistic simulation has been to use GENIE [10] to sample the neutrino interactions. It is believed that the parton distributions used in GENIE are more realistic than those used in LEPTO because the inelasticity distribution resulting from ν interactions in GENIE as shown in Fig 6 is more flat than the distribution from LEPTO.

5. An Alternative Neutrino Factory Far Detector

A totally active scintillating detector has also been proposed as a far detector for a neutrino factory. This detector would be constructed entirely of scintillator bars, with a square overall

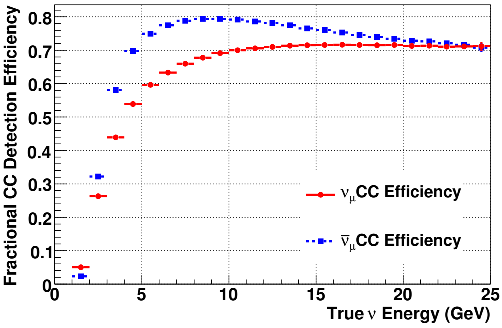

Figure 5. Charge current detection efficiency as a function of neutrino energy using a GENIE neutrino generator.

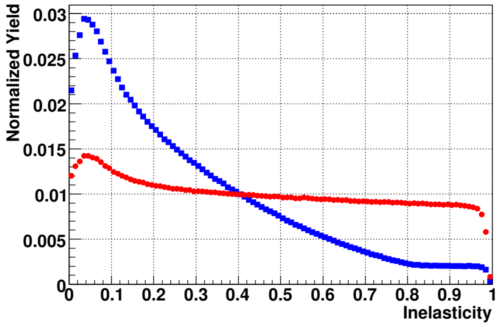

Figure 6. Inelasticity of neutrino interaction events generated using the GENIE neutrino generator.

detector cross-section, 15 m×15 m, and 150 m long. A simulation of a TASD has been produced by Malcolm Ellis for the purpose of studying its response parallel to the MIND simulations.

The benefit of using such a detector is a sensitivity to lower energies than a MIND allowing an effective reconstruction of electron showers generated by $\nu_e(\bar{\nu}_e)$ and neutral current $\nu_\mu(\bar{\nu}_\mu)$ interactions. Thus it can also measure $\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)$, platinum channel, oscillations in addition to the golden channel oscillations accessible to a MIND.

The challenge with such a detector is that the magnetic field must be generated for charge identification outside of the detector. The magnetic cavern proposed for this purpose is a technical problem as it is as yet unclear whether the superconducting transmission line[3], again proposed to carry current for the magnetic field generation, can operate when bent into a 7 m radius coil. MIND is still the leading candidate for this reason.

6. Conclusion

These proceedings have reviewed the status of a proposed far detector for the neutrino factory. A great deal of work has been done on the engineering of the detector for the publication of the IDR including structural simulation and field simulation of a realistic design. An interim simulation has demonstrated the feasibility and sensitivity of a MIND type detector using a cuboid geometry and a dipole field. This simulation has shown very high efficiency and good background suppression leading to a sensitivity to θ_{13} and CP violation that surpasses all of the proposed next generation neutrino facilities. The new MIND simulation, currently in progress, uses a more realistic assumptions, with the proposed specifications of the realistic design. The reconstruction and analysis of the simulation output requires optimization for this new detector and magnetic field geometry. It is expected that the results of the full realistic simulation will come within this year.

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