Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B Proceedings Supplement 00 (2010) 1–8

Nuclear Physics B Proceedings Supplement

Steps towards the Neutrino Factory

K.Long

High Energy Physics Group, Department of Physics, Imperial College London, Exhibition Road, London SW7 2AZ.

Abstract

The properties of the neutrino provide a unique window on physics beyond that described by the Standard Model. The study of sub-leading effects in neutrino oscillations has begun with the race to measure θ_{13}. A consensus is emerging within the international community that a novel neutrino source is required to allow sensitive searches for leptonic CP violation to be carried out and the neutrino mass-hierarchy to be determined. The Neutrino Factory, in which intense neutrino beams are produced from the decay of muons, has been shown to out-perform the other proposed facilities. The physics case for the Neutrino Factory will be reviewed and the baseline design of the facility being developed by the International Design Study for the Neutrino Factory (the IDS-NF) collaboration will be described.

Keywords: Neutrino Factory, neutrino oscillations, IDS-NF, EUROnu

---

1. Introduction

The phenomenon of neutrino oscillations is now established (for a review see [1]). The bulk of the data to date has been collected using the dominant, 'disappearance' channels $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$. The next generation of long-baseline experiments seek to discover the existence of sub-leading $\nu_\mu \to \nu_e$ oscillations while the next generation of reactor experiments seek to find evidence for the sub-leading transitions through the disappearance of $\bar{\nu}_e$. Such a discovery would be exciting indeed since it would herald the next phase in the study of neutrino oscillations: the search for CP violation.

Neutrino oscillations are readily described by postulating the existence of three neutrino-mass eigenstates, the flavour eigenstates being obtained by taking appropriately weighted combinations of the mass eigenstates. The rotation of the mass basis into the flavour basis results in the introduction of three mixing angles (θ_{12}, θ_{23}, and θ_{13}) and one phase parameter (δ) [2]. If δ is non-zero, then CP violation will occur via the neutrino mixing matrix. Measurements of neutrino oscillations may be used to determine the mass-squared differences $\Delta m^2_{31} = m^2_3 - m^2_1$ and $\Delta m^2_{21} = m^2_2 - m^2_1$. The status of the determination of mixing angles and mass-squared differences is discussed elsewhere in these proceedings. The sign of Δm^2_{31} is unknown and determines the neutrino mass hierarchy; the 'normal hierarchy' refers to the case in which the mass eigenstate ν_3 is heavier than the other two neutrinos while in the 'inverted hierarchy', ν_3 is lighter than the other two. The CP-violating phase, δ, is at present unconstrained.

Over the coming five or six years, the T2K, NOvA, Double Chooz, Daya Bay, and RENO experiments (each discussed elsewhere in these proceedings) will exploit the sub-leading, $\nu_\mu \to \nu_e$ and $\bar{\nu}_e \to \bar{\nu}_x$ channels to improve significantly the precision with which θ_{13} is known. Detailed, and precise, measurements of neutrino oscillations are required to elucidate the 'physics of flavour' that gives rise to neutrino oscillations. Unless the value of θ_{13} is found close to the present upper bound, a novel technique to produce high energy ν_e beams of extremely high flux is required. The Neutrino Factory [3], in which intense, high-energy ν_e and $\bar{\nu}_\mu$ (ν_μ and $\bar{\nu}_e$) beams are produced from the decay of muons confined within a storage ring, is able to provide the requisite beams.

2. The Neutrino factory; the facility of choice

The improvement in the sensitivity of the next generation of experiments to $\sin^2\theta_{13} \neq 0$ is expected to plateau by around 2016 [4]. This sets the timescale on which the high-precision, high-sensitivity programme must be brought forward. The sensitivity of super-beam experiments is limited by the presence of an irreducible electron-neutrino contamination in the muon-neutrino beam. In reference [4] the evolution of the sensitivity of super-beam experiments has been evaluated. Taking into account planned upgrades at J-PARC and FNAL and using plausible running assumptions, more than 70% of the parameter space remains uncovered even if the programme is taken to extend to 2025. Furthermore, the programme has no sensitivity to δ for values of $\sin^2 2\theta_{13}$ below ~ 0.02. The risk of pursuing the super-beam approach on its own is, therefore, that the technique lacks the requisite discovery-sensitivity and a novel facility will be required.

By providing intense ν_e beams, it would be possible to study the sub-leading $\nu_e \rightarrow \nu_\mu$ oscillation, evading the sensitivity limit of super-beams. Sensitivity to the mass hierarchy increases as the distance the neutrino beam propagates through the earth increases. The best sensitivity to CP violation is also found at large source-detector distances. Large source-detector distances imply a requirement for high neutrino energy, E_ν. In addition, the neutrino beam divergence falls linearly and the neutrino-nucleon (νN) cross section grows linearly as E_ν grows. These considerations indicate that the optimum sensitivity will be achieved with a facility that provides intense, high-energy ν_e and $\bar{\nu}_e$ beams.

Two techniques by which ν_e and $\bar{\nu}_e$ beams can be produced have been proposed: the ‘beta beam’ and the Neutrino Factory. The beta beam exploits the radioactive decay of ions confined within a storage ring to produce pure ν_e ($\bar{\nu}_e$) beams. The neutrino carries only a tiny fraction of the energy of the ion, making it necessary to accelerate the ion to very high energy in order to produce ν_e ($\bar{\nu}_e$) beams of the requisite energy. The small charge-to-mass ratio of the ions makes the rigidity of the ion beams significantly larger than the rigidity of proton or muon beams of the same energy. This implies that the systems required to accelerate and store the ions are of the scale of the SPS at CERN or the Tevatron at FNAL. The high ion-beam energy implies that the ion lifetime suffers considerable time-dilation. Very high ion fluxes are required to overcome the reduction in the neutrino-production rate that this implies.

At source, with muons circulating in the storage ring, the Neutrino Factory beam will contain equal fluxes of ν_e and $\bar{\nu}_\mu$; equal fluxes of $\bar{\nu}_e$ and ν_μ will be produced with μ^- in the storage ring. The muon charge-to-mass ratio is large and the neutrinos carry away a substantial fraction of the energy of the parent muon, so high neutrino energies can readily be achieved. Time-dilation is beneficial, allowing enough muons to survive long enough to circulate many times in the storage ring. Charged-current interactions induced by ‘golden channel’, $\nu_e \rightarrow \nu_\mu$ ($\bar{\nu}_e \rightarrow \bar{\nu}_\mu$), oscillations produce muons of charge opposite to that of the stored muons. A magnetised detector is therefore required to distinguish the golden-channel signal from the background produced by un-oscillated muon-neutrinos.

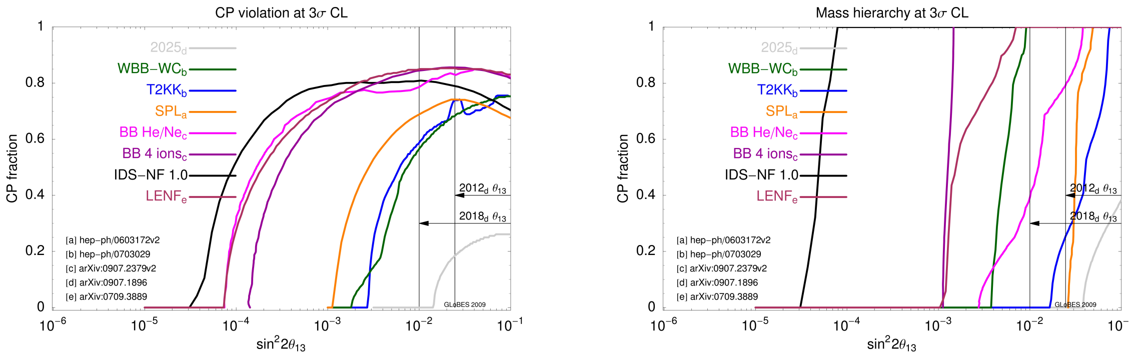

Figure 1: Comparison of the performance of the IDS-NF baseline Neutrino Factory with the proposed super-beam and beta beam facilities. The plots show, as a function of the true value of $\sin^2 2\theta_{13}$, the fraction of all possible values of δ for which δ (left panel) can be distinguished from zero and the mass hierarchy can be determined (right panel) at the 3σ confidence level. The sensitivity of the IDS-NF baseline Neutrino Factory is shown as the solid black line. The meaning of the other lines is shown in the legend. Figures taken from [6].

The performance of the baseline Neutrino Factory being developed by the International Design Study for the Neutrino Factory (IDS-NF) collaboration [5] is compared to the various beta-beam and super-beam alternatives in figure 1 [6]. With 10^{21} muon decays per year at a stored muon energy of 25 GeV serving two detectors sited at a distance of 4 000 km and 7 500 km from the source, the baseline Neutrino Factory significantly out-performs all other options in terms of the discovery reach for the mass hierarchy and θ_{13}. The baseline Neutrino Factory also out-performs the alternatives in the discovery reach for CP violation. The discovery reach of the beta-beam only approaches that of the Neutrino Factory if ion beams of very high energy are used or data taken using each of four ion species are combined. The sensitivities of the various facilities is comparable if θ_{13} is 'large' ($\sin^2 2\theta_{13} \gtrsim 10^{-2}$). In this case, consideration needs to be given to the precision with which the parameters that govern neutrino oscillations can be extracted. Figure 2 shows the excellent precision with which θ_{13}, δ, θ_{23}, and Δm^2_{31} can be measured at the Neutrino Factory [6, 7, 8].

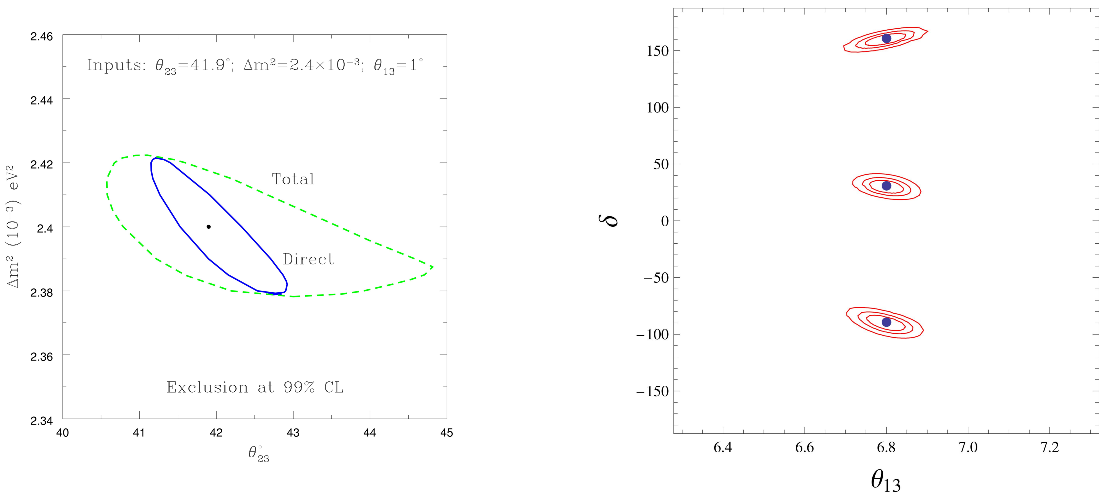

Figure 2: The precision with which the IDS-NF baseline Neutrino Factory can measure δ, θ_{13}, θ_{23}, and Δm^2_{31}. Left panel taken from [7]. Right panel includes data from two detectors at 4 000 km and 7 500 km [8].

The performance of the Neutrino Factory has been considered in detail in [3]. In addition to the excellent precision and outstanding discovery reach, the Neutrino Factory has great sensitivity to non-standard neutrino interactions, in particular to those that result in an anomalous rate of $\tau^{\pm}$ production. These properties make the Neutrino Factory the facility of choice to serve the precision era of neutrino oscillation measurements.

3. The IDS-NF baseline Neutrino Factory

The Neutrino Factory baseline set-up was derived by optimising the stored-muon energy and the distance from the source to two distant detectors (see [3] and references therein). A detector capable of detecting the golden channel with high efficiency, placed at the 'magic baseline', 7 000–8 000 km from the source, has excellent sensitivity to the mass hierarchy and $\sin^2\theta_{13}$. The best sensitivity to CP violation is obtained at a source-detector distance in the range 3 000–5 000 km and requires a stored-muon energy in excess of 20 GeV; a value somewhat larger than that required when optimising the sensitivity to $\sin^2\theta_{13}$ and the mass hierarchy. The sensitivity to non-standard interactions at the Neutrino Factory also improves as the stored-muon energy is increased, reaching a plateau at around $\sim$ 25 GeV [9]. A baseline stored muon energy of 25 GeV has therefore been adopted.

The baseline accelerator facility (see figure 3), a development of that described in [3], provides a total of 10^{21} muon decays per year split between two distant neutrino detectors. The process of creating the muon beam begins with the bombardment of a pion-production target with a 4 MW, pulsed proton beam. The target must be sufficiently heavy to produce pions copiously, yet not so large as to cause a significant rate of interaction of the secondary pions within the target material. In addition, the target must withstand the substantial beam-induced shock. The IDS-NF baseline calls for a free-flowing, liquid-mercury jet operating in a solenoid-focusing, pion-capture channel. A solenoid transport channel, in which the pions decay to muons, follows the capture section. The muon beam that emerges from the decay channel must be manipulated. First, bunching and phase rotation are performed to produce a beam with small energy spread, bunched at 201 MHz. At this point, the muon beam occupies a large volume of phase space which must be reduced, ‘cooled’, before it can be injected into the acceleration sections. The short muon lifetime makes traditional cooling techniques inappropriate. The required phase-space reduction is achieved by means of ionisation cooling in which the muon beam is passed through a material in which it loses energy through ionisation. The energy lost is replaced in accelerating cavities. The IDS-NF baseline calls for lithium hydride absorbers embedded in a solenoidal transport channel with re-acceleration achieved using 201 MHz cavities at a gradient of 16 MV/m. Muon acceleration must be rapid, especially at low muon energy. In the IDS-NF baseline, muons are accelerated to 0.9 GeV in a superconducting linac and then to 12.6 GeV in a sequence of two re-circulating linear accelerators (RLAs). The final stage of acceleration, from 12.6 GeV to the baseline stored-muon energy of 25 GeV, is provided by a fixed field alternating gradient (FFAG) accelerator.

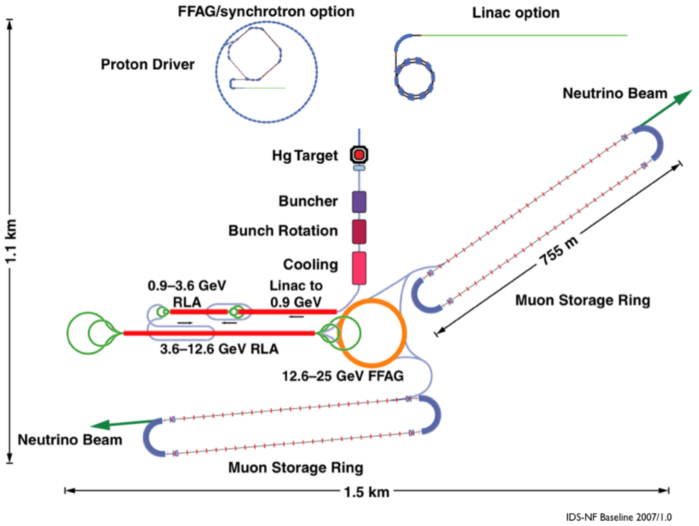

Figure 3: Schematic drawing of the ISS baseline for the Neutrino Factory accelerator complex. The various systems have been drawn to scale. More details can be found in [**?**] and references therein.

The baseline neutrino detector is the Magnetised Iron Neutrino Detector, (MIND). MIND is an iron-scintillator sandwich calorimeter similar in concept to MINOS, but with a sampling fraction optimised for the Neutrino Factory beam [10]. A detector of fiducial mass of 100 kT will be placed at the intermediate baseline. At the magic baseline, a fiducial mass of 50 kT is sufficient. Figure 4 shows that the performance of MIND is sufficient to resolve the principal features of the oscillation pattern [11]. The performance of the baseline setup is documented in [6, 10].

4. Neutrino Factory R&D summary

4.1. The accelerator facility

The IDS-NF is considering two, generic, options for the proton driver. One, based on a superconducting linac, could be implemented by suitable development of the Superconducting Proton Linac (SPL) proposed at CERN or the Project-X linac proposed at FNAL. The second option, based on Rapid Cycling Synchrotrons (RCS) or a novel non-scaling FFAG, could be implemented by upgrading the proton infrastructure at the J-PARC facility or the ISIS accelerator at RAL.

Accumulator and compressor rings are required in the case of the linac option. A suitable isochronous accumulator ring design has been developed [12]. Two bunch compression schemes, exploiting either superconducting or normal magnets, have been studied taking space-charge forces into account. These studies indicate that the required bunch structure can be delivered. An initial study of a scheme by which the ISIS proton accelerator could be upgraded to provide a MW-class, pulsed spallation-neutron source and a proton driver for the Neutrino Factory has been carried

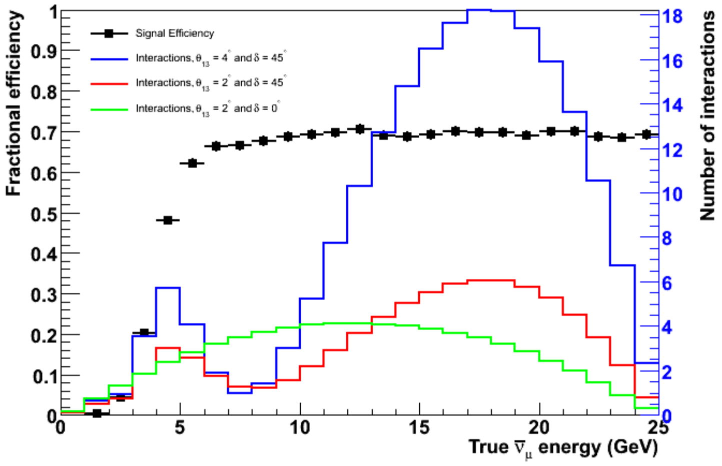

Figure 4: The efficiency of the MIND detector outlined in the text (solid squares) as a function of the true energy of the incident $\bar{\nu}_\mu$. The various solid lines show the number of events expected for an exposure of five years for a number of assumptions on the value of δ and θ_{13} [11]. The values of δ and θ_{13} are reported in the legend.

out [13]. By doubling the proton energy used to serve the spallation target, a 4 MW proton beam with appropriate bunch structure could be provided to serve the Neutrino Factory.

The principle of the mercury jet target was tested in the MERIT experiment in which a free-flowing mercury jet target was exposed to the intense proton beam from the CERN PS [14]. The effect of the passage of the beam through the mercury jet was observed in fields of up to 15 T. The results of the MERIT experiment indicate that a mercury-jet target can withstand the conditions that will pertain at the Neutrino Factory. Alternatives to the mercury-jet technology are being studied. The study of shock in solids [15] indicates that a target system in which tungsten bars are exchanged between beam pulses can withstand the beam-induced shock. Work continues to develop a solution to the problem of exchanging the tungsten bars in the confined environment provided by the pion-capture system. As an alternative to mercury, a fluidised tungsten-powder jet system is being developed [16]. Such a system would have the advantage of mitigating the radio-chemical issues related to mercury.

Work on the Neutrino Factory target is now increasingly focused on addressing the engineering challenges that the target station presents. Fluid-dynamics studies of the ‘splash’ caused by the mercury jet striking the mercury pool and the effect of the high-velocity droplets caused by the beam-jet interaction are under study. Studies of the coils in the superconducting pion-capture channel have been carried out and indicate that the large magnetic forces can be accommodated. The energy deposited in the super-conducting coils by particles produced in the beam-jet interaction has been estimated. The baseline design is being revised to accommodate the beam-induced heat load.

Pions produced in the target are focused using a series of solenoids in which the magnetic field is reduced from 20 T at the interaction point to 1.5 T at the exit of the pion capture section. The pions then enter a $\sim$ 100 m long transport channel in which the pions decay to muons and in which a strong energy-time correlation develops. The energy-time correlation is exploited in the bunching and phase rotation systems in which a sequence of RF cavities is used to produce a $\sim$ 220 MeV/c beam bunched at 201 MHz with an energy spread of $\sim$ 10%. The muons then enter the ionisation-cooling channel in which the transverse emittance is reduced in a series of lithium-hydride absorbers interspersed with 201 MHz cavities and superconducting solenoids. The international Muon Ionisation Cooling Experiment (MICE) collaboration is preparing an engineering demonstration of ionisation cooling [17]. A muon beam has been prepared on the ISIS proton synchrotron at the Rutherford Appleton Laboratory. MICE has successfully completed its first data-taking period; the data taken, which are presently being analysed, indicate that the MICE Muon Beam is able to deliver the beams required by the experiment [18, 19]. The collaboration is now moving on to construct the muon spectrometers and the MICE cooling channel.

The combination of systems, pion capture, transport channel, buncher, phase rotator, and cooling channel make up the ‘muon front-end’. The principal issue for the muon front-end in general, and for the cooling channel in particular, is the breakdown potential of high-gradient RF cavities in the presence of a magnetic field. Results from the MuCool collaboration's measurements on an 805 MHz cavity indicate that the maximum gradient falls by as much as a factor of 2 as the magnetic field is increased from 0 T to $\sim$ 1.6 T [20]. The IDS-NF baseline calls for an accelerating gradient of 16 MV/m from a 201 MHz cavity exposed to a field of $\sim$ 2 T. The MuCool 201 MHz cavity has achieved a gradient of 21 MV/m in the absence of a magnetic field; a substantial achievement. It is planned to expose the cavity to a high magnetic field in the coming year. In the light of the uncertainties over the stable operating gradient of the cavities in the cooling channel, the IDS-NF front-end team has studied alternative lattice configurations as well as active and passive magnetic-field screening schemes [21]. Such studies are important to 'manage the risk' that breakdown in magnetic field will limit the maximum operating gradient of cavities in the muon front end. The studies also clearly demonstrate the pressing need to expedite the MuCool and MICE R&D programmes.

The short muon lifetime implies that the energy must be raised rapidly so that the time-dilated lifetime is sufficient to allow enough muons to be transported to the storage ring. For this reason, the muon beam energy is raised in a series of linear accelerators to 12.6 GeV at which point it is injected into a non-scaling FFAG. In the first stage, the muon energy is raised to 0.9 GeV in a linac. Acceleration to 3.6 GeV is provided by a dog-bone recirculating linear accelerator (RLA); a second RLA takes the beam to 12.6 GeV. The linac and RLAs exploit niobium-on-copper (NbCu), superconducting RF cavities and superconducting solenoids. The study of the beam dynamics in the linac and RLA sections of the muon acceleration system now includes error-tolerance analysis and a novel 'graded focusing scheme' has been developed [22]. An initial design has been prepared for the cryo-modules that contain the superconducting cavities and superconducting solenoids.

The final stage of acceleration from 12.6 GeV to 25 GeV will be carried out in a non-scaling fixed field alternating gradient (FFAG) accelerator [23]. The baseline lattice for the FFAG consists of triplets of focusing and defocusing magnets. The individual magnets are straight-axis, combined-function superconducting magnets. There will be 48, two-cell, 201 MHz superconducting cavities with a maximum energy gain of 25.5 MV. Schemes for injection and extraction at opposite sides of the ring are under development [24]. The proof of the principle of muon acceleration in a non-scaling FFAG will be provided by the EMMA ('Electron Model of Muon Acceleration', aka 'Electron Model of Many Applications') accelerator which is being commissioned at the Daresbury Laboratory [25]. To date, electron bunches injected into EMMA have been transported around the ring successfully for many turns. The RF system is being commissioned; it is anticipated that acceleration in the FFAG will be demonstrated in the near future. The detailed study of the performance of EMMA will allow the Neutrino Factory muon FFAG to be optimised.

Detailed tracking studies of the Neutrino Factory storage ring are being carried out. These studies include the simulation of decay losses and particle tracking in realistic fields. To date these studies have been used to design the chromaticity correction required in the arcs and to demonstrate that the dynamic aperture of the ring is sufficient [26]. The need for the storage ring to include RF to maintain the inter-bunch separation is also being investigated. The storage ring design must include instrumentation by which the flux, divergence, and energy of the neutrino beam can be determined. The tracking studies are now being used to evaluate alternative designs for the instrumentation.

4.2. The neutrino detectors

The Magnetised Iron Neutrino Detector (MIND) that is the baseline for neutrino detection at the intermediate and 'magic' source-detector distances (baselines) is composed of interleaved iron and scintillator plates. The cross-sectional area of the plates is 15×15 m^2 and, at the time of the Neutrino 2010 conference, the iron and scintillator thicknesses were taken to be 4 cm and 1 cm respectively. The detector is assumed to be immersed in a 1 T dipole field; the field axis assumed to be perpendicular to the axis of the detector. The performance of the detector has been studied using LEPTO [27] to generate νN deep inelastic scattering (DIS) events and Geant3 [28] to simulate the performance of the detector [10]. The simulation characterised the response of the detector in terms of two-dimensional hits ('voxels'). A pattern recognition algorithm has been developed in which the scattered muon is identified by means of a Kalman-filter based algorithm if the muon track is sufficiently long and a nearest-neighbour ('cellular automaton') algorithm otherwise. The response of the detector to hadrons is parametrised by assuming an energy resolution of $55\%/\sqrt{E_{\rm had}} + 3\%$ and a hadronic-angle resolution of $10.4/\sqrt{E_{\rm had}} + 10.1/E_{\rm had}$, where $E_{\rm had}$ is the energy of the hadron shower.

The efficiency for detecting 'wrong sign' muons from the golden channel was determined using this suite of programmes. The efficiency rises rapidly at an incident neutrino energy of $\sim$ 2 GeV and reaches a plateau of $\sim$ 70% at just over 5 GeV [10]. The analysis was also used to study the background-rejection efficiency. The contamination of the golden-channel sample coming from ν_μ charged current (CC) events was estimated to be $\lesssim 10^{-3}$, the ν_e CC contamination $\lesssim 10^{-5}$ and the neutral current contamination $\lesssim 10^{-4}$. The discovery reach of the IDS-NF facility, including the MIND detector performance outlined above, is shown in figure 1.

Significant progress continues to be made in the analysis of the MIND. The sampling fraction is being re-optimised and the simulation of the νN interaction is being extended to include quasi-elastic and coherent scattering, resonance production and DIS using the NUANCE package [29]. In addition, a full Geant4 [30] simulation of the detector is being developed. This will allow the hadronic shower to be treated in a more realistic manner. The dipole field will also be replaced by a more realistic toroidal magnetic field.

Consideration of the engineering aspects of the construction of a large (100 kT) detector has begun. A hexagonal plate-geometry is under study and the superconducting transmission line, developed for SSC, is being considered to excite the toroidal field. A numerical analysis of the field produced indicates that, while it is possible to excite a field of $\sim$ 1 T, there are significant field inhomogeneities both towards the corners of the hexagon and in the neighbourhood of the welds that join sections of the large hexagonal plates. The field map will be used in the simulation of the MIND in order to refine the performance analysis still further.

The IDS-NF continues to consider detector options such as the liquid-argon time projection chamber and the totally active scintillator detector. These technologies (which are discussed elsewhere in these proceedings) offer the possibility of reconstructing τ mesons and of identifying the scattered electron (positron) produced in charged-current $\nu_e N$ interactions. A substantial benefit might accrue if it were possible, in addition, to measure the charge of the scattered electron (positron).

A suite of near detectors, close to the end of the straight section of the storage ring, is essential both to provide the flux and cross section measurements essential to the neutrino-oscillation analysis and to carry out a rich neutrino-physics programme. For the oscillation physics programme, the near detectors are required to: measure the flux of the neutrino beam by measuring the rate of elastic neutrino-electron scattering; determine the beam-energy distribution and composition to allow the flux to be extrapolated to the distant detector sites; measure the charm-production cross section to allow the contamination of the golden-channel signal arising from muons produced in charm decay to be estimated with precision; and measure the deep inelastic, quasi-elastic, and resonant scattering cross-sections.

The neutrino-physics programme at the near detector includes the precise determination of the Weinberg angle, the measurement of polarised and unpolarised parton distributions, the study of QCD and nuclear effects in νN scattering and many other topics. In particular, the near detector must be capable of searching for new physics, for example by the detection of anomalous rates of τ production.

Two options for the near detector are being considered. The first is based on a high resolution scintillating fibre tracker while the second is based on a transition radiation straw tube tracker. Both of these options will be evaluated to determine their performance.

5. Opportunities and conclusions

The appreciation within the international particle-physics community of the fundamental importance of understanding the properties of the neutrino continues to grow rapidly. The next step in the programme, the determination of θ_{13}, is being pursued energetically. A consensus is emerging that a novel, high intensity, accelerator-based facility is required to make definitive measurements of the parameters that govern neutrino oscillations. The Neutrino Factory is the facility of choice for this programme: it has the best discovery reach; offers the best precision; and, by varying the stored-muon energy, source-detector distance, and perhaps detector technology, it has the flexibility to respond to changes in our understanding of neutrino oscillations and the discovery of entirely new phenomena.

The Neutrino Factory accelerator R&D programme is internationally coordinated, in part through the annual 'NuFact' workshops. The established R&D programme encompasses each of the critical issues in the design of the accelerator complex: the high-power, pion-production target; ionisation cooling (MICE) and RF breakdown in the presence of magnetic field (MuCool); and the rapid acceleration of beams of large emittance (EMMA). This work informs the development of a detailed design for the whole facility within the IDS-NF collaboration. The strength of this collaborative effort is the basis on which the Neutrino Factory project can be taken forward.

The Neutrino Factory, which has a first-rate physics case of its own, is part of a larger muon-physics programme. Intense muon beams of the type required to serve searches for charged-lepton flavour violation in experiments such as

MUSIC [31], COMET [32], Mu2e [33], and PRISM [34] have many technological challenges in common with those presented by the Neutrino Factory. Viewed from the perspective of those who seek to develop the Muon Collider as the multi-TeV lepton-antilepton collider of the future, the construction of the Neutrino Factory is essential to mitigate the substantial technical risks that the Muon Collider presents. The scientific imperative, therefore remains: to make the Neutrino Factory an option for the field.

Acknowledgements

I would like to thank the organisers for giving me the opportunity to make the case for the Neutrino Factory. I gratefully acknowledge the help, advice, and support of my many colleagues within the IDS-NF, EUROnu, and the Neutrino Factory community who have freely discussed their results with me and allowed me to use their material. I acknowledge the financial support of the European Community under the European Commission Framework Programme 7 Design Study: EUROnu, Project Number 212372.

[1] C. Amsler *et al.* (Particle Data Group), Physics Letters **B667**, 1 (2008).
[2] B. Pontecorvo, Sov. Phys. JETP, 6, 429 (1957); B. Pontecorvo, Sov. Phys. JETP, 7, 172–173 (1958); Z. Maki, M. Nakagawa, and S. Sakata, Prog. Theor. Phys., 28, 870 (1962); S.M. Bilenky, S. Pascoli, and S.T. Petcov, Phys. Rev., **D64**, 053010 (2001).
[3] A. Bandyopadhyay *et al.* [ISS Physics Working Group], Rept. Prog. Phys. **72** 106201 (2009); M. Apollonio *et al.* [The ISS Accelerator Working Group], JINST, **4** P07001 (2009); T. Abe *et al.* [ISS Detector Working Group], JINST, **4**, T05001 (2009).
[4] P. Huber, M. Lindner, T. Schwetz and W. Winter, JHEP **0911** (2009) 044 [arXiv:0907.1896 [hep-ph]];
[5] The IDS-NF collaboration WWW site, https://www.ids-nf.org/wiki/FrontPage.
[6] J. Bernabeu *et al.*, arXiv:1005.3146 [hep-ph]; S. Choubey *et al.* [The IDS-NF collaboration], IDS-NF-017, https://www.ids-nf.org/wiki/FrontPage/Documentation?action=AttachFile&do=
get&target=IDS-NF-017-v1.0.pdf"
[7] D. Indumathi and N. Sinha, Phys. Rev. D **80** (2009) 113012 [arXiv:0910.2020 [hep-ph]].
[8] A. Donini, private communication.
[9] J. Kopp, M. Lindner, and T. Ota, Phys. Rev., **D76**, 013001 (2007) [arXiv:hep-ph/0702269].
[10] A. Cervera, A. Laing, J. Martin-Albo, and F.J.P. Soler, [arXiv:1004.0358] (2010).
[11] A. Laing, private communication.
[12] M. Aiba, CERN-AB-2008-060; E. Benedetto, proceedings of the 11th International Workshop on Neutrino Factories, Superbeams and Beta Beams, July 20–25, 2009, Illinois Institute of Technology, Chicago.
[13] J. Pasternak, proceedings of PAC09, Vancouver, BC, Canada" http://appora.fnal.gov/pls/pac09 (2009).
[14] K.T. Kirk *et al*, Proceedings of the Particle Accelerator Conference 2009, PAC09, Vancouver (CA), 4-8 May 2009.
[15] J.R.J. Bennett *et al*, J. Nucl. Mat. **377** 285-289 (2008).
[16] C. J. Densham, O. Caretta, P. Loveridge, T. W. Davies and R. Woods, Proceedings of the Particle Accelerator Conference 2009, PAC09, Vancouver (CA), 4-8 May 2009.
[17] Y. Torun, "MICE overview–status and facility", presented at the 12*th* International Workshop on Neutrino Factories, Superbeams and Beta Beams, October 20–25, 2010, Tata Institute for Fundamental Research, Mumbai. To be published in the proceedings.
[18] Y. Torun, presented at the 12*th* International Workshop on Neutrino Factories, Superbeams and Beta Beams, October 20–25, 2010, Tata Institute for Fundamental Research, Mumbai. To be published in the proceedings.
[19] M. Rayner, presented at the 12*th* International Workshop on Neutrino Factories, Superbeams and Beta Beams, October 20–25, 2010, Tata Institute for Fundamental Research, Mumbai. To be published in the proceedings.
[20] Y. Torun, "RF cavity operation in strong magnetic fields", presented at the 12*th* International Workshop on Neutrino Factories, Superbeams and Beta Beams, October 20–25, 2010, Tata Institute for Fundamental Research, Mumbai. To be published in the proceedings.
[21] A. Alecou *et al*, Proceedings of the International Particle Accelerator Conference 2010, IPAC10, May 2010 Kyoto.
[22] C. Bontoiu, M. Aslaninejad, J.K. Pozimski, Proceedings of the International Particle Accelerator Conference 2010, IPAC10, May 2010 Kyoto.
[23] J.S. Berg and S. Machida, Proceedings of the Particle Accelerator Conference 2009, PAC09, Vancouver (CA), 4-8 May 2009.
[24] J. Pasternak *et al.*, Proceedings of the International Particle Accelerator Conference 2010, IPAC10, May 2010 Kyoto.
[25] R. Barlow *et al.* NIM **A52302** DOI: 10.1016/j.nima.2010.08.109.
[26] M. Apollonio, M. Aslaninejad, J. Pasternak, Proceedings of the Particle Accelerator Conference 2009, PAC09, Vancouver (CA), 4-8 May 2009; M. Apollonio, A. Blondel, D. Kelliher, Proceedings of the International Particle Accelerator Conference 2010, IPAC10, May 2010 Kyoto.
[27] G. Ingelman, A. Edin, J. Rathsman, Comp. Phys. Comm. **101** 108V134(27) (1997). doi:10.1016/S0010-4655(96)00157-9.
[28] Geant 3.21 CERN Program Library.
[29] D. Casper, http://nuint.ps.uci.edu/nuance/files/nuance_nuint01.pdf
[30] http://geant4.cern.ch/
[31] M. Yoshida, AIP Conf. Proc. **1222** (2010) 400.
[32] Y. G. Cui *et al.* [COMET Collaboration], "Conceptual design report for experimental search for lepton flavor violating mu- - e- conversion at sensitivity of 10**(-16) with a slow-extracted bunched proton beam (COMET)," KEK-2009-10.
[33] R. M. Carey *et al.* [Mu2e Collaboration], "Proposal to search for $\mu^- N \to e^- N$ with a single event sensitivity below 10^{-16}", FERMILAB-PROPOSAL-0973.
[34] J. Pasternak *et al.*, Proceedings of 1st International Particle Accelerator Conference: IPAC'10, Kyoto, Japan, 23-28 May 2010, pp WEPE056.