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Status of the International Design Study of the Neutrino Factory

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Abstract. The International Design Study for the Neutrino Factory (the IDS-NF) has been established by the Neutrino Factory community to deliver the Reference Design Report (RDR) for the facility by 2012. The baseline design for the facility, developed from that defined in the International Scoping Study of a future Neutrino Factory and super-beam facility (the ISS), will provide 10^{21} muon decays per year from 25 GeV stored muon beams. The facility will serve two neutrino detectors; one situated at source-detector distance of between 3000–5000 km, the second at 7000–8000 km. The baseline design for the facility will be described and the status of the IDS-NF effort will be summarised.

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INTRODUCTION

The phenomenon of neutrino oscillations has been established through measurements of electron neutrinos produced in the sun (solar neutrinos), neutrinos produced in the bombardment of the upper atmosphere by cosmic rays (atmospheric neutrinos), electron anti-neutrinos produced in nuclear reactors, and using beams of neutrinos produced by particle accelerators [1]. If three neutrino mass eigenstates, ν_1, ν_2, and ν_3 are introduced, the three flavour eigenstates, ν_e, ν_μ, and ν_τ may be written as linear superpositions of the mass eigenstates. Neutrino oscillations may now readily be described as arising from the 'beating' of the mass eigenstates in the propagation of a neutrino produced as an eigenstate of flavour.

The matrix by which the neutrino mass basis is rotated into the neutrino flavour basis is usually parameterised in terms 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 are not sensitive to the neutrino masses themselves, but may be used to determine the mass-squared differences $\Delta m^2_{31} = m^2_3 - m^2_1$ and $\Delta m^2_{21} = m^2_2 - m^2_1$. By fitting the world's oscillation data, it has been possible to determine θ_{23} at the 15% level ($\sin^2\theta_{23} = 0.47^{+0.07}_{-0.06}$), θ_{12} at the 8% level ($\theta_{12} = 0.321^{+0.023}_{-0.022}$), and to place an upper bound of 0.049 on $\sin^2\theta_{13}$ at the 3σ confidence level [3]. Experiments are being carried out specifically to search for and measure θ_{13} if it is greater than a degree or so [4]. The same fit yields a value for $\Delta m^2_{21} = m^2_2 - m^2_1$ of $(7.67^{+0.22}_{-0.21}) \times 10^{-5}$ eV^2 and a value for $\Delta m^2_{31} = m^2_3 - m^2_1$ of either $(+2.49 \pm 0.12) \times 10^{-3}$ eV^2 or $(-2.39 \pm 0.12) \times 10^{-3}$ eV^2 depending on whether ν_3 is assumed to be heavier than, or lighter than, the other two neutrinos. The CP-violating phase, δ, is at present unconstrained.

The challenge to the neutrino community is to measure all the mixing angles as precisely as possible, to determine the sign of Δm^2_{31}, to measure Δm^2_{21} and Δm^2_{31} precisely, and, by measuring δ, to discover leptonic-CP violation if it occurs. The fundamental importance of the search for leptonic-CP violation is self-evident. Precision measurements of the parameters that govern neutrino oscillations are essential if a complete understanding of the nature of the neutrino is to be obtained. The ultimate theory must surely unify the quark and lepton sectors; so, for the experimentalist, the goal must be to measure the neutrino-mixing parameters with an uncertainty that matches the precision with which the quark-mixing parameters are known. Such measurements will either establish the minimal model outlined above or, by establishing parameter sets inconsistent with it, point to the existence of entirely new phenomena.

The Neutrino Factory, in which an intense, high-energy neutrino beam is produced from the decay of stored muon beams, has been proposed to serve a programme of precision measurements of neutrino oscillations [5]. The Neutrino Factory has been shown to outperform second-generation super-beam and beta-beam

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facilities [6]. The International Design Study for the Neutrino Factory (the IDS-NF) [7] has been established to deliver the Reference Design Report (RDR) for the facility, in time for the 2012 decision point identified by the Strategy Session of CERN Council [8]. The RDR will include [9]: the physics performance of the Neutrino Factory and the specification of each of the accelerator, diagnostic, and detector systems; the cost of the facility; and an estimate of the schedule for its implementation. The RDR will also include a discussion of the remaining technical uncertainties and an appropriate uncertainty-mitigation plan. As a step on the way, the IDS-NF collaboration will prepare an Interim Design Report (IDR) in 2010. The IDR marks the point at which the focus of the IDS-NF effort turns to the engineering studies required to deliver the RDR; it documents the baseline for the accelerator complex, the neutrino detectors, and the instrumentation systems.

THE IDS-NF BASELINE

The baseline accelerator facility (see figure 1), a development of that described in [10, 11], provides 5×10^{20} μ^+ and 5×10^{20} μ^- decays per year towards each of the distant neutrino detectors [12]. 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 in the passage of the beam through the material 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 12.5 GeV in a sequence of two re-circulating linear accelerators. The final stage of acceleration, from 12.5 GeV to the baseline stored-muon energy of 25 GeV, is provided by a fixed field alternating gradient (FFAG) accelerator.

The IDS-NF baseline provides for neutrino detectors at each of two source-detector distances. One detector will be placed at a source-detector distance of between 7 000 km and 8 000 km. This very long, 'magic', baseline was chosen because the effect of matter-enhanced oscillations balances the possible effects induced by CP violation (i.e. $\delta \neq 0, \pi$). As a result, oscillation measurements at the magic baseline are extremely sensitive to θ_{13} and are largely unaffected by parameter degeneracies and correlations. The very long baseline also results in excellent sensitivity to the mass hierarchy. The second detector will be placed at a distance of 3 000–5 000 km from the source. This, 'intermediate', baseline has been chosen to optimise the sensitivity to δ.

The baseline neutrino detector is the Magnetised Iron Neutrino Detector, 'MIND'. MIND is a 50 kT iron-scintillator sandwich calorimeter similar to MINOS. The efficiency for detecting 'wrong sign' muons from the 'golden' channel ($\nu_e \to \nu_\mu$) rises rapidly at an incident neutrino energy of ~ 3 GeV. A Magnetised Emulsion Cloud Chamber (MECC) is included at the intermediate baseline for the study of the silver channel ($\nu_e \to \nu_\tau$). ν_τ appearance is valuable in the investigation of non-standard interactions and to demonstrate that the neutrino mixing matrix is unitary. The performance of the baseline setup is documented in [12].

STATUS AND PROGRESS

The work of the IDS-NF is carried out within three working groups: the Physics and Performance Evaluation Group (PPEG) [13]; the Accelerator Working Group [14]; and the Detector Working Group [15]. The following paragraphs contain brief notes on the progress made by each of these groups since NuFact08 [16].

The Physics and Performance Evaluation Group

The work done by contributors to the PPEG are discussed in many of the contributions to these proceedings. Only one, particularly important, example of the work of the PPEG over the past year will be given here. In June 2009, PPEG organised the first 'NuFlavour' workshop [17] at which the theoretical description of neutrino oscillations was discussed. A clear outcome of the meeting was the close relationship between the physics

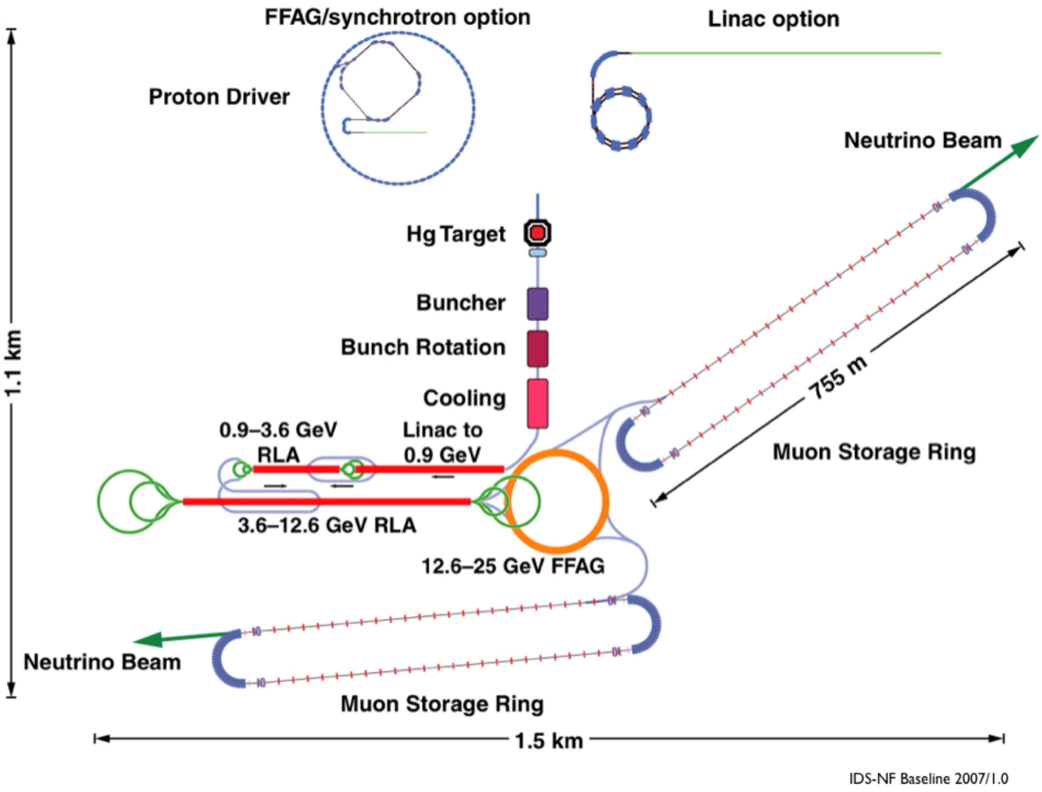

FIGURE 1. Schematic drawing of the ISS baseline for the Neutrino Factory accelerator complex. The various systems have been drawn to scale. More details can be found in [12] from which the figure is reproduced.

of charged-lepton-flavour violation (cLFV) with that of neutrino oscillations. This relationship strongly motivates the articulation of a muon-accelerator based programme that encompasses cLVF experiments such as COMET [18], Mu2e [19], and PRISM [20] and the study of neutrino oscillations at the Neutrino Factory. Such a programme could be carried out in the context of the development of a multi-TeV $\mu^+\mu^-$ collider capable of serving the energy-frontier programme of the future.

The Accelerator Working Group

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 [21]. Two bunch compression schemes, exploiting either superconducting or normal magnets, have been studied taking space-charge forces into account [22]. 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 out [23]. 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. It will be important to ensure that the schemes developed for inclusion in the IDR remain compatible with the infrastructure envisaged for the potential host laboratories.

Work on the Neutrino Factory target is now increasingly focused on addressing the engineering challenges that the target station presents. Studies of the coils in the superconducting pion-capture channel have been carried out and are being reviewed to determine an optimum configuration. Schemes for mitigating the ‘splash’ caused by the mercury jet striking the mercury pool are under investigation. In addition, the effect of the high-velocity droplets caused by the beam-jet interaction are under study. These mercury-handling issues, combined with the need to understand the re-circulation system and details of the mercury nozzle and mercury drain arrangements, are leading to the recognition of the need to build a mercury-target prototype. Progress is also being made in studies of solid target and powder-jet target alternatives.

The baseline muon front-end, and possible alternatives, are discussed elsewhere in these proceedings. The principal issue for the 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 [24]. The IDS-NF baseline calls for an accelerating gradient of 16 MV/m from a 201 MHz 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 [24]. 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 [25]. 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 [24] and MICE [26] R&D programmes.

The study of the linac and RLA sections of the muon acceleration system now includes error-tolerance analysis and the development of a graded focusing scheme [27]. Comparison of the results of simulation with OPTIM and MAD-X is underway. The muon FFAG lattice has been updated to accommodate the injection and extraction systems [28]. In addition, orbit distortions caused by the limited apertures at injection and extraction and chromaticity corrections required to mitigate time-of-flight differences are under study. Schemes have been developed for the injection and extraction sections [29]. In the case of the injection system, reasonable field strengths have been obtained for the kicker and septum magnets using either 6 or 10 kickers. In the case of the extraction system, a 6-kicker scheme has been evaluated in which the extraction septum requires a field of 4 T.

Tracking studies of the storage ring have been carried out using G4beamline [30]. The studies include consideration of chromaticity correction in the arcs and indicate that the dynamic aperture of the ring is sufficient [31]. The G4beamline simulation will now be used to carry out detailed studies of decay losses, particle tracking in realistic fields, and the development of the storage-ring diagnostics. The need for the storage ring to include RF to maintain the inter-bunch separation is also being investigated.

The Detector Working Group

The Detector Working Group has focused on the development of a common software framework in which the neutrino detectors can be studied. So far, the baseline MIND detector has been simulated using the new framework and the reconstruction algorithms have been optimised. A reconstruction efficiency of more than 96% has been achieved for golden-channel events–a substantial improvement over the efficiency of just under 90% reported at NuFact08 [32].

Progress has also been made in evaluating the potential of a Totally Active Scintillator Detector (TASD) as an alternative to MIND [33]. Simulations have shown that an efficiency of $\sim$ 80% for golden-channel events is reached at 0.5 GeV incident neutrino energy, with a plateau in excess of 95% reached at $\sim$ 1.5 GeV. The charge mis-identification rate is below 10^{-4} for neutrino energies greater than 0.5 GeV. More detailed studies, including pattern recognition in a realistic multi-hadron simulation, are now required to demonstrate the performance of the device. These will be performed in the common software framework outlined above.

At present, the IDS-NF baseline does not include a near detector. This serious omission will begin to be addressed at the fourth IDS-NF plenary meeting [34]. The near detector (or the suite of near detectors) is required to contribute to the neutrino oscillation programme by: making a direct measurement of the neutrino flux; measuring the charm production cross section; and making a detailed study of neutrino-nucleon scattering. In addition, the near detector must be capable of exploiting the enormous neutrino flux to carry out a definitive programme of measurements including:

- The measurement of polarised (and unpolarised) structure functions and the determination of α_S;
- The measurement of the Weinberg angle (θ_W);
- The study of charm including, for example, CP violation in $D^0/\overline{D}^0$ mixing and the study of Λ_C production; and
- The search for non-standard interactions, particularly through the search for anomalous rates of τ production.

CHALLENGING THE BASELINE

The IDS-NF baseline was obtained by maximising the discovery reach of the facility at low values of θ_{13}. If θ_{13} should be large enough to be measured in the near future ($\sin^2 2\theta_{13} > 10^{-2}$ or so) then the optimisation of the Neutrino Factory must be revisited. For a given stored-muon energy (E_μ), the oscillation spectrum has a rich structure at low neutrino energies, E_ν. So, if it were to be possible to design a detector with excellent efficiency at $E_\nu \sim 0.5-0.8$ GeV and with excellent energy resolution, then it would be possible to exploit the first and second (perhaps even the third) oscillation maxima. This would open the possibility that a Neutrino Factory with E_μ as low as 4.5 GeV, the Low Energy Neutrino Factory (LENF), could be competitive with the IDS-NF baseline Neutrino Factory, at least in terms of the measurement of the parameters of the standard, three-flavour, description of neutrino oscillations [35]. The LENF may also have advantages as part of a staged implementation of the facility.

The IDS-NF baseline is subjected to a review at each of the IDS-NF plenary meetings. The merits of the LENF, and the IDS-NF collaboration's approach to the LENF as an option, particularly in the case of 'large' θ_{13}, will be debated at the upcoming plenary meeting.

CONCLUSIONS

The search for leptonic CP violation and the ambition to understand the physics of flavour justify an energetic programme of high-precision measurements of neutrino oscillations. The Neutrino Factory, the facility that offers the best discovery reach and the best precision on the various parameters, is required as part of this programme. Indeed, the potential of muon accelerators for particle physics is outstanding, not only providing the tool of choice for the study of neutrino oscillations but also providing a means by which searches for cLFV of exquisite sensitivity can be made as well as a route to the energy frontier in lepton-antilepton collisions. The IDS-NF collaboration has been established to deliver a Reference Design Report for the facility by the 2012 decision point, so making the Neutrino Factory an option for the field.

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