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An international scoping study of a Neutrino Factory and super-beam facility

Executive summary

This document presents a plan for an international scoping study of a future accelerator neutrino complex. The physics case for the facility will be evaluated and options for the accelerator complex and neutrino detection systems will be studied. The principal objective of the study will be to lay the foundations for a full conceptual-design study of the facility. The plan for the scoping study has been prepared in collaboration by the international community that wishes to carry it out; the ECFA/BENE network in Europe, the Japanese NuFact-J collaboration, the US Muon Collider and Neutrino Factory Collaboration and the UK Neutrino Factory collaboration. CCLRC's Rutherford Appleton Laboratory will be the 'host laboratory' for the study. The study will be directed by a Programme Committee advised by a Stakeholders Board. The the international scoping study was launched at NuFact05 in Frascati on the 26th June 2005. The conclusions of the study will be presented at NuFact06 and published in a written report in September 2006.

1. Introduction

1.1 Overview

The recent discovery of neutrino oscillations [1] implies that neutrinos are massive and that the Standard Model is incomplete. These observations may have profound astrophysical consequences; in particular CP violation in the lepton sector may underpin the mechanism by which antimatter was removed from the early universe. The far-reaching implications of neutrino oscillations justify a dedicated experimental programme while the search for leptonic-CP violation requires the development of well-characterised, high-energy neutrino beams of extremely high intensity.

Several neutrino sources have been proposed to serve the high-precision neutrino-oscillation programme. The Neutrino Factory, an intense high-energy neutrino source based on a stored muon beam, gives the best performance over much of the parameter space. Second-generation super-beam experiments may be an attractive option in certain scenarios. Super-beams have most components in common with the Neutrino Factory. A beta-beam, in which electron neutrinos (or anti-neutrinos) are produced from the decay of stored radioactive-ion beams, in combination with a second-generation super-beam, may be competitive with the Neutrino Factory. The scoping study will therefore review the physics reach of the various proposed facilities and make quantitative performance comparisons. These comparisons will be used to define the programme needed to achieve international consensus on the facility or facilities required for an optimal programme of high-precision neutrino-oscillation measurements.

The definition of an optimal programme of neutrino-oscillation measurements requires that the performance, cost and feasibility of the various proposed facilities, including the detector systems, be evaluated. The conceptual design of the beta-beam facility is being developed in the context of the EU Framework-Programme-6 funded EURISOL design study. Therefore, this scoping study will focus on evaluating the various options for the Neutrino Factory accelerator complex and neutrino-detection systems. This evaluation will include consideration of the possibility that a second-generation super-beam is built as a step on the way to the Neutrino Factory. The scoping study will determine desirable values, or ranges of values, for the design parameters that specify the interfaces between the various accelerator sub-systems that make up the facility and define an accelerator-R&D roadmap that will be used as the basis for subsequent conceptual-design work. Similarly, for the neutrino-detection systems, the study will review the detector requirements and the various technological solutions that have been proposed and define the R&D programme required to realise the appropriate devices. Thus, the scoping study will lay the foundations on which a complete conceptual-design proposal can be built.

The work of the study will be organised in three working groups: the Physics and phenomenology working group; the Accelerator working group; and the Detector working group. The overall development of the study will be coordinated through a Programme Committee advised by a Stakeholders Board. The chairman of the Programme Committee will report to the Stakeholders Board. A committee of 'wise men' (Dr. S. Geer, FNAL, Prof. Y. Kuno, Osaka, Prof. V. Palladino, Naples, and Prof. K. Peach, CCLRC) has been appointed by the community to propose the membership of these bodies within the framework presented below. The study will be launched at NuFact05 in Frascati. Three plenary meetings will be held over the course of the year, the conclusions of the study will be discussed at NuFact06 and published in a written report in September 2006.

1.2 Background

The discovery of neutrino oscillations motivates a concentrated effort to develop novel neutrino sources and detectors. The use of muon storage rings to provide intense neutrino beams (the Neutrino Factory) was first proposed in 1998 [2] at about the same time as neutrino oscillations were discovered. The Neutrino Factory concept has been energetically developed by an international community since that time [3]. The R&D programme defined by the conceptual design studies that were carried out in the period 1999–2002 is now maturing [4–9]. Highlights of this programme include the international Muon Ionisation Cooling Experiment (MICE) [10] which has been approved at the Rutherford Appleton Laboratory (RAL) and the nTOF11 high-power target experiment [11] which has been approved at CERN. Each of these experiments will begin taking data in 2007. The success of this broad programme is the result of the significant investments that have been made by funding agencies worldwide. The approval of the MICE and nTOF11 experiments, in addition to the continuing support for work on the conceptual design of the facility, represents a far sighted strategic commitment to the development of the next-generation neutrino source.

The R&D programmes by which the partners in the study seek to develop future neutrino facilities are described below. Together, these programmes provide the foundation for the development of the neutrino facility that is required for the precision study of neutrino oscillations. Through the scoping study, the international community will produce a robust plan by which a full conceptual design for the entire facility can be produced by the end of the decade.

The US Neutrino Factory and Muon Collider Collaboration

In the US, Neutrino Factory R&D has been pursued by the Neutrino Factory and Muon Collider collaboration (MC) which consists of 130 scientists and engineers from national laboratories and universities, and includes participation from Europe and Japan. The collaboration became a formal entity in 1997 and received its first funding in 1998. Since that time, the MC has embarked on an intense program of design studies, together with a hardware-development program focused on targetry for high-power proton beams and muon-ionisation-cooling-channel components. Initially, the R&D was motivated by the desire to develop a high-energy muon collider. The Neutrino Factory concept emerged in 1997. In 1999 the emphasis of the MC R&D changed to the Neutrino Factory. In subsequent years, there have been two major US Neutrino Factory design studies, and one recent design update. The first Neutrino Factory design study (Study 1) was sponsored by Fermilab [4]. This study fully involved the MC and was supplemented by external contributions including engineering support at the level of ~$1M. Study 1, which lasted six months and was completed in April 2000, established the feasibility of the Neutrino Factory concept. However, the calculated performance of this initial design was less than desired, and no emphasis was placed on cost effectiveness. The lessons learned from Study 1 enabled a second study (Study 2) to be launched later in 2000, this time co-sponsored by BNL and the MC. Study 2, which also included about $1M of engineering support, was completed in May 2001 and emphasised performance while maintaining feasibility [5]. As hoped, the desired performance goal was met. However no emphasis was placed on cost-effectiveness. Further work over the next two years produced new ideas that have allowed the phase rotation, bunching, and cooling channels to be simplified, and an improved acceleration scheme to be developed. In 2004, the MC updated its baseline Neutrino Factory design incorporating these ideas (Study 2a) [6]. The calculated performance of the new design, which keeps both positive and negative muons throughout the front end, was comparable to that of the Study 2 design for each sign of muon. An estimate of the revised cost (based on scaling from the Study 2 cost estimates) indicates that the new design cost will be about 60% of that of Study 2. At this point, the MC is ready to participate in the next step – a globalisation of the effort to begin the optimisation phase of the Neutrino Factory design process.

The ECFA/BENE Working Groups

The European study groups for future neutrino beams and experiments involve about 200 physicists with the close exchange of communication between accelerator physicists, particle physicists and particle theorists. In 1998 an ECFA-sponsored ‘prospective’ study outlined a scenario in which a Neutrino Factory facility was evolved first into a low-energy muon collider and finally into a multi-TeV muon collider [7]. This study contained the first demonstration that leptonic-CP violation could be observed at a Neutrino Factory. Following the submission of this report, the Neutrino Factory Working Group was created at CERN. This group was renamed the European Neutrino Group (ENG) in 2003. A second ECFA-sponsored study, including several physics working groups, was conducted from 2000 to 2002. It established a CERN-based layout for a Neutrino Factory consistent with a low energy super-beam and contained the first description of the beta-beam concept [8]. Experimental efforts have been pursued actively with the HARP experiment [12], the MICE experiment, horn prototyping, and more recently participation in the nTOF11 experiment at CERN. There is also an important experimental activity on possible high intensity proton accelerators at CERN, and at RAL, as well as on high power targets and beta-beams.

Since 2003, the ECFA study groups are part of the Framework-6 funded Coordinated Accelerator R&D in Europe (CARE) initiative. The neutrino activities take place within the Beams for European Neutrino Experiments (BENE) Networking Activity [13]. The BENE working groups are: physics, proton driver, target and collection system, muon phase-rotation and cooling, muon acceleration and storage, and the beta-beam. The mandate of BENE is to coordinate and integrate the activities of the accelerator and particle physics communities, in a worldwide context, in order to achieve superior neutrino-beam facilities for Europe. The objectives are: i. to establish a roadmap for the upgrade of existing facilities and the design and construction of new ones; ii. to assemble a community capable of realising and exploiting these facilities; and iii. to establish and propose the necessary R&D efforts to achieve these goals.

An important workshop on "physics with a Multi-Megawatt proton driver" was held at CERN in 2004, the conclusions of which [14] were submitted to the CERN SPS Committee (SPSC). The SPSC concluded that *"… Future neutrino facilities offer great promise for fundamental discoveries (such as CP violation) in neutrino physics …".* and so recommended that *"… CERN should arrange a budget and personnel to enhance its participation in further developing the physics case and the technologies necessary for the realization of such facilities. This would allow CERN to play a significant role in such projects wherever they are sited."*

The Japanese Neutrino Factory Collaboration

The Japanese scheme for a Neutrino Factory, proposed in 2000, is based on a muon-acceleration system composed of a series of fixed-field alternating-gradient (FFAG) accelerators.The FFAG has a number of advantages for muon acceleration; the FFAG can accept a large-emittance beam and, since the magnetic field is fixed, rapid acceleration is possible. The first 'proof-of-principle' machine, an 0.5 MeV proton FFAG ring, was constructed at KEK in 2000 [15]. The machine was successfully operated, so establishing the FFAG principle. In 2003, a second proton FFAG ring, this time with an energy of 150 MeV was constructed at KEK [16]. This machine too has been commissioned and is in operation. Based on the demonstration of the FFAG, a report on the initial Japanese study of the FFAG scenario was completed by the NuFACT-J working group in 2003 [9]. At Osaka University, the construction of the PRISM FFAG ring (PRISM is the Phase Rotated Intense Slow Muon source) was funded in 2003 and is now being constructed [17]. PRISM is the first FFAG ring designed to accelerate muons and, in the Japanese staging approach, is the first step towards the realisation of the Neutrino Factory.

The UK Neutrino Factory Collaboration

Members of the UK particle-physics community have been enthusiastically involved in the European and international Neutrino Factory activities since their inception and are presently active members of BENE. CCLRC's invitation to the international community to carry out a scoping study with RAL as the host laboratory, and PPARC's support for this initiative, recognises the strength of the high-precision neutrino-physics programme and demonstrates both confidence in and support for the international community that wishes to carry it out. The Neutrino Factory R&D activity in the UK, which is supported jointly by CCLRC and PPARC and which forms the basis of the UK contribution to the study, is summarised below.

In 1999, CCLRC and PPARC jointly funded a three-year initiative in Accelerators for Particle Physics. This initiative funded a programme of accelerator R&D into both the Linear Collider and the Neutrino Factory. On the Neutrino Factory side, the initiative supported conceptual design work on the proton driver, the target, and the muon front-end. In addition, measurements of the effects of beam heating in tantalum samples were made. The initiative also funded the MuScat experiment, the UK contributions to the HARP experiment, and initial work on the MICE experiment. In 2002, the 56 strong MICE-UK collaboration was formed; a direct result of work funded by the joint CCLRC/PPARC initiative.

The UK Neutrino Factory (UKNF) collaboration [18] was formed in 2003 in response to the PPARC call for accelerator R&D proposals. The UKNF collaboration is composed of 80 physicists and engineers drawn from CCLRC, the Universities and the High Power RF Faraday Partnership. The UKNF collaboration's successful bid now funds a three year programme the goal of which, in collaboration with the international Neutrino Factory community, is to deliver a conceptual design for the facility that is based on the results of a hardware R&D programme by which the feasibility of the critical technologies have been demonstrated. In addition to the development of a conceptual design for the facility the UKNF collaboration is developing a proton-driver front-end test stand at

RAL, contributing to the development of the CERN 3 MeV test place and carrying out a study of shock in solid targets with a view to establishing whether a solid target is an option for the Neutrino Factory. At the heart of the UKNF activity is the MICE experiment. The UK contributions to MICE Phase 1 (the MICE Muon Beam on ISIS, the infrastructure for the experiment, the UK contribution to the spectrometer instrumentation and contributions to the software for the experiment) have recently been approved and funded.

2. The physics case

Neutrino oscillations can readily be described by extending the Standard Model (SM) to include neutrino mass eigenstates [19]. The minimal extension requires three mass eigenstates, ν_1, ν_2 and ν_3 and a unitary mixing matrix, *U*, which relates the neutrino mass basis to the flavour basis. The minimal extension requires seven parameters to be determined: three neutrino masses, m_1, m_2 and m_3; three mixing angles, θ_{12}, θ_{23} and θ_{13}; and one phase parameter, δ. The matter-antimatter (CP) symmetry is violated if $\sin\delta \neq 0$ (and $\sin\theta_{13} \neq 0$). The oscillation probabilities depend on the mass-squared differences $\Delta m_{12}^2 = m_2^2 - m_1^2$ and $\Delta m_{23}^2 = m_3^2 - m_2^2$. Hence, measurements of neutrino oscillations determine the neutrino mass-hierarchy but are insensitive to the absolute value of the neutrino masses. The complexity of the phenomenological description of neutrino oscillations allows correlations among the measured parameters to develop and for adequate descriptions of the data to be provided using different (degenerate) sets of parameters. Such theoretical uncertainties must be resolved.

The challenges for the neutrino-oscillation community are to measure, as precisely as possible, the parameters θ_{12}, θ_{23}, θ_{13}, Δm_{12}^2, and Δm_{23}^2, and to search for leptonic-CP violation by measuring δ. The sign of Δm_{23}^2 is of particular interest as it determines the mass hierarchy. Precise measurements of the parameters are required either to establish the minimal model outlined above or, by establishing parameter sets inconsistent with it, point to the existence of entirely new phenomena; for example, the three-generation scenario would have to be abandoned should MiniBOONE [20] confirm the presently unexplained LSND result [21–24].

Data from the Sudbury Neutrino Observatory (SNO) [25,26] and KamLAND [27,28] experiments, together with data from Super-Kamiokande [29] and elsewhere have been used to determine θ_{12} with a precision of around 10% and Δm_{12}^2 with a precision of 10% – 20%. The parameters θ_{23} and Δm_{23}^2 have been determined using atmospheric neutrino data from Super-Kamiokande [30] and verified using an accelerator-based neutrino source by the K2K experiment [31]. With five to seven years of running, the MINOS long-baseline experiment [32,33], which has begun to take data, will determine θ_{23} and Δm_{23}^2 with a precision of around 10%. The two CNGS experiments OPERA [34] and ICARUS [35,36], which are designed to observe ν_τ appearance and are scheduled to start data taking in 2008, will verify aspects of the mixing formalism outlined above. Two first-generation super-beam experiments, T2K in Japan [37,38] and NOνA in the US [39], are being mounted with the objective of demonstrating that θ_{13} is greater than zero. The T2K experiment will begin data taking in 2009 and, with five years of data taking, will be sensitive to $\sin^2\theta_{13}$ down to about 0.005 at 90% C.L. NOνA, which has recently been granted scientific approval by the FNAL PAC, will yield a comparable sensitivity. Both T2K and NOνA will improve the determination of $\sin^2\theta_{23}$ and Δm_{23}^2 to the level of a few percent after five years of data taking. However, neither T2K (Phase I) nor NOνA will have the sensitivity required to discover leptonic-CP violation or to deliver the precision measurements of the parameters that are required for a full understanding of neutrino oscillations.

To take the study of neutrino oscillations further requires a second-generation facility ready to begin operation in the second half of the next decade. This facility must be capable of making high-precision measurements of the mixing angles and mass-squared differences and of making searches for leptonic-CP violation of great sensitivity. The precision of the measurements must be such that sensitive tests of the consistency of the theoretical framework can be made. Three types of facility have been proposed to provide the neutrino beams required to serve this second-generation programme. The first is a conventional super-beam of high intensity illuminating a megaton-scale water Cherenkov detector [40,41]. The second, is a beta-beam facility in which beams of radioactive ions are stored and allowed to decay to produce pure electron-neutrino (and anti-neutrino) beams [42,43]. If the neutrino energies produced by the super-beam and beta-beam facilities are sufficiently similar, the same detector could be used for both. The Neutrino Factory is the third proposed option [2]. Existing studies indicate that the Neutrino Factory offers the best performance over much of the parameter space [3–9]. At high values of θ_{13} the beta-beam, in combination with a second generation super-beam, may be competitive. The first objective of the scoping study will be to perform a critical review of the physics reach of the various proposed facilities taking into account the likely state of knowledge of the parameters that govern neutrino oscillations at the time the facility will operate.

The cost of any of the proposed facilities for precision measurements of neutrino oscillations is large. Therefore, eventually, international consensus on the optimum route to precision measurements is essential. The second objective of the scoping study will therefore be to make a critical comparison of the performance of the three proposed facilities. This comparison must be made using appropriately chosen assumed parameter sets for the neutrino beams and the detection systems. Given the short duration of the study, this comparison cannot be definitive. Rather, it will be used to develop a roadmap that identifies the phenomenological calculations and simulation work that must be performed before such a consensus can be achieved. The roadmap will also indicate key decision points; i.e. branch points where measurements, for example the observation that θ_{13} is large, lead to a particular option being preferred over others.

A copious source of slow muons could also be provided at a Neutrino Factory. An exciting physics programme [8,44] that includes extremely sensitive searches for lepton-flavour violating muon decays, a high-precision measurement of the Fermi constant and the Michel parameters, precision measurements of the anomalous magnetic moment of the muon as well as a sensitive search for an electric dipole moment, and the detailed study of muonium. Intense slow muon beams would also find application in materials science. The scope of the physics study will include the physics programme that could be carried out using an extremely intense slow-muon source.

3. The accelerator facility

Since the conceptual design of a beta-beam facility [42] is being developed in the context of the EURISOL design study [45], the scoping study will focus on evaluating the various options for the Neutrino Factory accelerator complex and neutrino-detection systems. Since the technical difficulties presented by the proton source, target and collection systems for a second-generation super-beam are similar to those required for the Neutrino Factory and since the super-beam may be a desirable step on the way to the Neutrino Factory, the requirements of a second-generation super-beam [40,41,46] will also be considered. The following paragraphs indicate issues that will be addressed in the course of the study.

3.1 Overview

The first of the annual Neutrino Factory Workshops, NUFACT99 [47], set the initial parameters for the accelerating systems, and, while subsequent research re-defined certain details, the majority of the global parameters have remained largely unchanged. The accelerator complex comprises:

- A proton driver delivering 4 MW of mean beam power to a pion production target in bunches of a few nanoseconds duration;
- A pion capture channel and a system to control the muons into which the pions decay;
- A mechanism for rapid muon acceleration to an energy of 20 – 50 GeV; and
- A dedicated ring for storing the muons as they decay into neutrinos.

Details of developing scenarios were published in two subsequent studies in the US [4,5], one in Europe [8] and one in Japan [9]. The US studies gave estimates of costs and highlighted the need for additional features such as muon cooling. The studies were not intended to be definitive and assumed the proton driver could be based on the host laboratory's local accelerators. Aspects of the facility were developed independently and the individual optimisations did not always take into account the difficulties being imposed on other parts of the system.

An important feature of the conceptual design study will be to encompass an integrated work programme, based on experience from the last five years. Areas regarded as potential “show-stoppers” should be identified and solutions sought, possibly through compromise with other areas of the machine. The eventual goal is the development of a consistent, viable, and robust muon-based neutrino facility that could be brought into operation for an acceptable cost. The scoping study will determine desirable values, or ranges of values, for the design parameters that specify the interfaces between the various accelerator sub-systems that make up the facility and define an accelerator-R&D roadmap that will be used as the basis for subsequent conceptual-design work.

3.2 Accelerator and target aspects of the scoping study

An important task of the one-year scoping study will be to ensure close collaboration between working groups and to create an organisational structure that will ensure a coherent design. In addition to this integrated approach, the scoping study should ensure the correct balance between theoretical analysis and essential R&D, and include a measure of low-level costing and safety assessment.

Proton driver, target and capture

The proton driver is the one aspect of the facility that, for most accelerator physicists, is tied to their own laboratory. It is probably unrealistic to demand that a particular design be totally site independent, since, for example, some of CERN's ideas have been built around a superconducting proton linac (SPL) [48], which has uses in other areas, and RAL's studies include development of ISIS into a multi-purpose facility based on synchrotrons. Brookhaven may look for a proton driver based on an FFAG and already have a formal proposal submitted to the US DoE for a neutrino super-beam. The scoping study should nevertheless be able to determine the strategy for making the proton-driver choice, and address general issues such as the optimum driver energy and the frequency and structure of the proton pulses. It can gauge which of the previous studies best fit the requirements, and, within this framework, prioritise areas for research.

There is already a coherent target group that, within Europe, is based around ENG and BENE, and in the US is within the Muon Collaboration. An important aspect of the activities of this group is the nTOF11 experiment [11], which has recently been given scientific approval at CERN. In order to produce a baseline for the target, it will be necessary to ensure that the development of the proton driver and the target system are closely coordinated. In addition to heating and shock studies, current work on target materials and geometry should be continued. Consideration also needs to be given to continuity of operation, reliability and issues of remote handling, target maintenance, and safety. Much of the work can benefit from continued liaison with groups studying, for instance, targets for high-power neutron production. Optimisation of the capture system must include consideration of the relative merits of horn-based and solenoid-based designs.

Muon front-end; phase-rotation, cooling and acceleration

Aspects of pion capture, decay to muons and preparation of the muon beam for acceleration (including cooling) should be considered as a whole. Several initiatives are already underway in this area: the MICE experiment [10], a collaboration involving scientists and engineers from Europe, Japan, the US and the UK, has recently been approved and will provide an engineering demonstration of ionisation cooling; the Japanese phase-rotation experiment, PRISM [17], will allow a large-scale test of the principles of scaling FFAGs to be carried out; and the development of a proposal to construct a model of a non-scaling FFAG by a collaboration drawn from Europe, Japan and the US will allow the non-scaling principle to be proved. The scoping study will review the status quo, identify the most promising aspects and suggest a balanced programme involving code development, simulation and hardware R&D. Close collaboration with the target working group is essential so that muon front-end work is based on realistic pion distributions from the target.

Earlier ideas for rapid muon acceleration based on re-circulating linac structures have been supplanted by proposals involving FFAGs. A well-focused international group has six-monthly workshops and has made encouraging advances in beam dynamics and large-aperture FFAG-type magnet design, supported by the development at KEK of high-gradient RF cavities using metallic alloys. The group is now planning an electron model, likely to be built at the Daresbury Laboratory, to test aspects of non-scaling FFAG machines. Apart from R&D into hardware, specific FFAG simulation and design codes need to be developed and benchmarked. These might conceivably be sufficiently general so as to cover modelling of proton FFAGs.

Muon storage

Work on the muon storage rings has been modest in recent years. The development of computational tools for the design of the storage rings for beta-beam facilities may be taken over to handle muon storage and decay. Engineering expertise should also be exploited to address the challenges presented by construction of such a highly-inclined, multi-directional ring, and the detector and phenomenological groups will need to be consulted over geometrical aspects of the design.

4. The detection systems

The main aim for the detection systems at a future accelerator-based neutrino facility is to measure all the parameters of the neutrino mixing matrix with optimum sensitivity. This will be performed by carrying out long-baseline neutrino-oscillation experiments, in which a near detector is used to measure the flux and the relevant cross sections and a far detector is used to observe the neutrino-oscillation signal. Parameters such as baseline and neutrino energy can motivate the choice of detection technology and vice versa. The main scientific aims will be to optimise the sensitivity for the measurement of θ_{13}, δ and the mass hierarchy. The following paragraphs summarise some of the detector technologies that could be considered within the scoping study and some of the R&D issues that need to be addressed to make these detector options feasible.

4.1 Large Cherenkov detectors

Large water Cherenkov detectors have been shown to be superb neutrino detectors (for example, Super-Kamiokande and SNO). These detectors are well suited for neutrino energies of around 1 GeV or less and therefore may be ideally suited to second-generation super-beams or low energy beta-beams. At higher energies, the event multiplicity might make such detectors unsuitable. R&D is needed to determine whether such detectors would also be suitable for the Neutrino Factory and whether cheaper and more effective photon-detection technologies can be developed. The answer to these questions should be considered within the scoping study and an appropriate R&D roadmap drawn up. Synergies with non-accelerator physics (atmospheric, solar, super-novae neutrinos and proton decay) will also be considered.

4.2 Magnetised iron calorimeters

Magnetised iron calorimeters [49–52] have been proposed for use as far detectors for future long-baseline oscillation experiments as they may readily be used to provide a ‘wrong-sign-muon’ event signature. Such a detector would consist of steel plates sandwiching active elements such as resistive plate chambers (RPCs) or scintillator elements. In addition to considering the various options for the active medium, the scoping study will consider the extent to which such a detector can be optimised to identify electrons (or positrons) so that electron neutrinos (or anti-neutrinos) can be detected.

4.3 Low-*Z* scintillator detectors

Low-*Z* scintilllators offer the possibility of allowing a high-mass detector capable of identifying electron (anti-)neutrinos to be constructed for a reasonable cost. The NOνA collaboration has recently proposed a 30 kton detector that will be served by the Fermilab NuMI beam. Such a detector has been tuned for the ~2 GeV neutrinos expected from the NUMI off-axis beam. The main issues associated with this type of detector are the suitability of a low-*Z* detector at higher neutrino energies, whether these detectors can be scaled up to a large fiducial mass, and how to include a magnetic field in such a detector.

4.4 Liquid-argon time-projection chambers

A liquid-argon time-projection chamber (TPC), ICARUS, is currently under construction for the CERN to Gran Sasso (CNGS) neutrino beam. A 600 ton liquid-argon detector has been built. The technique offers superb electron identification. If a suitable magnet system can be designed, a liquid-argon detector would be capable of measuring simultaneously right- and wrong-sign muons, events containing scattered electrons or positrons, and neutral-current events [53,54]. The main issues associated with this type of detector that need to be studied in the context of the scoping study are whether one can implement a magnetic field and perform electron charge identification, whether these detectors can be scaled up in size to ~100 ktons.

4.5 Hybrid emulsion detectors

The OPERA experiment is also under construction at the Gran Sasso laboratory. This is a 1.8 kton hybrid emulsion detector consisting of cells of lead and emulsion. This type of detector is optimised for a ν_τ-appearance search, where the τ particles from ν_τ charged-current events appear as short-lived particles and are identified as kinked tracks in the emulsion-lead sandwich. A ν_τ-appearance signature in such a detector would reduce errors in the determination of the CP violating phase δ and remove ambiguities between θ_{13} and δ at a Neutrino Factory [55]. The main issues associated with such a detector at a future neutrino facility would be whether the detector can be scaled to the large mass required (4 kton or more), whether the time for scanning the emulsion can be reduced significantly by making an appropriate pre-selection of candidate events, and whether the cost can be kept to a reasonable level.

4.6 Near Detectors

The main purpose of a near detector at a Neutrino Factory is to measure the flux and energy of the neutrino beam [56]. Flux control can be carried out by measuring the rate of the well understood reaction $\nu_\mu + e \to \mu + \nu_e$ at a near detector [57]. One of the requirements of a near detector is high granularity in the inner region that subtends towards the far detector. One should also consider whether the near detector needs to be of the same or similar technology as the far detector or whether measuring the neutrino flux and energy as accurately as possible with a different technology is sufficient.

5. Organisation

The primary goal of the scoping study for a future neutrino complex is to generate a roadmap for the development of a world-wide consensus on the facility (or facilities) required to make precision measurements of the parameters that govern neutrino oscillations and to make high-sensitivity searches for leptonic-CP violation. The output of the scoping study will be a report in which:

- The physics case for the facility is defined;
- A baseline design for the accelerator complex, or, for some subsystems, the programme required to arrive at a baseline design, is identified;
- The baseline designs for the neutrino detection systems are identified; and
- The research-and-development programme required to deliver the baseline design is described.

In achieving its primary goal, the scoping study will have three objectives to:

- Evaluate the physics case for a second-generation super-beam, a beta-beam facility and the Neutrino Factory and to present a critical comparison of their performance;
- Evaluate the various options for the accelerator complex with a view to defining a baseline set of parameters for the sub-systems that can be taken forward in a subsequent conceptual-design phase; and to
- Evaluate the options for the neutrino detection systems with a view to defining a baseline set of detection systems to be taken forward in a subsequent conceptual-design phase.

The provisional programme by which the study will deliver the three objectives listed above is presented in Annex A. The provisional programme, which may be modified after consideration by the Programme Committee, is broken down into three sub-programmes each of which is designed to achieve one of the objectives listed above. A working group will be established to execute each of the sub-programmes.

A Programme Committee will be established to direct the scoping study. The organisational structure proposed is shown in Figure 5.1. Each Working Group will be led by a convenor and will execute its sub-programme through a set of separate or overlapping studies. From an organisational point of view, these studies appear as 'boxes' below the working-group box. In consultation with the Programme Committee, the working group convenors will define the set of sub-tasks required to deliver the programme.

The Programme Committee will be composed of a chairperson, the three working group convenors and possibly a deputy chairperson and deputy conveners. A plenary meeting will be held every three months and will be the main tool used by the Programme Committee to ensure that the Scoping Study converges. The Programme Committee will also ensure that the results of the study are presented at NuFact06 and that the Scoping-Study report is produced by the end of September 2006.

A Stakeholders Board will be established to monitor the scoping study. The Stakeholders Board will be formed from representatives of the various stakeholders. The key stakeholders are:

- Europe: ECFA/BENE (Beams for European Neutrino Experiments);
- Japan: the NuFact-J collaboration;
- US: The Neutrino Factory and Muon Collider collaboration; and
- UK: The UKNF collaboration with RAL as the host laboratory.

Work in the three regions will be organised through these existing networks. The various stakeholders and laboratories that support aspects of the study will be represented on the Stakeholders Board. This list of stakeholders is not to be taken as exclusive; any individual, institute, laboratory or collaboration that wishes to contribute to the work of the study will be very welcome to participate. The Programme Committee chairperson will report to the Stakeholders Board. The Stakeholders Board will meet at each of the three plenary meetings to receive a report from the Programme Committee chairperson and to review the progress of the study.

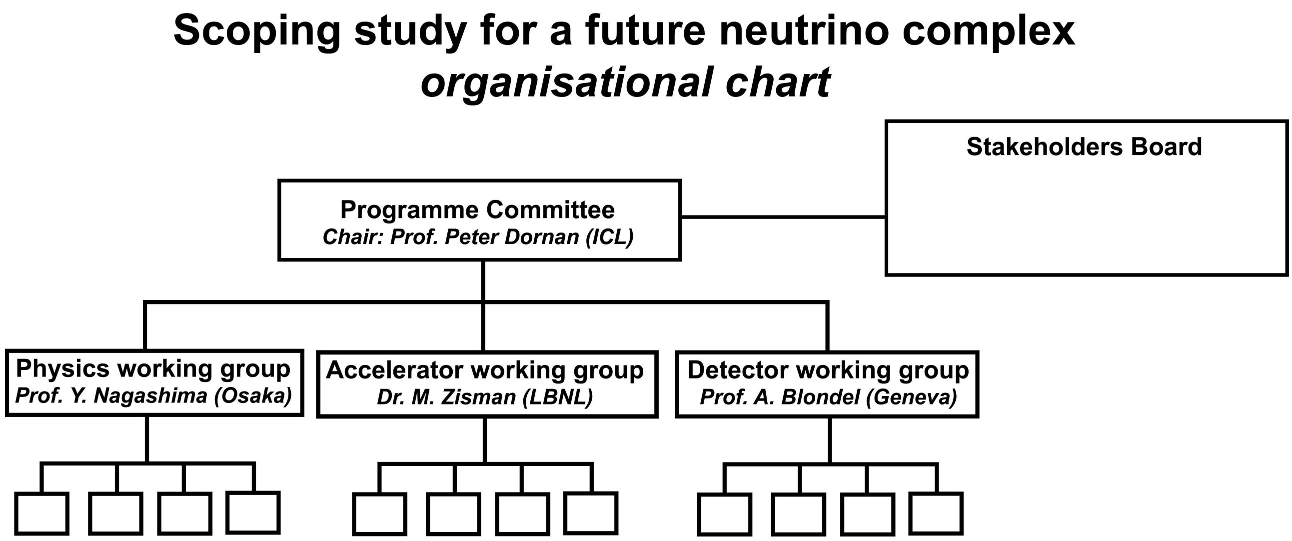

Figure 5.1: Organisational chart for the scoping study for a future neutrino complex.

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Annex A

The provisional programme for the scoping study is presented in the form of 'key success measures' in table A.1. The Programme Committee has the responsibility to coordinate the work and to ensure that appropriate contacts between the working groups is maintained.

Key success measures		
1	**Review the physics case for a future neutrino complex with a view to defining the baseline specification for the facility**	
	Description of goal	
1.1	Review previous analyses of physics reach of future facilities (super-beam, beta-beam, Neutrino Factory) for precision neutrino oscillation studies to identify areas in which data used, assumptions made, or analysis performed need to be extended.	Create list of existing analyses to be included.
		Report detailing additional phenomenological work required to extend existing analyses and identification of new data to be included in revised analysis.
1.2	Development of benchmarking codes (e.g. GLOBES) to allow performance comparison of options.	Create list of benchmarking codes with advantages and disadvantages of each.
		Select benchmark code(s) to be used with a specification of improvements to be made.
		Selected benchmark code(s) modified in accordance with the specification.
1.3	Evaluate sensitivity to theta_13, leptonic CP violation and the mass hierarchy as a function of the values of theta_13 and delta. Identify the regions of parameter space to which the Neutrino Factory, beta beam and superbeam facilities are sensitive. If there are regions of parameter space in which the sensitivities overlap identify the advantages, if any, offered by the multiplicity of modes available at the Neutrino Factory.	Report summarising study and presenting plots showing the sensitivity of each option separately and indicating their relative sensitivities to theta_13, delta and the mass hierachy.
		Summarise the information gained by the various appearance and disappearance modes (including tau appearance) at a future neutrino facility in both the standard three-flavour scenario and more exotic scenarios.
1.4	Identify the means by which parameter degeneracies and correlations are resolved and distinguished from four-flavour or other exotic scenarios either using each facility separately or in combination.	Report summarising options for removing such ambiguities and testing the three flavour framework at a Neutrino Factory using multiple baselines and/or neutrino beam energies, tau identification, electron-positron identification etc.
		Report summarising options for removing such ambiguities and testing the three-flavour framework at a beta beam facility.
		Report summarising options for removing such ambiguities and testing the three flavour framework at a super-beam facility using neutrinos and anti-neutrinos.
		Report summarising benefits of combining information from the various facilities both for parameter determination and for the study of sources of systematic uncertainty.
1.5	Recognising that each facility will have various sources of systematic uncertainty, identify strategies by which such uncertainties can be quantified.	List principal sources of systematic uncertainty for each facility and estimate size of the uncertainty.
		Evaluate strategies by which systematic uncertainties can be quantified and summarise requirements on the facility (for example simultaneous storage of mu+ and mu- at a Neutrino Factory) or the measurement programme (for example cross section measurements for superbeam experiments) required to minimise the uncertainties.

Table A.1: Key success measures for the scoping study for a future neutrino complex. The table lists the neutrino-oscillation physics goals and deliverables of the study. The due dates for the deliverables are matched to the schedule of plenary meetings.

Key success measures		
2	**Review the options for the accelerator complex with a view to defining a baseline, agreed among the various interested parties, that can form the basis of the full design study**	
	Description of goal	
2.1	Evaluate options for the various systems that make up the future-neutrino-facility accelerator complex taking into account the possibility that a super-beam may be a desirable step on the way to the Neutrino Factory and taking into account, as far as possible, the interaction between the various systems. Identify the key interfaces and the parameters that must be specified at these interfaces (for example the proton driver energy, bunch structure, emittance and power). Determine desirable ranges for the various parameters.	**Proton driver, target, and capture**
		Review existing or proposed proton drivers, target and capture systems to determine the key parameters. Identify the issues that couple the design/specification of these systems to each other (for example yield versus energy and/or peak stress in the target versus repetition rate) and the rest of the complex (for example implications for phase-rotation, cooling and acceleration systems).
		Through simulation determine proton-driver parameters that optimise yield.
		Produce an evaluation of the pros and cons of liquid and solid targets.
		Evaluate pros and cons of horn-based and solenoid-based capture systems and optimise the system(s) to identify option(s) to be carried forward.
		Phase rotation, cooling and acceleration
		Review proposed phase-rotation, cooling and acceleration schemes to identify options to be carried forward.
		Seek a performance/cost optimum frequency for the phase-rotation, cooling and aceleration systems.
		Initial performance/cost optimisation of the integrated phase-rotation, cooling and acceleration systems.
		Storage ring
		In consultation with the phenomenology group review options for storage-ring configurations and identify option(s) to be carried forward.
		Identify key issues for the storage-ring design (for example matches from straights to arcs and material for lining magnet apertures in arcs).
3	**Review the options for the neutrino-detection systems that such a facility would require with a view to defining a baseline set of options that can form the basis for further study**	
	Description of goal	
3.1	Evaluate options for neutrino detector technologies in order to identify the most promising techniques for muon identification and charge measurement, for electron/positron identification and charge measurement, and for tau identification. Identify an initial specification for the neutrino detectors for the neutrino facility, make a preliminary estimate of the cost of the detectors and identify the critical R&D programmes that are required.	Review the merits of the various detector options and of the simulation tools that are available to study them.
		In consultation with the phenomenology group define the desired performance of the neutrino detectors (for example electron charge measurement, tau identification etc.).
		Evaluate the performance of the various detector options and identify detector configurations capable of delivering the desired performance. Identify the set of options to be carried forward.
		In consultation with the machine group, make an initial performance/cost optimisation of the various detector options taking into account trade-offs between, for example, neutrino flux, energy and detector mass and performance. For each of the detector options, identify the R&D programmes required to meet the required performance and to reduce the cost of the detector.

Table A.1 continued: Key success measures for the scoping study for a future neutrino complex. The table lists the goals and deliverables of the study in the areas of the accelerator complex and the neutrino detection systems. The due dates for the deliverables are matched to the schedule of plenary meetings.