Plans for a Neutrino Oscillation Facility Design Study in FP7

Introduction

Neutrino oscillations form one of the most important and exciting discoveries in Particle Physics over the last 15 years. Oscillations can only take place if at least one neutrino mass eigenstate has a non-zero mass. Although neutrino masses could in principle be incorporated in a trivial extension of the Standard Model, this would require i) the addition of a new conservation law that is not now present in the SM, fermion number conservation, and ii) the introduction of an extraordinarily small Yukawa coupling for neutrinos, of the order of $m_\nu/m_{top} \cong 10^{-12}$. More natural theoretical interpretations, such as the see-saw mechanism, lead to the consequence that neutrinos are their own anti-particles, and that the smallness of the neutrino masses comes from their mixing with very heavy partners at the mass scale of Grand Unification (GUT). For the first time, solid experimental facts open a possible window of observation on physics at the GUT scale.

There are many experimental and fundamental implications of this discovery. In cosmology, a spectacular one is the possibility that the combination of fermion number violation and CP violations in the neutrino system could, via Leptogenesis, provide an explanation for the baryon asymmetry of the Universe. The discovery of CP or T violation in neutrino oscillations appears to be feasible, but it requires a new type of experimentation: precise appearance neutrino oscillation measurements involving electron-neutrinos. In addition, the precise measurement of mass differences, the ordering of masses and the determination of mixing angles may help explain the hierarchical nature of the SM and probe the complementarities and symmetries between quarks and leptons. However, precise neutrino oscillation experiments, and CP asymmetry in particular, will require a new generation of accelerator based neutrino beams. The best candidates for these are: i) a high intensity conventional Super-Beam of muon-neutrinos from pion and kaon decays, ii) a Neutrino Factory, in which electron- and muon-neutrinos are produced by the decay of a stored muon beam and iii) a Beta-Beam, in which pure beams of electron-neutrinos are produced from the decay of stored radioactive ions. The detector and monitoring systems have to be improved in size and precision to match the improved performance.

Europe has an established track record in the provision of world-leading facilities for particle physics in general and for the investigation of the neutrino in particular. The timely development of a strategy and of an R&D program for a first class European neutrino-physics programme is required for Europe to maintain and enhance its role in neutrino physics.

A considerable amount of R&D and beam dynamics work is already being undertaken in Europe on these machines. We have also greatly benefited from studies in the US and in Japan. A joint one year long International Scoping Study (ISS) has also been carried out (see http://www.hep.ph.ic.ac.uk/iss/) in 2005-2006. It is now planned to continue this work with International Design Studies for each proposed facility. It is expected these will be launched in August at NuFact’07 and produce design reports on a timescale of 2012.

In July 2006, the CERN Council Strategy Document (http://cern.ch/council-strategygroup/) recommended intensification of R&D towards a new high intensity neutrino facility: *"Studies of the scientific case for future neutrino facilities and the R&D into associated technologies are required to be in a position to define the optimal neutrino programme based on the information available in around 2012"*.

This important statement implies that this facility is now among those that may be considered in the formulation of future upgrades of the Road Map of EU Research Infrastructures and that a stronger collaborative European R&D program, with CERN participation, becomes now possible.

In September 2007 ESGARD, the European Steering Group for Accelerator R&D, has recommended that the CARE Networking Activity BENE (Beams for European Neutrino Physics) prepares several Proposals for the EU Framework Programme 7 (FP7). The first Proposal, to be submitted by May 2, 2007, will be a Design Study (DS) called EUROν, of a High Intensity Neutrino Oscillation Facility in Europe. The main aims will be:

- The delivery of Interim Design Reports (IDR) for the three facilities. In the case of the Beta-Beam, this will concentrate on enhancements to the baseline option already being studied in the existing EURISOL DS.
- An initial cost and performance comparison between the facilities, including the relevant detectors.
- Recommendations for the next steps.

This European DS (Euro-ν), that appears also to be a proper tool for Europe to contribute to the International Design Studies, is the main focus of this document.

Additional Proposals are recommended for the subsequent FP7 call, in early 2008, for R&D work relevant to these facilities, in the framework of a number of Integrating Activity proposals that are currently being formulated.

In this document, we list the necessary work that we plan to submit within these proposals. We are seeking now partners who might be interested in participating in any of this work and in joining the appropriate proposal.

If you would like additional information or would like to express an interest, please email both Marcos.Dracos@ires.in2p3.fr and Rob.Edgecock@rl.ac.uk.

The Proton Driver

The first crucial accelerator section of both a Super-Beam and a Neutrino Factory is the proton driver, capable of delivering a high power proton beam with a short pulse length on the pion target. The main parameters of this machine, as discussed and reported at NuFact06, are:

- **Energy:** **10 ± 5 GeV**
- **Beam power:** **4 MW**
- **Repetition rate:** **50 Hz**

This multi-MW proton machine has many aspects in common with other projects like spallation sources, drivers for hybrid reactors, machines for nuclear waste transmutation and the European project EURISOL. Overlap in R/D is likely to be beneficial and these synergies should not be neglected in the design study. We must also remark that two high power proton machines are under construction/commissioning: the American Spallation Source (SNS) at Oak Ridge and the JPARC complex at Tokai (Japan). While neither provides a beam power reaching the performances of the proton driver considered here, their achievement and experience should be taken into account.

Three schemes for the proton driver have been proposed and preliminary studies and reports exist for each of them:

1) The Linac option (CERN SPL and Fermilab approach), optionally followed by accumulator and compressor rings (see for example http://doc.cern.ch/yellowrep/2006/2006-006/full_document.pdf). In case of the SPL, this is considered as part of the LHC injector upgrade.

2) The FFAG option (UK studies).

3) The Synchrotron option (JPARC, AGS, UK).

This design study should make progress in the comparison between different schemes, taking into account the local synergies, cost and trade-off of each of them, coordinating with other studies and comparisons by qualified panels in the major HEP laboratories.

Key elements/operations of the proton driver that pose a technical challenge and need dedicated studies are:

a) the H- ion source, capable of delivering ~80 mA, with 5 % duty cycle and a lifetime of about 60 days,

b) the injection and accumulation into a synchrotron,

c) the in-depth analysis of disturbing collective effects in the ring and their possible cures (space-charge, electron-cloud instabilities etc.),

d) the compression to a final 1 ns rms bunch duration with a preliminary design of possible RF systems,

e) the overall management of the losses with the study of collimation schemes.

An essential issue of such a high power machine is the control of the losses that should be minimised and confined to specific areas. Finally, the design study should include an end-to-end simulation as an input to study the performance of the following machine elements (target, collector).

Target

A limiting factor and potential show-stopper for most high intensity neutrino facilities is the target on which the high power (4 MW) proton beam is sent to produce the hadrons necessary for the production of the final neutrino beam. All existing facilities use proton beams with a power lower than 0.5 MW. The proposed solutions for the next generation facilities present considerable difficulties and are at rudimentary stages of development. In order to maximise the integrated neutrino flux, it is necessary to consider not just the instantaneous efficiency of a target but also the lifetime and reliability. Since these latter issues are difficult to quantify, a major international effort is required to provide appropriate facilities to thoroughly test materials and technologies in order to make the best target technology choice. In addition the environment and handling constraints require a local implementation study.

The MERIT experiment at CERN is studying the twin problems of injecting a mercury jet into the capture solenoid and the response of the jet to a short-pulse high power density beam. It is anticipated that shock-wave induced cavitation will generate high velocity jets of mercury that may damage surrounding components. The SNS and J-SNS neutron facilities have adopted liquid mercury as the target material and have yet to solve the problem of cavitation causing damage to the window material. These facilities can also be regarded as test facilities for the handling and disposal of highly radioactive mercury and for problems of radio-chemistry and corrosion. Other experience in liquid metals exists in Latvia and Novosibirsk. The MEGAPIE facility at PSI can be considered as a similar test facility for liquid Pb-Bi targets, another potential Neutrino Factory target solution. The following actions on liquid metals are recommended:

- initiate a collaboration with liquid metal experts in PSI, Latvia and Novosibirsk,
- recruit or develop expertise in liquid metals and learn from the MERIT experiment,
- maintain a watching brief on the liquid mercury target developments at SNS and J-SNS.

Recent experiments at RAL using pulsed power supplies to generate shock-waves in thin tungsten wires have demonstrated the potential of the material to provide a radiation-cooled solid target solution with an expected lifetime of over 10^7 pulses under typical Neutrino Factory conditions, a full year of operation. However, the following issues still need to be addressed:

- extrapolation of results for thin wires to Neutrino Factory target dimensions,
- on-line experiments using proton beams to reproduce the conditions in a Neutrino Factory target,
- radiation damage of target material,
- engineering a solution to the problem of target insertion and extraction from the capture solenoid.

A new idea has recently been proposed, namely the use of a fluidised bed of solid tungsten particles in a helium carrier jet. This has the attraction of combining many of the advantages of a liquid target with those of a solid target while avoiding many of the problems. However it has not been studied in any depth and would need considerable investigation before being considered a serious candidate.

In most of the above target material solutions, the target material is renewed between proton pulses and the maximum intensity limitation is no longer driven by the target resistance, but rather by radiation handling and safety issues. It is completely essential that these issues be revisited for the specific choice of target and proton beam energy that is discussed as the proton intensity itself is generally the least expensive commodity in the system. These involve compilation of material resistance abilities and a careful study of maintenance, safety and decommissioning issues. Laboratories with expertise in high power beams, such as CERN, RAL, and PSI are expected to play a leading role in this aspect of the study.

Collection

For a neutrino beam, the hadron collection system is greatly influencing the beam intensity and neutrino energy spectrum and therefore the physics performance of the project. The Neutrino Factory project made the choice of a magnetic solenoid as collector which focuses at the same time both, negatively and positively charged hadrons. For Super-Beam project, only one hadron charge at the same time can be accepted and for this reason a sign selecting classical magnetic horn has been chosen.

The horns used up to now were pulsed with a rate of few Hz compared to the 50 Hz rate for the new systems. The required horn pulsing current (>300 kA) to obtain the desired focussing magnetic field is also significantly higher than that already used. The main challenge will be the longevity of the system in the presence of 4 MW proton beam (almost an order of magnitude higher than existing proton beams). Finally, this cavity will have to stand a large amplitude rapidly varying electromagnetic wave, thermo-mechanic stresses, vibrations, fatigue and radiation damages. An efficient cooling system, in order to maintain the integrity of the horn despite the large amount of heat generated by the energy deposition of the secondary particles provided by the impact of the primary proton beam onto the target, has to be designed.

For Super-Beam facility, the integration of the target inside the horn has to be considered from the beginning of the project. A prototype horn for a few GeV proton beam has been constructed at CERN and could be used for tests and measurements of power dissipation in presence of a target, pulsers, fatigue etc.

To understand the system better and more quickly, a reliable simulation has to be established. This contribution will greatly benefit from the experience with existing horns.

For the solenoid solution, similar problems to those of the magnetic horn exist. This possibility will be tested in MERIT experiment. The possibilities of constructing high field magnets (20 Tesla or more) constitute an important technological challenge and synergies with specialized laboratories will be sought.

Muon front-end

In the Neutrino Factory, the muon front-end, just after the hadron collection system, consists of the accelerator components required to prepare the muon beam for acceleration. The diffuse muon beam that emerges from the pion-decay channel has a very large energy spread.

A phase-rotation and bunching section is required to produce a bunch train of defined momentum. The baseline system, as defined by the ISS, is a linear channel in which phase rotation is achieved by adiabatically varying the RF field in a series of large-aperture normal-conducting RF cavities. An alternative, based on the use of a non-scaling FFAG, is being considered.

The baseline cooling channel is a linear channel including low Z absorbers and high-gradient 201 MHz cavities in a solenoidal transport channel. Alternatives to the linear cooling scheme include ring coolers and FFAG-based coolers. A potentially highly efficient alternative is the helical cooler (http://www.muonsinc.com/reports/PRSTAB-HCCtheory.pdf).

The principal objectives for the muon front-end package are to develop:

- the ISS baseline concept for the phase-rotation and cooling systems into fully simulated and engineered designs,

- the design of the alternative phase-rotation and cooling-channel options to a level of maturity such that a revised baseline can be chosen and presented in the Interim Design Report (IDR).The international Muon Ionisation Cooling Experiment (MICE, see http://www.mice.iit.edu/) is scheduled to be completed in time for the results of the basic experiment (demonstration of transverse cooling) to be used in the preparation of the IDR. Several extensions to use the facility to test further cooling techniques are being investigated, such as helicoidal cooling, allowing longitudinal emittance exchange, and lithium lens cooling allowing further reduction of emittance. Present plan is to propose these tests as a JRA in an IA proposal on advanced accelerating technologies.

Muon acceleration

The acceleration of particle beams for neutrino production is facing the difficult issues of providing high power beams and fast acceleration and/or manipulation of short lived beams. FFAG circular accelerators offer a radical alternative to current designs (synchrotrons, linacs) as they can deliver ultra-high repetition rate (kHz range), synonymous with fast acceleration, and allow very large geometrical and momentum acceptance, implying low losses. Fast acceleration is based on high gradient RF and potentially allows high average power, or alternatively, the transmission of unstable beams with high efficiency.

The main objective of this activity is the contribution to R&D on the Fixed Field Alternating Gradient (FFAG) accelerator technology applied to ultra-fast acceleration of unstable beams, and contribution to high intensity, high repetition rate proton accelerators in 100s MeV to GeV range.

For the design study, R&D and technological efforts, contributing to the realization of a systematic study of several technological alternatives are needed. The proposed R&D activities are intended to surpass the level of competence achieved outside Europe and provide the technological background for substantial improvements of knowledge and technological competences of the Laboratory and Industrial partners. The main topics to be studied are:

- *Lattice design and beam dynamics studies* – scaling and semi-scaling FFAG methods; fast acceleration, resonance crossing, alignment and field tolerances; geometrical and momentum acceptance, magnet apertures; momentum range; injection and extraction.

- *Component design studies, prototyping and experimental tests* – non-linear and linear magnets: broad band modulated RF systems, high gradient fixed frequency RF systems, injection and extraction kicker systems, beam diagnostics, vacuum.

- *Proof-of-principle accelerator prototypes* – contribute to prototypes: the linear electron model (EMMA) and the 200 MeV proton accelerator (RACCAM).

- *Comparison of the FFAG methods* – scaling, semi-scaling and non-scaling: advantages and drawbacks, best versus applications.

Muon storage ring

Three shapes are considered for the muon storage and decay rings of the Neutrino Factory: triangle, bowtie and racetrack, for 20 GeV up-gradable to 50 GeV muon beam storage energy. The rings depend on the upstream, proton driver, pion production, phase rotation and cooling, stages, bunch train pattern, as well as on the neutrino detector locations. Designs differ for the triangle/bowtie and the racetrack lattices. The triangle/bowtie rings use combined function magnets for the arcs and solenoid focusing in the production straights, whereas the racetracks adopt separated quadrupoles and dipoles for the arcs and a FODO, focusing arrangement for the straights.

The main objectives of this activity concern lattice design and optimization, backed up by beam and spin dynamics simulations, with the following goals:

- geometry of the ring, focusing methods and properties, injection;
- detailed study of possible working points, including dynamic acceptance, sensitivity to defects, corrections;
- beam loss, collimation;
- beam and spin dynamics, RF regimes;
- development of simulation and tracking tools;
- comparison of triangle and racetrack geometries.

Beta-Beam

In the last few years there have been several new proposals for how to improve the Beta-Beam concept (P.Zucchelli, Phys. Let. B, 532 (2002) 166-172) using different ions and higher energies in the decay ring, e.g., the high-Q value (^{8}Li and ^{8}B) isotopes in a γ=100 facility (http://xxx.lanl.gov/pdf/hep-ph/0609235), the electron-capture facility for monochromatic neutrino beams (J. Bernabeu et al., JHEP12 (2005) 014) and the high-γ facility (http://xxx.lanl.gov/pdf/hep-ph/0312068). However, all these concepts share the same major problem of how to produce enough radioactive ions to generate a sufficiently intense neutrino beam. Recently it has been proposed that radioactive ions of interest for Beta-Beam facilities could be produced with a high flux in a compact storage ring with an internal target (http://xxx.lanl.gov/pdf/hep-ph/0602032 and Y. Mori, NIM A 562 (2006) 591). In the next phase of the Beta-Beam design work beyond the EURISOL DS Beta-Beam task, we propose to focus the work to the critical parts and most notably the production of ions with such a ring. The possible sub-tasks in a Beta-Beam work package could be:

- an in-depth machine study of the production ring concept,
- measurement of relevant cross sections for such a ring,

- tests of the radioactive ion collection system in the ring,
- continued tests of the EURISOL 60 GHz ECR source for bunching,
- adapt the decay ring design for new isotopes and energies and continue collimation and magnet protection studies.

Instrumentation and detectors

The near detectors and beam instrumentation are critical in long baseline oscillation experiments providing measurements of neutrino cross-sections, neutrino event properties and determination of the neutrino beam flux and composition. Future experiments will aim at a precise determination of appearance probabilities and will require precise knowledge of the flux of the initial flavour neutrinos and of the final flavour cross-sections separately. This is a considerable challenge and, for the first time, understanding of neutrino fluxes with permil precision is being discussed.

The determination of absolute flux for a Super-Beam from a standard pion decay neutrino beam traditionally involves several detectors for the muons produced by pion and kaon decays. The design of such a facility in case of a 4MW primary proton beam power at low energy (~5 GeV) and the evaluation of the electron neutrino contamination in the beam will require a dedicated study of the beam dump and its instrumentation, with simulation and analysis of the ancillary experiments that will be necessary.

For the instrumentation of a storage ring for the Neutrino Factory and Beta-Beam the following studies are essential:

- Beam Current Transformer for absolute determination of the number of stored particles (measurement of decay products).
- Beam divergence monitoring device, such as a gas Cherenkov device, either permanently or occasionally.
- Polarimeter for a muon storage ring Neutrino Factory and determination of the actual precision in the polarization measurement.

The implementation of the above in the storage ring geometry and optics and study of performance are also necessary. Prototyping of a very thin-walled Cherenkov device and test on a stored beam, since the practical feasibility has been called into question, is mandatory.

The measurement of neutrino cross sections both for disappearance and appearance channels is one of the main challenges faced by future neutrino facilities. In the low energy beams (Super-Beam and Beta-Beam) the design of near detectors of the right chemical composition able to determine exactly the topological properties of neutrino interactions will be needed. For the storage ring geometries, design of shielding at the end of the neutrino-producing straight sections is required. Small scale prototypes of water-based scintillator tracking calorimeters, or of liquid argon detector with ice inserts will be necessary.

In the case of Neutrino Factory, the detection of high energy electron-neutrino interactions will offer absolute cross-section determination. Design of a dedicated near detector geometry will be necessary. In addition, a detector dedicated to the precise measurement of charm production and precise topological and differential cross sections will be needed.

The cost and interest of the facility includes the large far detector systems. Baseline detectors have been defined as follows in the ISS:

For low energy neutrino beams (100 MeV to 1 GeV), the most economical and efficient detector is the Large Water Cherenkov detector. This has been very successfully pioneered by the IMB, Kamiokande and Super-Kamiokande detectors the largest in operation featuring 50kton of total mass. Further upgrades are being studied with the aim of reaching 0.5 to 1 Megaton of fiducial mass. For the Design study, link to these collaborations will be carefully kept so as to take into account the most up-to-date cost and performance estimates. This detector offers interesting physics possibilities in its own right, including the search for proton decay, cosmic (solar, supernova) and atmospheric neutrinos.

On the other end of the spectrum, the high energy neutrinos of the Neutrino Factory require a magnetic detector for lepton sign determination. The basic detector here is the large magnetized iron detector the largest presently in operation (MINOS) featuring an active mass of 5.8 kton. A 100 kton detector seems feasible but the exact cost and feasibility estimate remains to be established. Part of the target mass could be constituted of nuclear emulsions in order to achieve tau detection.

Other interesting possibilities at a Neutrino Factory include large magnetized volume inside of which finer grain detectors (totally active scintillator, liquid argon, or nuclear emulsions) could be situated allowing a richer set of reactions to be detected. The cost or feasibility of these options cannot be assessed until a design study of the large magnet is performed.

Relations with the International Design Studies

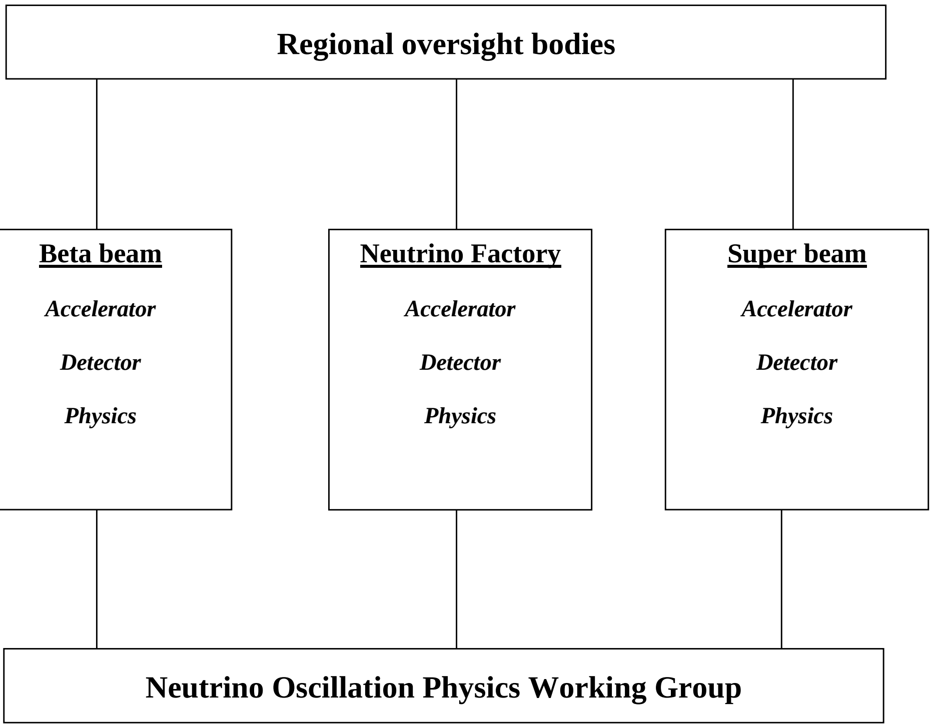
European initiative in the accelerator neutrino sector is part of an international effort, whose home has so far been the yearly International Workshop on Neutrino Factories, Super-Beams, and Beta-Beams. The Workshop has promoted and reviewed all the Neutrino Factory studies carried out regionally since 1999 and the "reference" Beta-Beam FP6 (EURISOL) first Design Study. In this context were developed the international collaborations to execute the International Muon Ionization Cooling Experiment (MICE) at RAL (UK) and the Mercury International Target experiment (MERIT) at CERN. More recently, it promoted in 2005 the International Scoping Study of a future Neutrino Factory and Super-Beam facility (the ISS) and then in 2006 scrutinized its results and recommended that complete few-years-long Design Studies (IDSs) are now internationally undertaken, in parallel, for each of the presently proposed facilities: (a few options of) Super-Beam, the Beta-Beam and the Neutrino Factory.

The proposals to the European Union under Framework Programme 7 will therefore also aim at providing the resources that are necessary to allow Europe to play a substantial role in these International Design Studies.

The 2012 decision point is indeed internationally recognized. Delegates at last, 8th Workshop of the series (NuFact06, 24 – 30 August, 2006, Irvine, California) noted that: "*The decision on the precision accelerator-based neutrino-oscillation programme should be possible soon after the reactor and long-baseline neutrino oscillation experiments which are presently being implemented, have provided information on the key parameter θ_{13}. Meeting this timescale requires that CDRs (Conceptual Design Reports) for the considered facilities be* *available by ~2012. In addition, it is important that interim design reports containing reliable estimates of performance and cost are available by ~2010.*”

As it is also evident that “*... the particle-physics community will eventually have to make choices. The criteria upon which these choices will be made include: the measured values of the oscillation parameters, in particular the value of* θ_{13}*, the physics reach and the cost of each of the proposed facilities; and the schedule on which each facility can be implemented. It is important that the best possible information be available at the time the decisions are needed.*”, NuFact06 recommended that an over-arching “Neutrino Oscillation Physics Group” be set up so that objective performance comparisons can be made and consensus on the best way forward eventually to be reached. The ISS physics group, that compared the performance of the different options on an equal footing, and outlined a number of accelerator and detector baseline scenarios, proved that this goal can be achieved.

In addition, in order for the different Design Studies to report their progress to impartial oversight bodies, the community recognised the need for regional oversight bodies to be set up. In Europe, such a body would best be established by CERN Council. That would appear also be the appropriate partner for tighter coordination with similar bodies in USA, Japan and elsewhere.



Organisation for the design-study programme agreed at NuFact06.