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Action to be taken | *Voting Procedure*

Take note	**SCIENTIFIC POLICY COMMITTEE** 264th Meeting **15 and 16 March 2010**	-
For information	**RESTRICTED COUNCIL** 154th Session **18 March 2010**	-

Relations between CERN and the ongoing development work regarding future neutrino facilities

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I. Summary

1. Introduction

At the SPC meeting in December 2008 a request was received from the CERN Council asking for an assessment, by the Scientific Policy Committee, of the relation between CERN and the ongoing work regarding future neutrino facilities. A subpanel of the SPC (R. Aleksan, A. Blondel, P. Dornan, K. Meier/T. Nakada, A. Zalewska – chair, F. Zwirner) was set up to carry out this assessment. The panel made partial reports to the SPC at the meetings in March, September and December 2009. The assessment uses information from the panel's meetings with the CERN Management and with several experts as well as from various documents prepared at the request of the panel.

Two workshops held at CERN in 2009 were also important sources of information. The CNGS programme and possible upgrades of the CERN accelerator complex were discussed at the workshop "New Opportunities in the Physics Landscape at CERN" on May 10-13[1]. The definition of a future neutrino programme was the main topic of the workshop "European Strategy for Future Neutrino Physics" on October 1-3[2] . The latter workshop, with 254 registered participants and 44 submitted posters, demonstrated the need for a strategy felt by the European neutrino community. A CERN yellow report from the workshop will become an important reference document.

The CERN Council posed four questions to the SPC. The questions are answered in Section 2. Conclusions and recommendations are summarised in Section 3. Extensive explanations are presented in a separate document "*Relations between CERN and the ongoing development work regarding future neutrino facilities. II. Supporting document*".

2. Answers to the Council Questions

Question 1: ***What is the view of the SPC on the importance of precise measurements of the neutrino oscillation parameters, in particular the CP violating phase and mass hierarchy?***

After intensively studying hadron flavour physics for many decades, a comparable effort to study lepton flavour physics and determine all the neutrino oscillation parameters as precisely as possible is the next logical step. Neutrino properties are very likely to provide a unique window on physics beyond the Standard Model, irrespective of the existence of new particles at the TeV scale.

Discovering either the violation of total lepton number in neutrinoless double beta decay or leptonic CP violation in neutrino oscillations would be a top-class scientific achievement.

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[1] http://indico.cern.ch/conferenceDisplay.py?confId=51128

[2] http://indico.cern.ch/conferenceDisplay.py?confId=59378

Determining the mass hierarchy and precisely measuring the other neutrino oscillation parameters are also very important as they could shed light on possible flavour symmetries. Solid evidence for a non-zero value of the mixing angle θ_{13} would greatly increase the chances of discovering CP violation at a future neutrino factory, beta beam facility or high-power superbeam, even though such a discovery cannot be guaranteed as it is dependent on the actual values of θ_{13} and the Dirac phase, as well as the particular technique employed.

Overconstraining the standard framework of unitary 3x3 mixing in the neutrino sector, as has been achieved for the quark sector, is also crucial. Possible deviations could be linked to new degrees of freedom near or even below the TeV scale.

If experimentally established, a connection between neutrino physics and the findings of the LHC experiments and/or the experiments on charged lepton flavour violation would be revealing.

Question 2: ***One of the most promising techniques for such measurements is the neutrino factory and there is currently an International Design Study (IDS) to produce a conceptual design report for a neutrino factory by 2012. This is not site specific. What is the view of the SPC on the overall value of the IDS for the future of the subject? Should CERN take a more active role in enabling the study to reach its goals, irrespective of where such a facility would be sited?***

The neutrino factory, associated with large magnetic detectors, constitutes the most powerful neutrino facility with potential for discovery, which can currently be envisaged. It enables several elements in the neutrino mixing paradigm to be studied to an unmatched precision: the mixing angles θ_{23} and θ_{13}, the mass difference Δm^2_{13} and its sign, and the CP violating phase δ, for $\sin^2 2\theta_{13} > 2\ 10^{-5}$. It is unique in producing high energy $(\nu_\mu, \bar{\nu}_e), (\bar{\nu}_\mu, \nu_e)$ pairs in an identical environment, which, with suitably fine grained detectors, allow tests of unitarity by detectable transitions, including those to tau neutrinos at the near and/or far detector stations. It appears today very likely that without a neutrino factory several questions will remain unanswered.

The presently ongoing study IDS-NF is pursuing the essential goal of preparing a costed and feasible Conceptual Design Report by 2012/2013. The IDS-NF effort is lacking manpower in several critical areas, in particular costing and safety.

CERN has the ability to contribute in a significant way to the International Design Study. Although the study is not site specific, investigating in concrete terms the cost and feasibility of such a machine located at CERN would give great credibility to the IDS-NF study. The high power version of the Superconducting Proton Linac (SPL) would be a suitable proton driver for a neutrino factory. Building on the success of the CERN-NTOF11 MERIT experiment, a study of the design and safety implications of a high power target station, particularly with a mercury (or alternative liquid metal) jet, should be given high priority. The Muon Ionization Cooling Experiment (MICE) at RAL, to which CERN has contributed, is also a crucial demonstration and CERN participation should continue.

The magnetised detectors for the neutrino factory require R&D and test beam studies, which should be supported at CERN.

Question 3: ***What other high intensity neutrino facilities are technically possible and how would they address the measurements above? What should be the involvement of CERN in studies of these facilities, in particular with regard to the planned LHC upgrades?***

Two other techniques considered feasible for the determination of the CP phase, the mass hierarchy and precise measurement of other oscillation parameters are the beta beam and a high power superbeam.

The beta beam concept has been studied at CERN since 2002. Radioactive ions undergoing β^+ (β^-) decay are accelerated in the PS and SPS and accumulated in a storage ring to produce pure ν_e ($\overline{\nu}_e$) beams. The baseline facility has been investigated in the FP6 EURISOL design study, based on the SPL and much of the existing CERN infrastructure. The ions are ^{6}He and ^{18}Ne, accelerated to a γ of 100 which yields a neutrino end point under 1 GeV. Production of ^{6}He is considered straightforward by spallation from the SPL or an alternative proton driver of a few hundred kW, however a means to produce ^{18}Ne ions with sufficient intensity has yet to be established. Ideas for this exist and a demonstration of feasibility is now of high priority. In EUROnu another procedure for the production of ^{8}Li and ^{8}B is being investigated. These ions have a higher Q-value and hence give rise to higher energy neutrinos for the same γ, however establishing the overall viability of a beta beam facility with these ions is still in its infancy. Other beta beam solutions using the He and Ne ions accelerated to a much higher γ (350) have been considered but would require, at CERN, a new 1 TeV SPS and so they are considered impractical. A limitation on ion intensities for all beta beam options is given by the need to top up in the storage ring with a finite number of short bunches in order to preserve the required small duty factor. The cost estimate of a beta beam facility is not available yet and will be necessary for decision making.

A future superbeam will require a high power (2-4 MW) proton driver. At CERN there would appear two superbeam alternatives, a low energy one based on a high power SPL, and a high energy one based on a new high power 50 GeV proton synchrotron. The former requires detectors within <~300 km of CERN whilst the latter could possibly use detectors placed at much greater distances from CERN, even as far as Pyhäsalmi, 2300 km away. Whilst the high energy version has attractions the timescale for construction would appear non-competitive when related to ongoing projects elsewhere in the world.

Studies of the possible upgrade of the CNGS beam have also been examined and were discussed at the May workshop. For this to be an effective long term solution the intensity would need to be increased by roughly an order of magnitude, the beam energy for a detector in Gran Sasso should ideally be less than at present and the absence of a near detector station is a weakness.

The low energy superbeam is being studied in the framework of a EUROnu workpackage, with many issues in common with the neutrino factory target study. Alone it is of similar performance as other facilities planned around the world, but it offers a powerful synergy with the baseline ^{6}He/^{18}Ne beta beam. This synergy between beta beam and superbeam could be one of the possible strengths of a future programme based at CERN. At these low energies the Water Cherenkov constitutes the baseline far detector, however the interactions of low energy neutrinos are imperfectly known or understood and so, in such a scenario, particular attention must be paid to the near detector station for this information. The low energy superbeam/beta beam combination could achieve sensitivity to CP violation for $\sin^2 2\theta_{13} > 2\ 10^{-4}$, and some sensitivity to the mass hierarchy in combination with atmospheric neutrinos.

Superbeams and beta beams can be aimed at large underground detectors, which could also be used in the search for proton decay and for astroparticle physics applications. This is being investigated, in particular in the framework of the LAGUNA design study. R&D and test beam studies for such detectors would be greatly helped by a support at CERN.

Elsewhere in the world, two superbeams will be operational in the next few years. In Japan the T2K experiment, with very substantial European participation, observed a first neutrino event in the near detector on 22 November 2009 and a first neutrino event in the far detector on 24 February 2010. In the USA the upgraded FNAL NUMI neutrino beam will be exploited by a new 15 kton segmented scintillator detector, NOνA, 810 km away. Data taking will start in 2013. On a foreseen time scale of 6 to 15 years, upgrades of T2K in Japan and a new beam within the framework of Project-X in the USA, will have higher power, larger detectors, longer baselines and higher neutrino energies (1-3 GeV). They expect a potential sensitivity to CP violation and the mass hierarchy down to $\sin^2 2\theta_{13} \sim 10^{-3}$.

A CERN-based program in direct competition with the Japanese and American ones would be of interest only if it can be timely or demonstrably superior in performance. Otherwise, participation by European groups in those programs could be usefully supported at CERN.

Originally it was assumed that the discussion of the future neutrino facilities should be related to the planned upgrade of the LHC injection chain, however the SPC is informed that the form of any LHC upgrade has yet to be decided.

Should the LHC upgrade consist of the SPL & PS2 then the basic SPL would probably be adequate for the standard beta-beam, whilst the neutrino factory and superbeam would require at least upgrading the SPL to a high power (~4MW) version. A new 50 GeV PS2 would only be of interest for neutrino physics if it was of substantially higher power than the PS2 which has been envisioned for the LHC.

The most powerful options for CERN for the 2020's are a beta beam/superbeam combination or a neutrino factory and for both of these a high power proton driver is an essential. This would have numerous other uses outside the neutrino area.

Question 4: ***What is the view of the SPC on the merit of a European strategy in this phase of neutrino experimentation and whether it should have a place on the future CERN road map?***

No global strategy exists concerning accelerator-based neutrino facilities.

In Europe, in line with the recommendations of the 2006 Strategy for Particle Physics, a number of R&D efforts have been undertaken to understand by 2012 the feasibility of the major options and their cost. Establishing an agreed R&D strategy supported by a medium-term road map and a review process, would be highly desirable. This should include specific aspects for beta beam and neutrino factory.

CERN, as the European particle physics organisation, should play an important role in the process leading to the definition and implementation of the European strategy with respect to a neutrino physics programme. A targeted contribution from CERN on specific aspects related to the development of intense neutrino beams, for which CERN has unique expertise, would provide vital support to the European neutrino physics community, enabling it to achieve its goals.

On the 2012/2013 timescale, new experimental results from the neutrino oscillation experiments and from the LHC, as well as the results of the design studies and R&D work, will serve as input to the definition of the long term strategy. Europe should then be in a position to devise a road map for the production of intense neutrino beams in its Strategy for Particle Physics.

3. Conclusions and recommendations

General recommendations

- CERN, as the European particle physics organisation, should play an important role in the process leading to the definition and implementation of the European strategy with respect to a neutrino physics programme. To do so CERN must create stronger links with the European neutrino community.

- Re-establishing neutrino groups in PH and AB departments would, if it is practicable, be a positive step in this direction. However, the SPC recognizes that the desire to set up such groups has to be balanced against the many other competing demands on CERN's resources.

- The workshop on the European Strategy for Future Neutrino Physics was very successful. Regular meetings of this type, organized under the auspices of CERN and ECFA, could help in the integration of the European neutrino community and in increasing the role of CERN in the strategic global planning for neutrino physics.

Recommendations for specific support from CERN to enable strategic decisions

- Costing. Support for providing comparable costing of the superbeam, beta beam and neutrino factory options is needed within the EUROnu/IDS-NF framework. In Europe the expertise required for such a comprehensive work is only available from CERN.

- Radioprotection and general safety issues. The development at CERN of a high power target facility, preferably with international collaboration from other laboratories, would be a major asset, not only for the neutrino programme but also for the increasing number of areas where high power proton beams are needed.

- Completing key R&D programmes. For the beta beam, it is vital to demonstrate the feasibility of producing sufficient ^{18}Ne. For the neutrino factory continued contributions to the MICE experiment are important to demonstrate ionization cooling in a timely fashion for 2012/2013.

- R&D for future neutrino detectors. This has been taking place in Europe for some time and support from CERN, e.g. by supplying test beams, would be highly beneficial.

Long term strategy planning

- It is unrealistic to expect to have a high intensity neutrino source of any kind in Europe before the early 2020's.

- By this time it is reasonable to expect that there will be a number of years of operating and upgrading superbeams in Japan and in the USA. This should be closely followed.

- Thus if Europe is to be competitive in the 2020's it should concentrate on the R&D for a new intense source, i.e. the neutrino factory or the beta beam. It would be advisable to organise a systematic review of the progress and prospects of this work.

ANNEX

Relations between CERN and the ongoing development work regarding future neutrino facilities

II. Supporting document

1. The importance of neutrino physics

Some of the most pressing questions in particle physics, about the mechanism of mass generation via electroweak symmetry breaking and the possible existence of new particles at the TeV scale, will be answered by the LHC in the next decade. Other, equally important questions concern: the experimental and theoretical understanding of fermion masses, mixing angles and phases; the possibility of a more unified theory of the fundamental interactions than the Standard Model; the origin of some observed properties of the Universe such as its large-scale structure, the cosmic microwave background, the matter-antimatter asymmetry, dark matter and dark energy. The optimal path for addressing these questions and the time scales needed for finding the answers are less precisely defined, and a variety of approaches is required, adapting the strategy to the inflow of new information and technological progress.

Neutrinos play a key role in many of the above problems. Leaving aside the importance of neutrinos in astrophysics and cosmology, and concentrating here on particle physics, precise determinations of the neutrino properties will shed light on the breaking of the SM symmetries associated with total baryon and lepton number and lepton flavours. Moreover, neutrinos are potentially a window (through the so-called see-saw mechanism, where the smallness of neutrino masses is explained by the interplay of weak-scale Dirac masses with much larger Majorana masses) to very high mass scales, directly inaccessible to foreseeable colliders.

The last decade has witnessed important experimental progress in flavour physics, both hadronic and leptonic. In the quark sector, precise measurements from experiments at the B factories, at the Tevatron and at other facilities have strongly confirmed the SM picture of flavour breaking, including CP violation, as encoded in the CKM matrix. Hadronic flavour physics is now an experimentally mature subject, where all the SM parameters (six quark masses[3]) three mixing angles and one CP-violating phase) are determined precisely from a largely redundant set of measurements, and high-statistics experiments are being performed or planned to search for small deviations from the SM predictions. The situation in the lepton sector is quite different: leptonic flavour physics is at a much earlier phase of development, with some fundamental parameters still undetermined and room for big discoveries.

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[3] Barring the theoretical limitations in the determination of the light quark masses.

In the minimal, renormalizable version of the SM, including only left-handed neutrinos, the latter are massless and both total (baryon minus) lepton number and lepton flavour are conserved. The evidence for oscillations of both atmospheric and solar neutrinos, later supported by terrestrial experiments with neutrinos produced by accelerators and reactors, shows conclusively that lepton flavour is not conserved and that neutrinos do have mass. The questions of whether total lepton number is perturbatively conserved[4] and to what degree charged lepton flavour-changing transitions occur remain open. Their answer is crucial for identifying the more fundamental theory that will supersede the SM.

Present observations can be incorporated by a minimal extension of the SM, where: there are only three fermion families; each fermion family includes a right-handed neutrino, carrying no SM charge; total lepton number is conserved; neutrinos get Dirac masses in the same way as the other SM fermions from their Yukawa couplings to the Higgs field; mixing in the neutrino sector is governed by a 3x3 unitary matrix analogous to the CKM matrix. Even with this minimal SM extension, several new parameters are required to define the lepton sector: three neutrino masses (m_1, m_2, m_3), three mixing angles (θ_{12}, $\theta_{23,}$ θ_{13}) and one CP-violating phase. This minimal SM extension appears straightforward, but it requires addition to the SM of a new conservation law, B-L conservation, and introduces Yukawa couplings for the neutrinos that are many orders of magnitude smaller that those of all other fermions.

An appealing possibility, however, is that total lepton number is not conserved. Then, neutrinos can have Majorana masses and, if the right-handed ones are large enough, the smallness of the light neutrino masses arises from the ‘see-saw’ mechanism. This has potentially major consequences for particle physics, with the possibility of observing lepton-number non-conserving processes such as neutrinoless ββ-decay. It could also impact our understanding of the evolution of the early universe, in combination with leptonic CP violation[5]: neutrinos may play a role in the generation of the cosmological matter-antimatter asymmetry by leptogenesis. With three light Majorana neutrinos, the number of physically meaningful CP-violating phases in the mixing matrix increases from one to three, although only one of them, δ, affects neutrino oscillation phenomenology.

Assuming only three light neutrinos, and irrespective of their Dirac or Majorana nature, oscillation measurements can be sensitive to two squared neutrino mass differences, the three mixing angles and one CP-violating phase, δ. Currently, two of the mixing angles, θ_{12} and θ_{23}, have been measured, but there is only an upper limit on θ_{13} and no information on the phase δ. $(\Delta m^2)_{12}$ has been determined from solar neutrino experiments and KamLAND. The sign of $(\Delta m^2)_{13}$ is presently unknown (the two signs correspond to the normal and inverted mass hierarchies), whereas its magnitude is measured by atmospheric neutrino experiments and by experiments with muon neutrino beams. Non-oscillation data (from β-decay, cosmology and neutrinoless ββ-decay) have only been able to constrain some combinations of neutrino masses, with upper bounds of the order of the electronVolt, but their absolute scale is still undetermined.

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[4] Non-perturbative violations of baryon and lepton number are present already in the SM: they are negligible in particle physics experiments, but can play an important role for baryogenesis.

[5] The CP-violating phases and other parameters in leptogenesis are in general different from those of neutrino oscillations, but the two sets could be related in specific models.

Many crucial questions in neutrino physics are thus unanswered today. A very important one, perhaps the most important, is whether total lepton number is conserved, and is addressed by the current and planned experiments on neutrinoless $\beta\beta$−decay. A positive result would not only establish that total lepton number is not conserved, but also give an indication on the absolute neutrino masses, although Majorana phases and nuclear effects complicate the interpretation. Another important constraint on the absolute scale of neutrino masses will be provided by the Katrin tritium β-decay experiment, irrespective of whether neutrinos are Dirac or Majorana. The links between cosmology or astrophysics and neutrino properties will become more stringent in the future, but the most likely and solid outcome will be to input information from the latter to the former.

The other most important question in neutrino physics is whether CP is violated in the leptonic sector. If the source of CP violation is a sufficiently large non-vanishing phase δ, and the mixing angle θ_{13} is sufficiently far from zero[6] a positive answer can be achieved in oscillation experiments. There are other important issues that can be answered by precise neutrino oscillation experiments. How close is θ_{23} to 45°? How close is θ_{13} to zero? What is the sign of $(\Delta m^2)_{13}$? The answers to such questions could point to some underlying flavour symmetry.

The next step in future neutrino oscillation experiments will be to determine the value of θ_{13}. The size of this parameter affects both the sensitivity to leptonic CP violation and the sensitivity to the sign of $(\Delta m^2)_{13}$ via matter effects. Determination of θ_{13} is the main aim of the next generation of long baseline accelerator experiments, T2K in Japan and NOνA in the USA, as well as of the reactor experiments, Double Chooz in Europe, RENO and Daya Bay in Asia. First results, possibly still upper limits, can be expected in the next three years. They will guide measurements of CP violation and the mass hierarchy with more powerful long baseline experiments, such as can be carried out by a neutrino factory, a beta beam or possibly, if θ_{13} is close to the present limit, by a higher power conventional superbeam combined with larger detectors.

Neutrino oscillation experiments must also ultimately test the validity of the minimal 3-neutrino scheme with unitary mixing, further constraining alternative possibilities such as light sterile neutrinos. To achieve this goal, the parameters must be measured in more than one way to check consistency. Such checks have been very successful for the CKM theory, but are much harder for neutrino mixing, as there are fewer opportunities for measurements. This requires flexibility in the nature of the source and the ability to detect as many final states as possible, ideally including taus.

To which accuracy should the neutrino parameters be measured? Without a theory of flavour, this question is difficult to answer theoretically, and it becomes the role of experiment to take the lead. A goal of particle physics is to establish a theory constraining these parameters and devising relationships between them. It could be that the leptonic sector is more directly connected with a possible underlying flavour symmetry than the hadronic one, as suggested by the success of some simple models.

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[6] It is actually sufficient that θ_{13} be as large as 0.1 degrees ($\sin^2 2\theta_{13} > 2.10^{-5}$) for CP violation to be observable at e.g. a neutrino factory for the range of δ shown in Fig. 2.

Finally, we may ask about possible relations between neutrino parameters and new physics, observable at the LHC or in experiments on charged lepton flavour violation. Such a relation is by no means guaranteed, but could arise in models where the physics behind neutrino masses and mixings is not much above the TeV scale. If so, it would be extremely important to establish all possible correlations by performing precise measurements on all fronts.

2. Experimental Neutrino Physics – Now and in the Near Future

2.1. Oscillation experiments

Neutrino oscillations between the three known families are by far the best theoretical explanation of the features of all the collected data on atmospheric, accelerator, solar and reactor neutrinos. The present knowledge of neutrino oscillations can be summarized as follows. Four of the six oscillation parameters have been measured so far. The 'atmospheric parameters', $|\Delta m^2_{23}|$ and θ_{23}, result from oscillations of atmospheric and accelerator neutrinos for values of baseline L and energy E such that L/E ~500 km/GeV with best fit values of $(2.40\pm0.12)\ 10^{-3}\ \mathrm{eV}^2$ and $(45\pm4)^o$, corresponding to maximal mixing of the neutrino mass eigenstates into muon and tau neutrinos. The 'solar parameters', Δm^2_{12} and θ_{12}, are determined from the oscillations of solar and reactor neutrinos for L/E ~ 20,000 km/GeV. The present best fit values of $(7.7\pm0.2)\ 10^{-5}\ \mathrm{eV}^2$ and $(34.8\pm1.2)^o$ correspond to large but not maximal mixing of the first mass eigenstate into electron neutrino and the mixed muon and tau neutrinos. Information is missing on: i) the value of θ_{13} describing the electron-neutrino content of the neutrino mass eigenstate ν_3; ii) the sign of Δm^2_{23} related to the neutrino mass hierarchy; and iii) the value of the CP-violating phase δ. The present upper limit on $\sin^2 2\theta_{13}$ of 0.14 comes from the reactor experiment CHOOZ, and is compatible with the information extracted from three-neutrino fits to all oscillation data.

The running experiments KamLAND and BOREXINO in the solar region, MINOS and OPERA in the atmospheric region, will improve knowledge of the dominant oscillations in these regions. MINOS, using the Fermilab NuMI beam, is a disappearance experiment, measuring the survival probability $P(\nu_\mu \rightarrow \nu_\mu)$, and currently dominates the $|\Delta m^2_{23}|$ determination. The OPERA experiment, using the CERN CNGS beam, aims at the observation of ν_τ appearance in the initial ν_μ beam. In this way $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, dominant in the atmospheric region, will be directly demonstrated. The OPERA detector is characterized by its fine granularity and capabilities for kinematic measurements, necessary for background-free searches of the ν_τ interactions. The OPERA and MINOS experiments could also provide further constraint on $\sin^2 2\theta_{13}$.

The near future approved oscillation experiments aim at discovering the effects resulting from a finite value of $\sin^2 2\theta_{13}$. The expected sensitivity of these first stage experiments is ~0.01. It can be reached in two ways: either by searching for the ν_e appearance in the $\nu_\mu \leftrightarrow \nu_e$ oscillations in accelerator experiments, or by looking, á la CHOOZ, for the $\overline{\nu}_e$ flux disappearance in reactor experiments.

The leading term in the very complex probability formula describing the ν_e appearance in $\nu_\mu \leftrightarrow \nu_e$ oscillations is proportional to $\sin^2 2\theta_{13}$. The CP violating term is proportional to $\sin\theta_{13}\sin\delta$ and there is also a matter effect term sensitive to the sign of Δm^2_{13}, the size of which is dependent on the baseline and $\sin\theta_{13}$. Several observations are important here: i) the possibility to measure CP violation depends on the values of $\sin\theta_{13}$ and δ; ii) the measurement of $\sin^2 2\theta_{13}$ itself depends on the other oscillation parameters (hence correlations) quadratically and trigonometrically (hence degeneracies). Thus, the results of the measurement of $\sin^2 2\theta_{13}$ obtained in a few years will help to determine the best strategy for the subsequent searches for CP violation. However, in order to resolve the ambiguities, redundant measurements or several measurements under different experimental conditions will be needed.

Two off-axis accelerator experiments will take place in the near future: the T2K (Tokai to Kamioka) experiment at JPARC, currently in a beam commissioning phase and the NOvA experiment at Fermilab, recently approved for construction. In these "off-axis" experiments the detectors are located at a certain angle (of the order of a few tens of mrads) with respect to the central neutrino beam direction. Due to the kinematics of the π meson decay, the off-axis neutrinos have a narrower energy spectrum while on-axis neutrinos have a larger spread. This solution yields a substantial background reduction and allows better tuning of the neutrino energy to the first oscillation maximum.

The near detector of the T2K experiment, ND280, is placed at a distance of 280 meters from the neutrino target and is a multi-purpose magnetic spectrometer. The famous 50 kton Water Cherenkov SuperKamiokande detector at a distance of 295 km from the source will serve as the far detector during the first stage of experiment. The T2K experiment has a very sizeable European participation, specifically with the new proton beam to the neutrino target, the neutrino target station itself and the beam dump at the end of the decay tunnel, all designed to be able to stand high power (~1MW for the target, 4 MW for the other elements). The near detector station has important European contributions with the ND280 magnet and the TPC, ECAL, SMRD and INGRID sub-detectors. The measurement of particle production in the T2K target is performed in the NA61 experiment at CERN. T2K is currently in the beam commissioning phase and a first neutrino event was recorded in the near detector station on the 22 November 2009 and in the far detector station on the 24 February 2010. The beam intensity will increase in steps up to the nominal 0.75 MW in a few years. First oscillation results are expected for summer 2010. It is estimated that 1 MW·year of integrated power is needed for a 3σ measurement of $\sin^2 2\theta_{13}$ if it is of the order of 0.05. The ultimate goal of a 3σ sensitivity to $\sin^2 2\theta_{13} \approx 0.01$ will require integrated power of (3-3.5) MW·year. The experiment by itself has no sensitivity to CP violation or the mass hierarchy, but should improve the atmospheric parameters Δm^2_{13} and θ_{23} significantly.

The far detector of the NOvA experiment will contain 15 ktons of fine grained segmented scintillator with wavelength shifter/APD readout. The detector will be placed off axis on the NUMI beam at a distance of 810 km from FERMILAB. It is aimed only at beam neutrino measurements and for this reason will be situated near the surface with only a small overburden. It expects similar sensitivity to $\sin^2 2\theta_{13}$ as T2K, but has a different baseline and is planning to also run anti-neutrinos. The combination of NOvA, T2K and the reactor experiments, could yield, if $\sin^2 2\theta_{13}$ is very close to the present upper limit, some sensitivity to mass hierarchy and CP violation. when all are completed.

As mentioned above, the alternative approach to the θ_{13} determination relies on reactor disappearance experiments with the baseline corresponding to the atmospheric Δm^2_{23}. A big advantage of this approach is that the survival probability for these low energy $\overline{\nu}_e$'s is sensitive to $\sin^2 2\theta_{13}$, but not to the CP phase or matter effects. The question is how much the new experiments would improve over the sensitivity of CHOOZ. At least two identical detectors (near and far) are needed in order to reduce the error on the $\overline{\nu}_e$ flux. Three new reactor experiments are under construction: Double CHOOZ in France, Daya Bay in China and RENO in Korea. The Double CHOOZ experiment will start data taking with only the far detector in 2010 and with both detectors in the fall of 2011. After three years of data taking with two detectors the experiment should exclude $\sin^2 2\theta_{13} > 0.03$ at 90% C.L. The Daya Bay experiment should start data taking with one near detector station in 2010 and with three detector stations (two near and one far) in 2011. It should exclude $\sin^2 2\theta_{13} > 0.01$ at 90% C.L. after two years of data taking with the full setup. The RENO experiment, expected to start data taking with two detectors in summer 2010, is designed for an ultimate sensitivity in the $\sin^2 2\theta_{13}$ measurement of 0.02 at 90% C.L. A sensitivity of 0.01 in $\sin^2 2\theta_{13}$ determination is probably the ultimate value that can be achieved in reactor experiments.

The main challenge for subsequent future experiments is the determination of the CP violating phase, δ, which means entering a field of very precise measurements. Precision measurements in the case of weakly interacting neutrinos represent an enormous experimental challenge. It is not only a question of huge and preferably high granularity detectors but also of adequate neutrino sources in the form of very intense accelerator beams which can be provided by a high power superbeam, a beta beam facility or a neutrino factory. Second phase programmes, relying on the higher intensity superbeams, are being considered for the T2K experiment at JPARC and for the Fermilab neutrino program. They are described in Section 3.2.

2.2. The importance of Non-Oscillation Experiments for Neutrino Properties

Oscillations demonstrate that lepton flavour is not conserved and that neutrinos are massive. The oscillation rate is dependent on the modulus of the mass squared differences, $\left|\Delta m^2_{ij}\right|$ and in matter it can be sensitive to the sign. However no information can be retrieved on the absolute mass. This is one of the most important but also one of the most difficult measurements to make. Even more fundamental is the possibility that total lepton number is not conserved and if this is the case neutrinos can be Majorana particles. This has profound consequences, however the only experimental procedure to determine this is to search for neutirnoless double beta decay in nuclei.

Mass determination

Cosmological data can give bounds on $\sum m(\nu_i)$ but these are model dependent and there is not total agreement about the interpretation. A conservative current bound is <~0.7 eV and there are hopes that this could improve within the next few years but the systematic uncertainty arising from the model dependence is likely to remain difficult to quantify. The rate of neutrinoless double beta decay (0νββ) depends on the quantity $m_{ee} = \left|\sum U_{ei}^2 m_i\right|$ and thus the absolute mass, but this requires neutrinos to be Majorana and extracting an accurate value is complicated by uncertainties in the nuclear matrix elements

Currently the only procedure which can approach the sensitivity required to give a measure of the neutrino mass with minimal theoretical uncertainty is the measurement of the endpoint of the electron spectrum in beta decay. Tritium is the preferred element for this. The sensitivity results from both the measurement of the maximum electron energy and the shape of the spectrum very close to the endpoint,. The measurement yields the square of the 'electron neutrino' mass defined by $m^2(\nu_e) = \sum |U_{ei}|^2 m_i^2$. Previous experiments at Mainz and Troitsk have set upper limits around 2.2 eV for $m(\nu_e)$ but within the next few years the KATRIN experiment at Karlsruhe has the goal of ~0.2 eV. This is a major extrapolation on the earlier Mainz experiment, it is a very large spectrometer, over 60 m long, and almost certainly represents the ultimate accuracy which can be achieved with this technique. Data taking is now scheduled for 2012.

Neutrinoless Double Beta Decay

The most probable explanation for an observation of neutrinoless double beta decay is that it has proceeded by the exchange of a massive Majorana neutrino, i.e. for neutrino and antineutrino not to be distinct. At the present time this would appear to be the only method to prove the Majorana nature which is assumed in many theories for the low neutrino mass and the necessary rate of CP violation to explain the baryon-antibaryon asymmetry via leptogenesis. It is thus of vital importance.

The rate of 0νββ is given by $(T_{1/2})^{-1} = G^{0\nu}\left|M_{GT}^{0\nu} - M_F^{0\nu}\right|^2 m_{ee}^2$ with the unknowns the nuclear matrix elements and the quantity $m_{ee} = \left|\sum U_{ei}^2 m_i\right|$. Thus a measurement of a double beta decay rate will confirm the Majorana nature of the neutrino and give a value for the absolute mass to the degree that the nuclear matrix elements are known. A positive observation has been claimed, but it is not universally accepted and is certainly in need of confirmation. Excluding this, current limits give lower limits on the 0νββ half life in the region of 10^{23} to 10^{25} years corresponding to m_{ee} values ~ 1eV.

The experiments focus on isotopes which undergo normal double beta decay and then look for a signal corresponding to the two beta electrons having an energy sum equal to the Q-value of the transition. The expected rates are very small, from 6 to 10 orders of magnitude lower than the two neutrino rate, and hence energy resolution and background elimination are critical. The experiments can be broadly split into two categories, purely calorimetric homogeneous ones where the signal is an energy pulse at the correct value and heterogeneous ones which also add tracking capabilities to identify the two electrons. Dominant backgrounds are from the end of the two neutrino beta decay spectrum and from contaminant radioactive decays, hence the need for high purity components and a low background environment. The tracking detectors have an advantage in eliminating the radioactive background but have poorer energy resolution and so the two neutrino decay becomes more serious.

As systematics, particularly the backgrounds, are crucial for the sensitivity it is necessary that the search for $0\nu\beta\beta$ is conducted with different techniques and different nuclei. As a result there is a very lively programme in this area which is evolving rapidly. Some of the experiments which aim for results during the next decade are:

- GERDA, Semiconductor calorimeter experiment using ^{76}Ge building upon the expertise from the original Heidelberg-Moscow and IGEX experiments. A first aim is to establish if the claimed observation of a signal by Klapdor-Kleingrothaus et al. is valid.
- CUORE. A cryogenic bolometric experiment using ^{130}Te, evolving from CUORICINO.
- SuperNEMO. A heterogeneous tracking + calorimeter detector evolving from NEMO-3 which will concentrate on ^{100}Mo and ^{150}Nd
- EXO-200. Employing a liquid Xe TPC this will use both ionisation and scintillation from ^{136}Xe.
- Majorana. This will also use ^{76}Ge and it is assumed that if the next generation of investigations fail to see a signal it will combine with GERDA for a multi tonne experiment.
- MOON. Investigating the use of tracking and calorimetry for ^{100}Mo.
- COBRA. Prototyping the use of the semiconductor CdZnTe.
- SNO+. Planning to fill the SNO detector with liquid scintillator containing ^{150}Nd. This will be significantly larger than other experiments although with less good energy resolution.
- XMASS. Employing a multipurpose scintillating liquid Xe detector.

These experiments aim to reach half lives $>\sim 10^{27}$ years corresponding to values of m_{ee} $<\sim 0.02$ eV. Regrettably, even such sensitivities may not be adequate, particularly if the normal hierarchy of masses holds. They may just result in an improved upper limit on the Majorana mass and no information at all if neutrinos are Dirac. Nevertheless, the question they aim to answer is of such fundamental importance that they must be strongly supported.

3. Future Neutrino Facilities

3.1. Neutrino Factory

The Neutrino Factory is based on the possibility to produce, accelerate and store high intensity beams of muons. As will be discussed below, the neutrino factory is the most powerful device to study neutrino oscillations. Although it is substantially less challenging, it has many design features in common with a Muon Collider, from where the idea originated. Both the Muon Collider and the Neutrino Factory are novel accelerators and their development is of great interest for the future of the field of particle physics. Great emphasis has recently been placed on developing this technology at Fermilab and a collaboration of CERN in this enterprise seems highly desirable on general grounds.

R&D for the Neutrino Factory is largely synergetic with that of the muon collider. It comprises accelerator physics conceptual design and simulations, design effort, and experimental R&D activities. Most of the concepts originated in the 1990's under the auspices of the 'Neutrino Factory and Muon Collider Collaboration' organized as a consortium of efforts from Fermilab, Berkeley National Laboratory and Brookhaven national Laboratory and other institutions in the United states. The design of the Neutrino Factory has been developed since 1998 and has been the object of several design studies, both in the USA and in Europe. From this earlier work the basic feasibility and principles of the Neutrino Factory, as well as its physics potential, have been established, as well as a first cost estimate: US study II (2002) gave an estimate of 2 B$ (not including salaries) and the study IIa (2004) indicated possible cost optimizations of the order of 30%. A performance of 10^{21} 20 GeV muon decays per year starting from a 4 MW proton beam on target was considered achievable. A programme of experimental R&D has been launched to establish the feasibility of the most critical elements of the Neutrino Factory: the MUon COOLing R&D program MUCOOL at Fermilab, the target experiment MERIT at CERN, the Muon Ionization Cooling Experiment MICE at RAL and the EMMA non-scaling FFAG[7] development at Daresbury Lab. The International Scoping Study (ISS), initiated at the request of the RAL director in 2005, also covered to some extent the potential of both a conventional neutrino superbeam and the beta-beam. It spelled out well-defined baseline parameters for the accelerator and detectors, to be brought forward for a more detailed study including cost estimate, the International Design Study (IDS-NF), which has been ongoing since 2007.

These experiments and studies are carried out so far by somewhat project-dependent collaborations comprising: 1) in the USA: the Neutrino Factory and Muon Collider collaboration; 2) in Europe: a consortium of UK institutions (UK-NF, MICE-UK), university groups in Bulgaria, France, Germany, Italy, Spain, Switzerland, and contributions from

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[7] Fixed Field Accelerating Gradient synchrotron. Due to the short muon life time, standard synchrotrons with ramping magnets cannot be used, and a new design, based on large aperture fixed field dipoles accepting a factor of >= 2 in momentum has been devised to accelerate muons.

CERN; 3) collaborating institutions in Canada, China, India and Japan. The European institutes receive support from EU via the FP7 programmes: EUROnu design study and EUCARD. A Neutrino Working Group at CERN was created in 1999 but terminated in 2002. Since 1998 the European working groups on future neutrino facilities have been sponsored by, and reporting to, ECFA.

The Neutrino Factory baseline layout is shown in Figure 1. Obtaining a beam of 10^{14} muons per second with the desired phase space properties is unprecedented. For comparison the beam intensities at PSI are 10^{9} muons per second. A high power 4 MW proton accelerator delivers a train of a few (3-5) short pulses (<3 ns) on a high Z target embedded in a 20 T solenoid. The energy of the primary protons is not a very sensitive parameter, pion production being within 20% of the optimum in the energy range of (4-15) GeV, and degrades only slowly above. The time structure is critical; the high power version of the SPL has been shown to be an adequate possibility but requires two additional proton storage rings to provide the desired pulse trains. A rapid cycling synchrotron would be directly applicable if the required high beam power can be achieved.

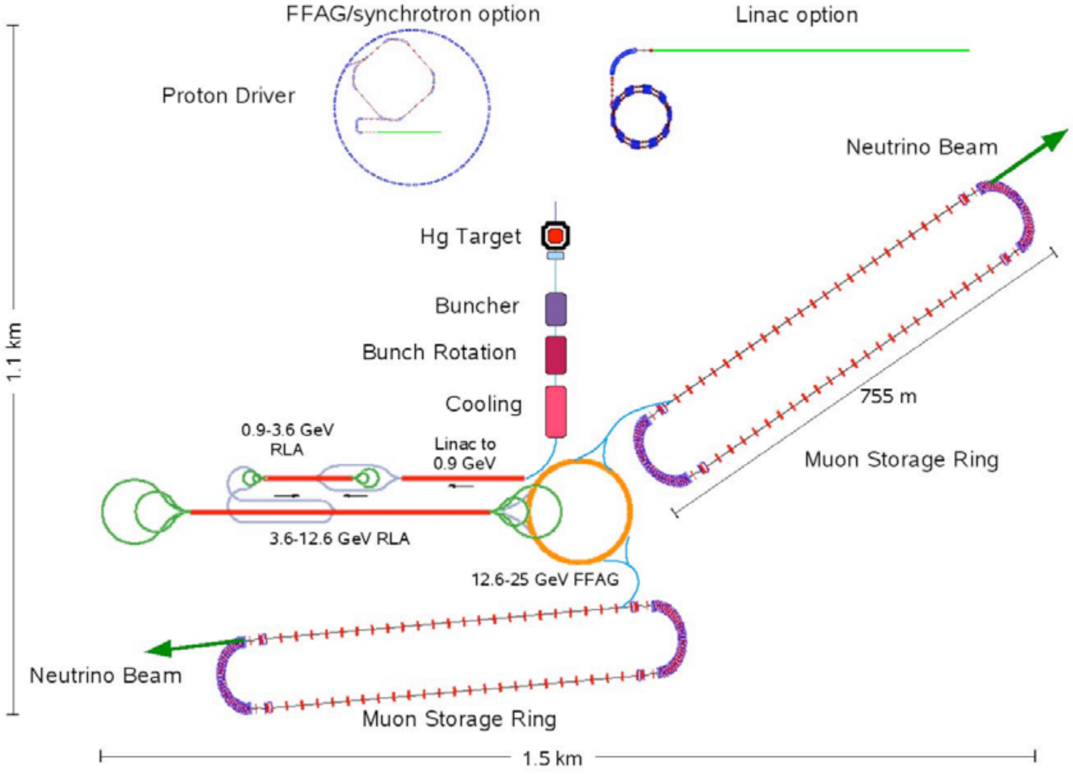

Figure 1 Layout to scale of the Neutrino Factory baseline

The feasibility of the target system was the aim of the MERIT experiment. MERIT demonstrated the safe operation of a mercury jet in a 15 T solenoid; it measured the properties of the jet when exposed to instantaneous intensities similar to those of an 8 MW proton beam; the effect of the train time structure was investigated. What MERIT has not demonstrated is the feasibility, including safety implication, of a production target infrastructure operating continuously at this high power. The study of a 4 MW liquid mercury converter target for EURISOL has been carried out in the EURISOL design study. The integration of the converter target, liquid-metal loop and associated fission targets into a facility which can provide safe and easy access to researchers, whilst guaranteeing optimal extraction of the radionuclides was achieved by the design team at CERN. While the similarities and synergies are evident, the set-ups are sufficiently different that the application of the EURISOL study to the specific case of a neutrino facility based at CERN needs to be worked out.

The muons of both signs produced from the decay of pions are spread over a large phase space. The reduction of longitudinal momentum is obtained by phase rotation and the transverse emittance is reduced by ionization cooling. Ionization cooling is the only possible technique given the short muon lifetime. It is a critical component in the performance and cost optimization of the Neutrino Facility, and even more for the Muon Collider. It has never been applied to muons in this energy range. It involves a succession of energy loss in low Z absorbers (Liquid Hydrogen or Lithium Hydride) and re-acceleration with RF cavities. The demonstration of the feasibility of a channel that performs according to calculations is the aim of the MICE experiment at RAL.

Throughout the first section of the accelerator, the muons of (100-300) MeV/c are contained in a longitudinal magnetic field in which the high gradient RF cavities are operated. Obtaining high accelerating gradient in magnetic field is the key accelerator physics challenge in muon ionization cooling. This question is addressed specifically in the MUCOOL test program at FNAL, but will be applied in MICE. Acceleration of the resulting beam must be extremely fast and perfectly synchronized. Synchrotron radiation by muons is suppressed and circular accelerators can be used, but the magnets must have fixed field. This leads to the use of recirculating linacs or fixed field accelerators with large momentum aperture (FFAG, Fixed Field Alternating Gradient), which can typically accelerate the particles by a factor 2-3. The principles of the FFAG have been known for more than 50 years and scaling FFAGs have been developed in the last 10 years for proton accelerators. For the neutrino factory a new version, the non-scaling FFAG, has been proposed for cost-saving reasons, making use of the fact that the muons remain only 10-20 turns in the accelerator. The practical application and operation are not well known. EMMA at Daresbury Lab aims at developing such a machine using electrons of similar velocity as the muons in the Neutrino Factory.

The accelerator can be designed in such a way as to accelerate both signs of muons simultaneously, as long as the neutrinos from $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ are separated in time by more than ~100 ns from those of $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ in the detectors. The stored muon energy is defined to be 25 GeV in reference to the effective tau production threshold (around 15 GeV), and the matter resonance (around 12 GeV). It is also well suited for maximal performance in detecting CP violation. The storage ring design is guided by the requirement of low angular divergence but is otherwise straightforward. There are no major issues of radiation or intensity in the storage ring.

Muon decays $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ (and $\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$) produce simultaneously two types of neutrinos. The appearance signal of most interest is $\{\nu_e \leftrightarrow \nu_\mu\ ;\ \nu_\mu + N \rightarrow \mu^- + X\}$(wrong sign muons) which must be separated from the non-oscillated signal $\bar{\nu}_\mu + N \rightarrow \mu^+ + X$ (right sign muons) by magnetizing the detector. This is a severe constraint and prevents the use of the large liquid detectors foreseen in the search for proton decay – although magnetizing a totally active scintillator or liquid argon detector of somewhat reduced size is considered. Wrong sign muon detection can be performed with very little background with a magnetized iron-scintillator neutrino detector (MIND). Based on the cost and performance of MINOS, NOvA and of the T2K near detector system, which demonstrate the progress made in light detection with avalanche photodiodes, a detector with a fiducial volume of 100 kton is considered as baseline detector. The MIND is also capable of measuring the muon neutrino disappearance and the neutral current channels. Additional detector types are required to take full advantage of the physics potential of the neutrino factory, for tau detection or for the detection of the wrong sign electrons; magnetized versions of the Totally Active Scintillator Detector (TASD), Liquid Argon or Emulsion detectors have been described in the ISS detector study. One of the main challenges is the design of an open magnet of this size. A lack of the emulsion suppliers can also be a problem for future developments.

Near detector systems are presently under simulation and design. By combination of muon flux measurement and measurement of the energy by muon spin precession the neutrino fluxes can be predicted with high accuracy. The high flux at the near detector allows significant samples of purely leptonic reactions to be observed, thus providing a normalization against which precise measurements of hadronic cross-sections for $\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e$ become possible – another important set of measurements of interest.

The precision that can be reached by experiments at a neutrino factory is typically one or more order of magnitude better for the oscillation parameters θ_{23} θ_{13} Δm^2_{13} and for the CP violating phase δ than for any other machine considered so far, with the possible exception of high gamma beta-beams. The sensitivity reach for measuring the parameter θ_{13}, should it be very small, is also better than for any other facility considered. Unlike most set-ups considered, the Neutrino Factory with two long baselines and a full analysis of the energy spectrum of appearance events is able to solve degeneracies and ambiguities completely over most of the parameter space to which it is sensitive. The ability to measure interactions of tau neutrinos offers unique possibilities to test the unitarity of the neutrino mixing matrix at either far or near detector stations. The optimum setup for a neutrino factory is mildly dependent on the existing knowledge on the value of the mixing angle θ_{13}. In particular one can note, as an existence proof, that there is a pair of baselines that are close enough to the optimum baselines stated by the ISS: CERN to Pyhasalmi in Finland (2285km), which is also a LAGUNA site, and CERN to INO in India (7152km).

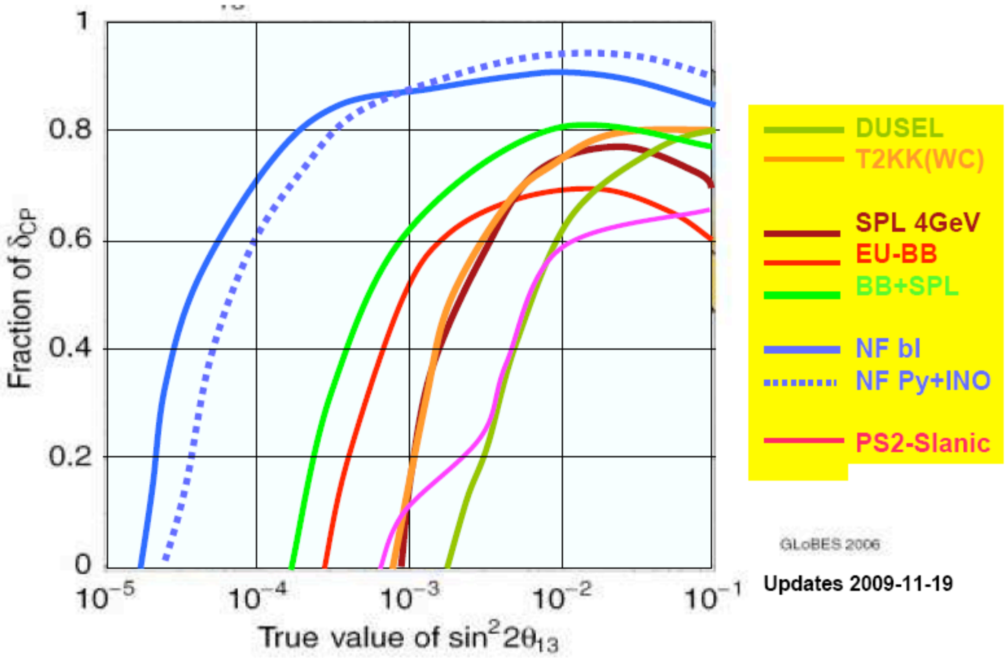

Figure 2

A representative compilation of sensitivities of some future long baseline projects. Here the fraction of δ_{CP} *where CP violation can be observed at 3 standard deviations is plotted as a function of* θ_{13}*. T2KK: T2K 1.66 MW beam to 270 kton fid volume Water Cherenkov detectors in Japan (295km) and in Korea (1050 km)*[8]*; DUSEL: a WBB from Fermilab to a 300 kton WC in Dusel (1300km)*[9] *; SPL 4 GeV, EU-BB and BB+SPL curves stand for the CERN to Fréjus (130km) project*[10] *; NF bl is the optimised ISS Neutrino Factory baseline with two 50 kton detectors*[11] *(4000km and 7000km baselines) and NF Py+INO represents the concrete baselines from CERN to Pyhaslami mine in Finland (2285 km) and to INO in India (7152 km)*[12]*; PS2-Slanic is a preliminary study of an experiment at 1500km based on an upgrade of PS2 to 1.66MW and a 100kton Liquid Argon TPC*[13]

The decision of if, when and where to build a neutrino factory will be determined by several factors, including, at any given time, the perceived relative feasibility and reach of more

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[8] T2KK: F. Dufour, T. Kajita, E. Kearns, and K. Okumura: *Further study of neutrino oscillation with two detectors in Kamioka and Korea,* NP08, KEK, 2008 http://arxiv.org/abs/1001.5165; a 100 kton of LArg TPC at the far location would give similar sensitivity.

[9] DUSEL, V. Barger et al Fermilab-081-AD-E Report on the long baseline neutrino experiment study (2006); a 50kton LArg in DUSEL would give similar sensitivities.

[10] Physics potential of the CERN-MEMPHYS neutrino oscillation project, (130 km)
Jean-Eric Campagne, Michele Maltoni, Mauro Mezzetto and Thomas Schwetz, JHEP04(2007)003. These curves have been recalculated by T. Schwetz-Mangold to take into account the present baseline intensities for the beta beam.

[11] The ISS Accelerator Working group (M. Apollonio et al.), “Accelerator design concept for future neutrino facilities”, 2009 JINST 4 P07001; The ISS Detector Working group (T. Abe et al.) “Detectors and flux instrumentation for future neutrino facilities”, 2009 JINST 4 T05001; The ISS Physics Working group (Bandyopadhyay et al.) “Physics at a future Neutrino Factory and super-beam facility”, Rep. Prog. Phys. **72** No 10 (Oct. 2009) 106201

[12] W. Winter, private communication; A. Blondel, IDS-NF meeting 4, Mumbai (2009)

[13] A. Rubbia, private communication to the SPC panel

conventional alternatives. The CERN strategy document recommends the information to be available in 2012. Although this date might be somewhat shifted due to the practical delays in one or both of the points above, we believe that this is an appropriate time scale that should not be changed at this point.

For the Neutrino Factory to be considered a credible possibility the following will be required.

1. The ongoing accelerator R&D experiments must be successful. This includes the MICE and EMMA experiments underway in Europe, and the MUCOOL program at Fermilab. Clearly support for these projects should receive the highest priority.
2. The potential show-stopper safety issues related to the 4MW target station handling a high Z liquid target such as mercury (or other metal i.e. a lead-bismuth eutectic used at PSI) must be addressed.
3. A credible estimate of the cost and time scale will be needed.
4. A credible and coherent scenario for at least one possible location must exist.

The stated aim of the IDS, the determination of cost and practical feasibility of a neutrino factory, is an important question that needs to be answered in a reasonable time scale, similar to the time scale at which the next large project in particle physics will be decided. The study is delocalized. The study appears to be lacking manpower in several aspects in particular for costing, safety, high power RF and other accelerator physics issues, which are precisely the points of expertise of CERN.

The points 1-4 above are very much the points expressed by the management of the IDS-NF in their answer to the question asked by the SPC panel. Although the IDS-NF (and EUROnu) study is delocalized, we believe that a credible answer to the points 2, 3, and 4 above requires a practical study at a given location.

3.2. Superbeams and Beta beams

Many other possibilities for competitive neutrino beams suitable for neutrino oscillations have been studied in the world, and in particular at CERN, in the context of the existing infrastructure and of the LHC upgrade. The CERN specific possibilities comprise: 1) upgrade of the muon-neutrino beam to Gran Sasso; 2) a conventional low energy muon-neutrino beam produced directly from the 4 GeV high power SPL proton beam or higher-energy beams from the 50 GeV PS2; 3) pure electron neutrino (anti-neutrino) beams produced by beta+ (beta-) decays of radioactive ions accumulated in a storage ring (‘beta beams’). All these alternatives have one dominant flavour of neutrino, thus, unlike the neutrino factory, do not require magnetized detectors; the giant detectors being discussed to search for proton decay and for other astroparticle applications can therefore be used, although for the pion-decay muon neutrino beams a deep underground site and its associated costs are not required due to the short time structure,. All the facilities currently considered produce neutrino beams between a few hundreds of MeV up to 5 GeV.

High intensity neutrino facilities in Japan and USA

Before discussing experiments that may take place at CERN it is in order to describe the program that is foreseen internationally. Facilities involving competitive high intensity conventional neutrino beams are considered for the 30 GeV proton synchrotron at JPARC in Japan (upgrade of the T2K experiment) and for Fermilab in the USA (the new Project X).

Upgrades to T2K are part of the KEK high energy physics roadmap, with increased beam power up to a maximum of 1.66 MW by around 2016. Above 1MW beam power the target technology must be changed, and an interesting study of a metal powder target has been pursued at RAL. A detector upgrade to 540 kton (fiducial) Water Cherenkov has been studied in two modules of 270 kton. There is great expertise on this technology in Japan. A Liquid Argon detector of 100 kton has also been suggested, and KEK has recently become engaged in R&D on this technology. Both detectors could be situated at the Kamioka site, or could be installed in a far detector location situated up to 1050 km in Korea or 658 km on the island of Okinoshima. A decision point could occur as soon as a significant $\nu_\mu \rightarrow \nu_e$ oscillation signal has been observed. By making use of the increased mass, anti-neutrino running and longer baseline the experiment could become sensitive to signs of CP violation down to $\sin^2 2\theta_{13} \approx 2\cdot 10^{-3}$ both in the appearance event energy distribution or in the neutrino vs antineutrino comparison. The experiment would also have sensitivity to the mass hierarchy over a more limited range.

A new project exists at Fermilab, “Project X” to increase the performance of the proton accelerator complex up to 2 MW by means of a superconducting proton linac based on a technology close to that of the ILC. At the same time support has been obtained to refurbish the Homestake Mine in South Dakota, 1300 km from Fermilab. The DUSEL project is considering the installation at this location of large underground detectors for proton decay, astrophysical neutrinos and beam neutrinos. A large Water Cherenkov (several 100 kton) or a large Liquid Argon detector (from 20 to 100 kton) would be exposed to a wide band pion decay neutrino beam from the Main Injector operating at 60 GeV. Fine grained calorimeters such as a Totally Active Scintillator Detector like NOvA or the Liquid Argon TPC, offer for these higher energies the advantages of better granularity and energy resolution.

Performance estimates for the discussed T2K upgrade and the DUSEL project have been reported in Fig2. In the same way as for T2K, the contributions of European groups to these experiments could be usefully supported at CERN. A CERN-based program in direct competition with these would be of interest only if it can be timely and demonstrably superior in performance.

Possibilities at CERN: 1) CERN to Gran Sasso beam

The performance of experiments on the CERN to Gran Sasso neutrino beam is limited in several aspects: the available beam power from the SPS, the absence of a near detector and the fact that the beam is set-up for high energy neutrinos suitable for the observation of

$\nu_\mu \rightarrow \nu_\tau$ transitions. Going off axis with a neutrino peak energy at the suitable value of 1.4 GeV with a 20 kton detector and assuming a beam power increase by a factor 2-4 could match or slightly improve the NOvA performance, but, as the baseline is so similar, the experiment would bring no qualitative improvement. The possibility for beam power improvement for CNGS has been carefully reviewed at CERN, however due to other users of the SPS and the present overall proton deficit, substantial gains would have to await the SPL and the PS2 operation. They would require reclassification of the facility. Changes to the beam line in the already activated environment are problematic. The near detector station needs to be defined or the allegedly small impact of its absence on physics results well justified. The time scale for both the beam power improvement and the construction of such a detector system would need to be carefully assessed to understand if this can be a competitive proposal.

Possibilities at CERN: 2) Low energy superbeam from high power SPL.

A low energy superbeam from the high power 4 GeV, 4 MW SPL is under study in the framework of EUROnu. The neutrino beam from pion decay (~300-400 MeV peak energy) is aimed at a very large Water Cherenkov (MEMPHYS project) situated at the Fréjus Laboratory. The low energy of the primary proton beam ensures a very low contribution to the neutrino beam from kaon decays, which are a source of an uncertain high energy tail in conventional neutrino beams. The focusing system considered consists of a single open horn in contrast with the more sophisticated systems at T2K, NUMI and CNGS and could probably be optimized further. The Water Cherenkov is very efficient at these low energies where quasi-elastic interactions dominate. However, low energy neutrino interactions on nuclei require important corrections for Fermi motion, binding energy, nuclear re-interactions and lepton mass effects. To cope with these, the near detector station needs a careful design, which at present does not exist. The performance of the setup is given in Fig2., assuming 10 years of running at 4 MW with a fiducial mass of 440 kton.

Possibilities at CERN: 3) High energy superbeam

If the 50 GeV PS2 originally discussed in the context of the LHC injector upgrade could be redesigned to give higher power, one could consider a pion decay superbeam with neutrino energies tuned to the 1st oscillation maximum at distances longer than 300 km, which are inaccessible to the low energy superbeam from the high power SPL. The physics potential is being studied in one of the work packages of LAGUNA, where apart from the Fréjus location (at 130 km from CERN) six underground sites at distances from CERN ranging from 630 km for Canfranc to 2300 km for Pyhäsalmi are considered. This corresponds to neutrino beam energies from 1.27 GeV for Canfranc to 4.65 GeV for Pyhäsalmi. To identify the electron neutrinos at energies from about 2 GeV, where the contribution of the quasi-elastic scattering to the total charge current neutrino cross-section is small, a fine grained detector, e.g. LAr TPC or TASD could be needed. Such detectors, as compared to water Cherenkov detectors, are limited in mass, but at high energy this is compensated by the increase of neutrino cross-section and better efficiency. The scheme is being studied within LAGUNA and one can expect a performance similar to that of T2KK or DUSEL, as shown in Fig.2.

Possibilities at CERN: 4) Beta beams

An original, and synergetic, possibility studied at CERN is the beta beam. The decay in a storage ring with long straight sections of ^{6}He and ^{18}Ne ions accelerated in the SPS to a maximum of 150 GeV per nucleon for ^{6}He ($\gamma < \approx 159$), produces neutrinos of $E=2\cdot\gamma\cdot E^*$ where E^* is the energy of the neutrino in the centre of mass of the decaying ion. For ^{6}He or ^{18}Ne, $<E^*> \sim 2$ MeV and $<E>\sim 600$ MeV, which is in the same energy range as the neutrinos from the SPL superbeam. The great virtues of the betabeam is to provide well understood beams of pure $\bar{\nu}_e, \nu_e$ beams; this allows appearance experiments free of beam-related backgrounds, as well as $\bar{\nu}_e, \nu_e$ cross-section measurements in the near detectors.

The combination of the beta beam with a superbeam permits an interesting test of time reversal symmetry T, by comparison of $\nu_\mu \rightarrow \nu_e$ (the superbeam appearance signal sensitive to θ_{13}, the sign of Δm^2_{13} and δ), and $\nu_e \rightarrow \nu_\mu$ (the beta-beam appearance signal sensitive to θ_{13}, the sign of Δm^2_{13} and δ). In the combination, the near detector of the superbeam measures the ν_μ cross-sections which are the signal process for the beta beam and vice versa, the near detector in the beta beam measures the ν_e cross-sections which are the signal process for the superbeam. The beta-beam-superbeam synergy appears to be one of the potential strengths of a future programme based at CERN. This synergy can only be achieved if the two types of neutrino beams have similar energy. For the SPL superbeam and a beta beam based on the present SPS and the ^{6}He and ^{18}Ne ions, one is limited to neutrino energies up to about 600 MeV, i.e. an optimal baseline of 300 km.

Since its invention is relatively recent, the performance limitations of the beta beam are still under evaluation. The baseline beta-beam uses as much as possible the present or foreseen CERN infrastructure and accelerates ions to $\gamma=100$. The main limitations occur i) at the source and ii) in the storage ring. The production of ^{6}He is feasible by interaction of spallation neutrons created by a ~200 kW beam on a BeO target using the ^{9}Be(n,α)^{6}He reaction. Capture of this noble gas by the ISOL technique and beam bunching with an Electron Cyclotron Resonance Ion Source (ECRIS) is well known technology for radioactive ion beams.

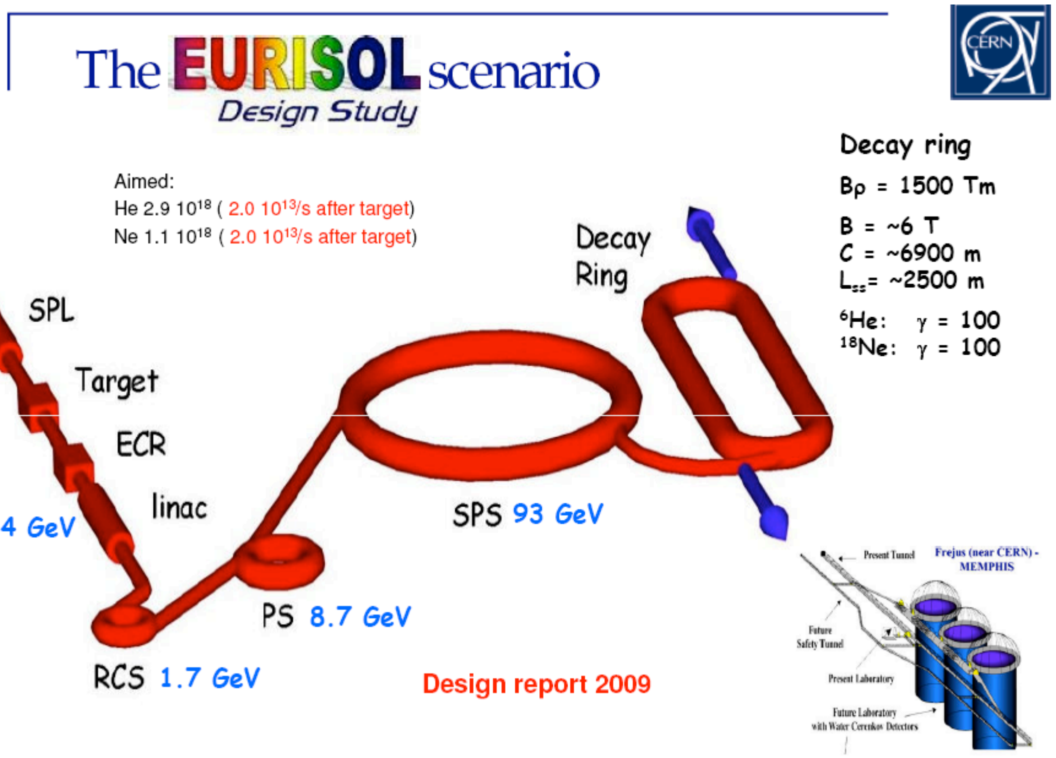


Figure 3 The beta-beam baseline scenario of the EURISOL design study.

The intensity limit for 6He arises in the storage ring: the lifetime of ^{6}He is 0.8 s which becomes more than a minute after acceleration. The storage ring has to be filled into already populated ion bunches ("topping up"), producing a continuous neutrino beam. In order to keep the background of atmospheric neutrinos in the detector at a level that does not degrade the performance, a low duty factor of 0.5% is required. This implies that the circulating beam has to be bunched into a finite number of short (5ns) bunches with very large populations of a few 10^{12} ions per bunch. This limitation leads to an estimated performance of 2.9 10^{18} electron anti-neutrinos per year produced in the production straight section of the storage ring. At these intensities the irradiation due to decay products of the ion beams in the injectors and in the storage rig are substantial but within limits.

The ^{18}Ne production by the ISOL technique would result in a factor 40 lower intensity than for ^{6}He while $1.1 \cdot 10^{18}$ decays per year would be necessary for CP violation measurements. Other production techniques envisaged comprise use of a very powerful (over 2 MW) ^{3}He beam on a magnesium oxide target via ^{16}O(^{3}He,n)^{18}Ne, or of an intense 30 mA proton beam of 70 MeV on an Al_2O_3 target. Either solution requires substantial R&D to understand how to handle unprecedented power deposition in these targets. Demonstrating a viable scenario for sufficient production of ^{18}Ne should be given high priority.

A very elegant possibility is to accelerate radioactive ions that decay by electron capture, such as $^{156}_{70}Yb$. This decay produces a monochromatic beam of neutrinos. It is not clear that sufficient intensities of these long lived elements could be produced or stored to make interesting neutrino oscillations but this would at least allow for the first time a complete measurement of cross sections for low energy neutrinos.

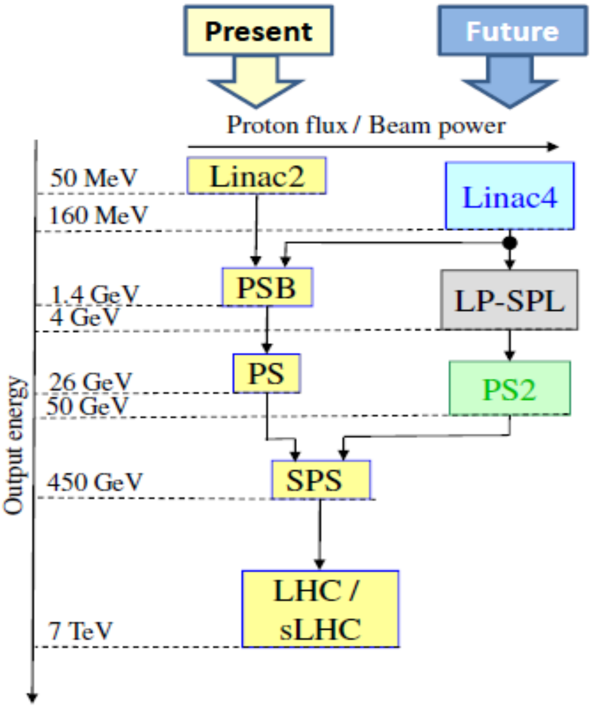
It has been pointed out that the performance of a beta beam improves rapidly with increasing values of γ; for a beta-beam accelerated up to 1 TeV in the upgraded SPS (SPS+) one could reach $\gamma=350$. This scheme requires a storage ring of the corresponding rigidity. The energy, flux and baseline are correspondingly increased, and a performance in the reach for CP violation becomes more comparable to that of a neutrino factory. We have not considered this further as SPS+ is presently not envisaged.

An interesting production technique is studied in EUROnu for the production of alternative beta emitters with higher Q-value (^{8}Li and ^{8}B, but perhaps also ^{18}Ne and others). Injecting a nearby isotope such as ^{6}Li or ^{7}Li in a small storage ring into a H_2 or D_2 gas target could lead to high production rates. High Q isotopes provide higher energy neutrinos, suitable for a longer baseline. However increasing Q and increasing γ have opposite effect on the performance, since the number of events detected at oscillation maximum scales as γ/Q. A competitive performance with the higher Q isotopes thus requires a corresponding increase of intensity in the storage ring for equal oscillation performance, but, as shown above, this is where intensity limitations occur. The irradiation issues in the accelerator complex also become accordingly more significant than for the baseline scenario. There is a well defined work plan for the production of ^{8}Li but the production of ^{8}B is uncertain. Achieving the required production and storage intensities of high Q isotopes to make it a competitive proposal appears to require a considerable amount of R&D, which in turn should also benefit the baseline scenario.

The beta beam is clearly a very elegant and attractive possibility at CERN. In order for beta beam to become a realistic option on the horizon of 2012, it is necessary first to consolidate the EURISOL study by completing the ^{18}*Ne production study and the cost estimate.*

4. Upgrade of the CERN Accelerators – Opportunity for the European Neutrino Physics

In order to ensure a steady and robust operation of the LHC and to enable its possible upgrade toward high luminosity (SLHC), it is necessary to examine carefully whether one should consolidate or renew the entire injection complex, which includes linac2, PS booster, PS and SPS. It is thus natural to take this opportunity to study to what extent optimizing the necessary modifications to accommodate other important applications is possible. One of these applications is the production of intense neutrino beams; super-beam, beta-beam or neutrino factory.

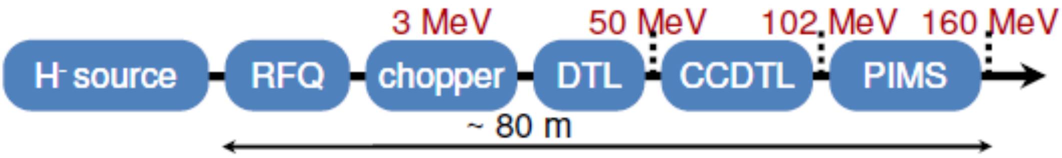


Possible scenarii for updating the LHC injection chain are being considered by CERN. So far, the only step, which has been decided, is the construction of a new injection linac, Linac4, replacing the linac2, and enabling higher injection energy in the PS booster. However, decisions concerning the remaining components of the present injection chain are still to be taken. One option is to renovate and modernize these components while an alternate option includes the construction of several new components; SPL and PS2, and an improvement of the SPS, as shown in the diagram on the left. The different acceleration steps in this latter scheme would be as follows; Linac4 will bring the proton/ion beam from the source up to 160 MeV using warm acceleration structures. The Superconducting Proton Linac (SPL) would take over and accelerate the beam up to 4 GeV for injection into a new Proton Synchrotron (PS2), in which the beam is further accelerated up to 50 GeV to enter the SPS.

In the following, we review very briefly these new components and confront their envisaged specifications to the one needed for carrying a competitive neutrino physics program. We mention, en passant, other possible applications for information.

4.1. Linac4

The linac4 is the first acceleration step after the proton/ion source. It is aimed at replacing the present Linac2. Its design is based on warm technology including RFQ, DTL, CCDTL and PIMS accelerating structures as shown below.



The main purpose of Linac4 is to produce a proton beam of 160 MeV with 0.9 ms long pulses of about 10^{14} protons (≅20mA) each at a repetition rate of 2Hz for the LHC. Its construction is underway and is expected to be achieved by the end of 2013. This accelerator is well suited for a number of accelerator-based physics programmes, amongst which neutrino physics through all methods for producing ν-beams, namely β-beam, Super-Beam or muon-based ν-factory.

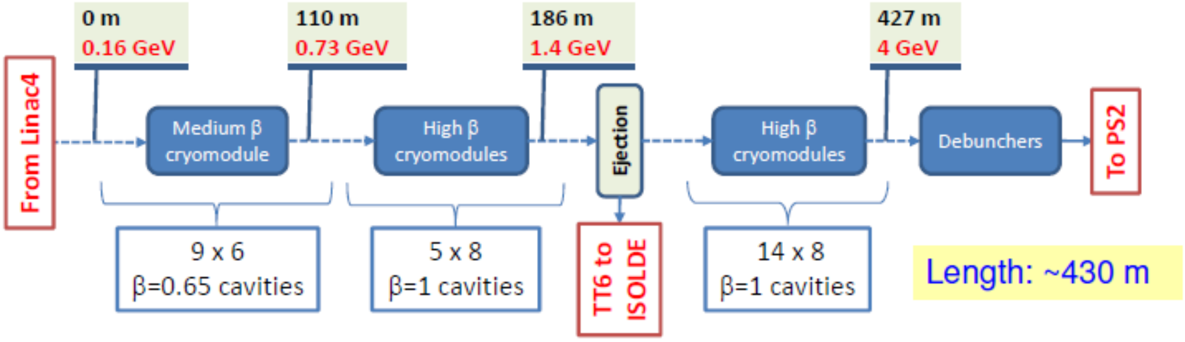
However, for the two latter, the repetition rate would need to be increased up to 50Hz to enable high power operation. Linac4 is dimensioned for such an operation mode (i.e. no new accelerating structure is necessary and radioprotection issues have already been taken into account). Nonetheless some specific upgrades are to be carried out, including

- A new H^- source
- Power supplies and modulators for
  - LEP Klystrons (2MW/klystron)
  - new klystrons (5MW/klystron)
- Additional cooling power
- New electronics

Altogether, an incremental cost of about 15% would be required but no technical show stopper preventing high power operation is identified.

4.2. Superconducting Proton Linac (SPL)

A low power SPL (LP-SPL) is considered as the second acceleration step of the new injection complex of the LHC and would replace the PS booster, although at a higher energy. Its design is based on superconducting technology medium- and high-β elliptical accelerating structures as sketched below.



The LP-SPL would accelerate further the beam up to 4 GeV with 0.9ms pulses of 1.1 10^{14} protons (≅20mA) with a repetition rate of 2Hz (≅150kW), as produced by Linac4.

It is important to note that the LP-SPL is rather well matched for a β-beam facility with an important caveat: There is no demonstrated means to produce ^{18}Ne beams, even using a high power proton beam with the standard ISOLD method. It is thus essential to address this issue, which may be a show stopper.

In order to deliver intense neutrino beams by means of super-beam or ν-factory, a High-Power SPL (~4MW) will be needed, with possibly higher energy (5 GeV or slightly more). It is worthwhile noting that a HP-SPL would also be useful for the production of high intensity radioactive beams (EURISOL) and the developed technologies would have important synergies with ESS and ADS. Such an accelerator would be unique in Europe.

The SPL could accommodate High Power operation; however, major upgrades would be required, such as

- new power supplies (essentially modulators) for reaching a repetition rate of 50 Hz
- higher cooling power
- an upgrade of the electrical infrastructure.

In principle, these modifications would enable reaching 4.5 MW at 5 GeV using the same parameters as LP-SPL. A preliminary design exists, which needs to be further assessed. A 2nd option is also considered with twice as many protons in the bunches and a lower pulse duration (0.4ms). One would also reach 4MW at 5GeV with probably safer parameters for the ν-factory accumulator ring. However, double the number of klystrons are required in this scheme.

The incremental cost would be of the order of 30% as compared to the LP-SPL, for option 1.

We note finally that the target system will be a major challenge for exploiting such a high power beam. A high power target test-stand will be essential to develop the appropriate target technology.

4.3. Proton Synchrotron 2 (PS2)

The Proton Synchrotron (PS), which is the third step of the injection chain, has now been operating for 50 years. Therefore it needs to be either refurbished and modernized or possibly rebuilt. Within this latter option the construction of a new PS2, reaching twice the energy of the PS and enabling a higher flexibility for the LHC injection chain is considered. The decision has to be taken by the CERN management.

For the SLHC injection complex, a “Low Power” PS2, accelerating further the beam up to 50 GeV and storing 168 bunches of $4\ 10^{11}$ protons each would be appropriate. The design of such a synchrotron is on-going as part of the CERN white paper.

Should the PS2 be used for fixed target physics, a proton beam of about 350kW could be delivered. This would allow about $4\text{x}10^{20}$ pot for 10^7s, which is roughly one order of magnitude higher that the present CNGS beam, though at lower energy.

In order to use the PS2 for a long baseline superbeam facility, at least a 2MW machine (HP-PS2) would be required. A new design will be needed for such a machine, requiring significantly higher resources than presently planned, both for design and R&D.
In particular, several technical aspects would need to be addressed, such as

- The development of large aperture magnets
- An optimized high power collimation and dump system
- Additional RF power sources (about twice more RF power is needed)

It is therefore difficult to envisage that such a machine would be ready before 2020.

The additional cost for a HP-PS2 is likely to be at least 50% more as compared to the LP-PS2.

4.4. SPS

Finally, to be complete, some modifications of the SPS will be needed to accommodate injection at 50GeV, such as the treatment of the beam pipe against the electron cloud and the upgrade of the RF system, in particular by adding amplifiers.

The SPS is currently able to provide nominally 4.5 10^{19} proton on target (pot). It is could be possible to reach 5.7 10^{19} with some improvements with 45% beam sharing. With an upgraded SPS, one could deliver 1.3 10^{20} pot.

4.5. Conclusion

The usefulness of a possible new LHC injection chain for the production of intense neutrino beam has been examined. The Linac4 and the SPL are clearly identified as essential elements and could be parts of next generation of neutrino facilities.

However, some important aspects require to be investigated further. They include

- radioprotection and safety issues,
- costing of the various options
- the feasibility for producing ^{18}Ne (2.10^{13} /s)

In addition, a strong R&D programme and the development of the corresponding R&D infrastructures will be needed.

5. Strategy for Neutrino Physics – the Ways to Continue

The neutrino physics community in Europe consists of more than 400 physicists[14] and is increasing. It is involved in a rich experimental program: studies of neutrino oscillations, searches for neutrinoless double beta decays, measurement of the mass from tritium decay, as well as the use of neutrino detectors for astrophysical observations. In the oscillation area in Europe there are the CNGS and Double Chooz experiments, but more physicists work in the leading experiments outside Europe, particularly in the T2K experiment in Japan where about 50% of physicists are from European institutions. The design studies such as IDS-NF, and more generally the R&D program for future neutrino accelerator facilities is carried on within international collaborations, but as yet there is no generally accepted global or European strategy. In other areas European physicists work mostly in European experiments.

CERN, which has a key role in developing the European strategy in particle physics, is a natural candidate to coordinate aspects of the European activity in neutrino physics and to influence planning on the local and global scale. It is useful to distinguish three types of

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[14] According to the ECFA counting.

recommendations: general recommendations, recommendations for specific support from CERN to enable strategic decisions and actions related to long term strategy planning.

General recommendations

- CERN, as the European particle physics organisation, should play an important role in the process leading to the definition and implementation of the European strategy with respect to a neutrino physics programme. To do so CERN must create stronger links with the European neutrino community.

- Re-establishing neutrino groups in PH and AB departments would, if it is practicable, be a positive step in this direction. However, the SPC recognizes that the desire to set up such groups has to be balanced against the many other competing demands on CERN's resources.

- The workshop on the European Strategy for Future Neutrino Physics was very successful. Regular meetings of this type, organized under the auspices of CERN and ECFA, could help in the integration of the European neutrino community and in increasing the role of CERN in the strategic global planning for neutrino physics.

Recommendations for specific support from CERN to enable strategic decisions

- Costing. Support for providing comparable costing of the superbeam, beta beam and neutrino factory options is needed within the EUROnu/IDS-NF framework. In Europe the expertise required for such a comprehensive work is only available from CERN.

- Radioprotection and general safety issues. The development at CERN of a high power target facility, preferably with international collaboration from other laboratories, would be a major asset, not only for the neutrino programme but also for the increasing number of areas where high power proton beams are needed.

- Completing key R&D programmes. For the beta beam, it is vital to demonstrate the feasibility of producing sufficient ^{18}Ne. For the neutrino factory continued contributions to the MICE experiment are important to demonstrate ionization cooling in a timely fashion for 2012/2013.

- R&D for future neutrino detectors. This has been taking place in Europe for some time and support from CERN, e.g. by supplying test beams, would be highly beneficial.

Long term strategy planning

- It is unrealistic to expect to have a high intensity neutrino source of any kind in Europe before the early 2020’s.

- By this time it is reasonable to expect that there will be a number of years of operating and upgrading superbeams in Japan and in the USA. This should be closely followed.

- Thus if Europe is to be competitive in the 2020's it should concentrate on the R&D for a new intense source, the neutrino factory or the beta beam. It would be advisable to organise a systematic review of the progress and prospects of this work.

It would be desirable to investigate the following scenarios for performance, practicality and cost:

1. A low energy beta beam from CERN to Fréjus, alone and supplemented with a low energy superbeam to the same detector. A major problem is the sufficient intensity of the ^{18}Ne ion beam.
2. A high-Q beta beam as is being investigated in EUROnu. So far this has had least investigation although the production of an adequate number of B^8 ions is a serious concern.
3. The neutrino factory. This is probably the most investigated solution with a number of previous studies, mainly from the USA but technically feasible solutions, particularly for the targetry, cooling and fast acceleration need to be verified.

The performance of such a new facility will depend critically on development and optimisation of the detectors employed and this must also be pursued.

CERN has unique expertise both with accelerators and detectors to ensure an appropriate choice is made around 2012/2013 for the long term future.

Acknowledgements

The members of the SPC panel acknowledge the help received from all people who agreed to meet the panel, contributed to the workshops or prepared documents at the panel's request.

The panel met (always in 2009):

- The CERN Management: Rolf Heuer on the 14th of September, Sergio Bertolucci and Steve Myers on the 17th of March and on the 10th of November;
- Representatives from the International Design Study for the Neutrino Factory and from the EUROnu and EURISOL EU projects: Robert Edgecock, Kenneth Long, Mats Lindroos, Michel Martini and Elena Wildner on the 17th of March;
- Representatives from the MERIT and MICE R&D experiments: Ilias Efthymiopoulos, Harold G. Kirk and Alain Blondel on the 18th of March;
- Experts from the Accelerator Division: Mats Lindroos, Malika Meddahi, Michel Martini and Elena Wildner on the 17th of March, Thierry Stora, Stefania Trovati and Elena Wildner, on the 16th of June;
- John Ellis from the Theoretical Physics Group at CERN on the 16th of June;

- The SPC members from the USA and Japan: Don Hartill on the 16th of June and Katsuo Tokushuku on the 17th of June.

In March 2009 the panel members participated in a kick-off meeting of the EuCARD/NEU2012 network.

We are most grateful to our colleagues who helped us to organize the workshop on European Strategy for Future Neutrino Physics held at CERN in October 1-3: Sergio Bertolucci, Anselmo Cervera Villanueva, Fanny Dufour, Ilias Efthymiopoulos, Patricia Mage-Granados, Steve Myers, Silvia Pascoli, Ewa Rondio, Steinar Stapnes and David Wark.

The following documents were prepared at the panel's request:

- Antonio Ereditato: *Personal considerations on the future of neutrino physics at CERN;*
- The IDS-NF Steering Group: *The International Design Study for the Neutrino Factory: Organisation and responsibilities, resources, and potential for developing CERN's role;*
- Robert Edgecock: *Proposal for increased contributions from CERN to future neutrino oscillation facilities via the EUROnu FP7 Design Study;*
- Elena Wildner: *The Beta Beam study;*
- André Rubbia: *A high power CERN PS2 for long baseline experiments with next-generation large underground detectors for proton decay searches and neutrino physics and astrophysics – DRAFT 18/11/09.*