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THE EUROPEAN SPALLATION SOURCE NEUTRINO SUPER BEAM DESIGN STUDY

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On behalf of the ESSνSB Project.

Abstract

The discovery of oscillations and the latest progress in neutrino physics will make possible to observe, for the first time, CP violation in the lepton sector, if it exists. This will help to understand the disappearance of antimatter in the Universe. To go further beyond the current knowledge, it is necessary to develop more and more powerful instruments, but also to combine skills by creating strong international networks between researchers. In this framework, the ESSνSB project proposes to use the proton linac of the European Spallation Source (ESS) currently in construction in Lund (Sweden) to produce a very intense neutrino Super Beam, in parallel with the spallation neutron production. The ESS linac is expected to be fully operational by 2023 delivering 5 MW average power, 2 GeV proton beam, with 2.86 ms long pulses at a rate of 14 Hz. By doubling the pulse rate, an average power of 10 MW can be obtained, providing at the same time 5 MW for the neutron facility and the 5 MW for the production of the neutrino beam. The primary proton beam-line completing the linac will consist of an accumulator ring to compress the beam pulses to 1.3 µs and a switchyard to distribute the protons onto the target station. The secondary beam-line producing neutrinos will consist of a four-horn/target station, a decay tunnel and a beam dump. A megaton scale Water Cherenkov neutrino detector will be located at a baseline of about 500 km in one of the existing mines in Sweden, to measure the neutrino oscillations.

INTRODUCTION

Thanks to the relatively large value of the last measured neutrino mixing angle θ_{13}, the observation of a possible CP violation in the leptonic sector becomes now possible. This will greatly help to understand the matter-antimatter asymmetry observed in the Univers.

Under the present conditions, the sensitivity of a CP violation observation and measurement of the violating parameter δ_{CP} is enhanced at the second oscillation maximum instead of performing observations at the first one [1–3]. For this observation next generation high intensity neutrino beams are needed. The European Spallation Source (ESS) facility under construction in Lund, Sweden, to produce spallation neutrons, will have a 5 MW, 2 GeV proton linac (Fig. 1) operated at a rate of 14 Hz (4% duty cycle). This linac could also be used to produce an intense neutrino beam, which, when combined with a megaton Water Cherenkov detector, could observe for the first time a CP violation by being operated at the second neutrino oscillation maximum. This is what is proposed by the ESS neutrino Super Beam (ESSνSB) project [4].

THE FACILITY

The ESS linac will initially provide 5 MW, 2 GeV protons pulsed with a rate of 14 Hz and a pulse duration of 2.86 ms (the main linac parameters are given in Table 1). There is free space in the downstream end of the linac tunnel that is long enough to install in future additional accelerating cavities to reach up to 3.6 GeV proton energy.

The linac pulse rate could be doubled in order to provide one pulse for neutron and one pulse for neutrino production. Due to limitations of the hadronic collector (horn) used to produce the neutrino beam, the duration of the proton pulses has to be limited to few µs. For this reason, a ~400 m circumference proton accumulator will be added between the linac and the neutrino target station to enable the compression of the proton pulses to about 1.3 µs.

Table 1: Main ESS Facility Parameters of the Proton Beam

Parameter	Value
Average beam power	5 MW
Peak beam power	125 MW
Proton kinetic energy	2.0 GeV
Average macro–pulse current	62.5 mA
Macro–pulse length	2.86 ms
Pulse repetition rate	14 Hz
Annual operating period	5000 h

Due to charge effects at the injection into in the accumulator ring, H^- ions have to be produced and accelerated in the linac instead of protons. For this, an H^- source has to be added at the beginning of the linac. These ions have to be stripped at the entrance of the ring. Because of the high power of the proton beam the classical foil stripping methods could be problematic and other innovative methods could be necessary, such as those using lasers.

An evaluation of all required upgrades of the linac can be found in a CERN note [5]. In this note it is stated that no showstoppers have been identified or incompatibilities with the present design of the ESS neutron facility.

For this project a target station dedicated to neutrino production is necessary. This station is placed just downstream of the accumulation ring and consists of the target, the magnetic horn, the hadron decay tunnel and the beam dump. In order to mitigate the effects of the high proton power, a

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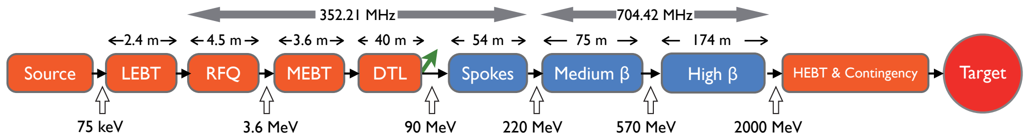

Figure 1: Schematic view of the ESS proton linac.

system of four targets associated with four horns, has been adopted. Due to the relatively low proton energy the target has to be placed inside the magnetic horn for better hadron collection. This creates extra power dissipation complications. The magnetic horn is followed by a 25 m decay tunnel allowing the produced mesons (mainly pions) to decay and produce neutrinos. Due to the short length tunnel, only a negligible amount of the muons produced together with the muon neutrinos will have enough time to decay producing electron neutrinos contaminating the primary neutrino beam. The muons are stopped by the beam dump placed at the end of the tunnel. This scheme has been extensively studied by the previous EU FP7 Design Study EUROν [6].

For the neutrino detection, a far megaton Water Cherenkov is needed. This kind of detector has been extensively studied by two previous EU FP7 projects, EUROν and LAGUNA-LBNO [7]. The MEMPHYS type detector [8] has been adopted in order to evaluate the physics performance of the proposed facility. The neutrino detection performance of this detector is given in [9]. Compared to this performance, the MEMPHYS detection capability can now be improved, maintaining the same cost, by increasing the number of photomultipliers having higher Quantum Efficiency, thus profiting from recent developments on this subject.

In this project it is also proposed to use a near detector, not only to monitor the unoscillated neutrino beam, but also to measure neutrino cross-sections at the energies relevant to this project and thus further reduce the systematic uncertainties. ESSνSB could profit from R&D done on other long baseline experiments, such as has been done for the upgrades of T2K in Japan [10].

Figure 2 presents the ESS facility with a possible implementation of the neutrino facility including the near detector. The neutrino beam is directed towards the north in the direction of the Garpenberg mine, 540 km away, which could host the far detector. Some preliminary studies showed that the rock quality around this mine is satisfactory for excavating cavities large enough to hold the MEMPHYS detector.

Figure 3 presents the unoscillated neutrino energy distribution which could be obtained by the proposed facility at an arbitrarily chosen on-axis distance of 100 km from the neutrino target. This distribution corresponds to a one year neutrino run (200 days). An almost pure muon neutrino beam is produced with a main contamination of 0.5% of electron neutrinos. In the study of $\nu_\mu \to \nu_e$ conversions, this undesirable contribution polluting the primary muon neutrino beam, could be used to measure the electron neutrino cross-section in an adequate near detector.

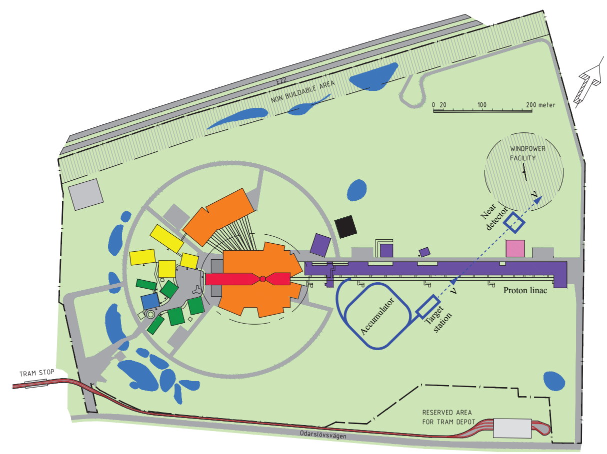

Figure 2: Layout of the ESS installation with a possible neutrino facility implementation (accumulator, target station, near detector).

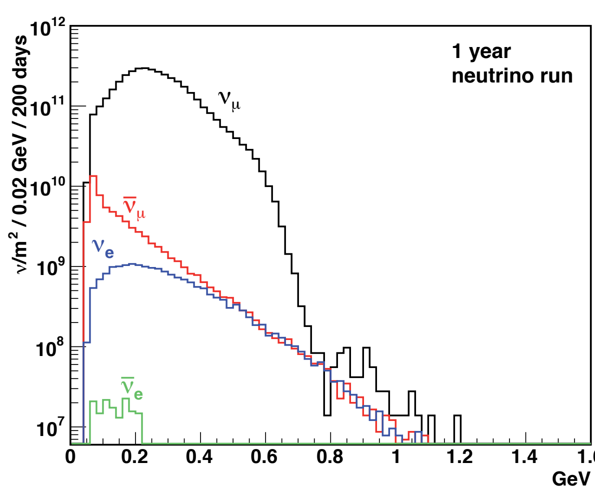

Figure 3: Neutrino energy distribution at a distance of 100 km on–axis from the target station, for 2.0 GeV protons and positive horn current polarity.

PHYSICS PERFORMANCE

The physics performance of all long baseline neutrino projects strongly depends on the analysis of systematic uncertainties. For this evaluation the systematic errors reported in publication [11] have been considered, with a 5% error on the signal and 10% on the background. As previously said, operating the facility on the second oscillation maximum reduces the dependence on systematic errors while increasing the CP violation observation sensitivity.

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Figure 4 presents the muon neutrino oscillation probability to electron neutrinos at a distance of 540 km for several values of δ_{CP} and for normal and inverted neutrino mass hierarchies. The overlapping grey distribution is the electron neutrino energy distribution coming from the muon neutrino oscillation. It is clearly seen that the second oscillation maximum is fully covered proving a good choice for the facility parameters. It is also seen that the CP violation discovery potential is not affected by the unknown neutrino mass hierarchy. On top of this and due to the relatively short baseline and the operation at the second oscillation maximum, matter effects affect only very slightly the physics performance of the facility.

For 10 years of operation of the facility, it is expected, under the present still unoptimised conditions, that about 600 electron neutrinos and antineutrinos will be detected by the far detector and used for the observation of CP violation. Studies have now been started to increase the number of detected neutrinos by further optimising the magnetic horn shape and the far detector performance.

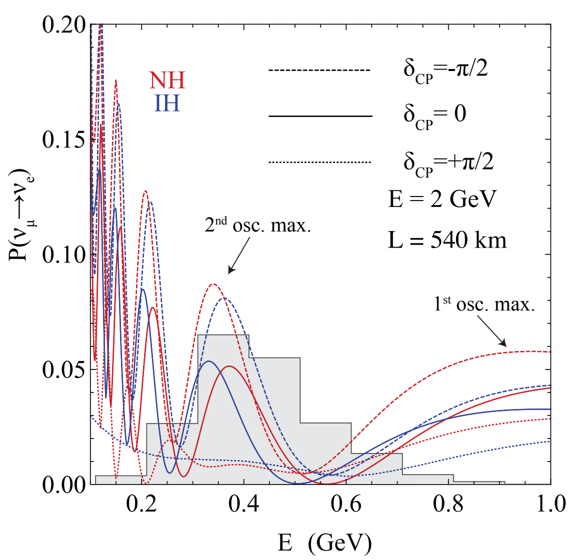

Figure 4: $\nu_\mu \rightarrow \nu_e$ oscillation probability as a function of the energy. The solid (dashed) lines are for normal hierarchy (inverted). The shaded histogram is the energy distribution of electron neutrinos produced by the muon neutrino oscillation and detected by the far detector.

Figure 5 shows the CP violation discovery significance versus the covered δ_{CP} fraction. It is seen that for a confidence level corresponding to 5 σ, more than 60% of the δ_{CP} values are covered, which demonstrates that this project is very competitive. This example is for a facility running with 5 years in "neutrino" mode (positive current in the magnetic horn) and 5 years in "antineutrino" mode (negative current).

FURTHER ESS UPGRADES

Together with the neutrino production, a very large number of muons is also produced. It is estimated that more than 10^{21} muons could be collected at the level of the beam dump of the neutrino facility.

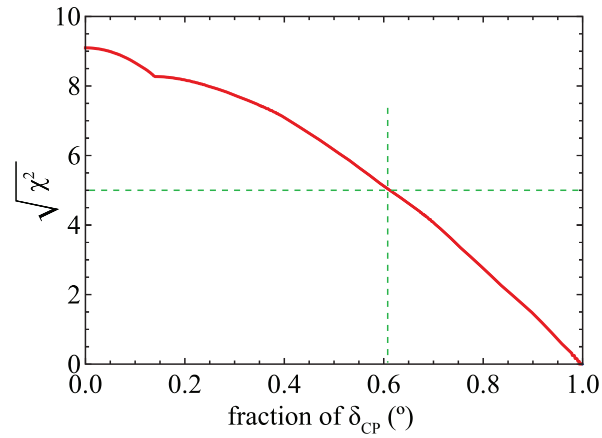

Figure 5: The significance with which CP violation can be discovered as function of the fraction of the full δ_{CP} range.

These muons have a mean energy of about 0.5 GeV. They could be used by a Neutrino Factory, depending on the needs of the neutrino physics at that moment. These muons could also be used for muon cooling and re-acceleration R&D projects, thus eventually opening the possibility to construct a muon collider in Lund.

CONCLUSION

The European Spallation Source under construction in Lund, could, after some upgrades, produce a very intense neutrino beam in addition to neutron production. This beam could be used to observe, for the first time, CP violation in the neutrino sector, which, under some hypotheses, could explain the antimatter disappearance in the Universe. The high power of the neutrino beam allows the facility to operate at the second oscillation maximum where the CP violation sensitivity is enhanced compared to the first oscillation maximum. For this reason, at this position the physics performance is less affected by the systematic uncertainties.

In order to produce the neutrino beam, the ESS facility needs few modifications like the additional acceleration of H^- ions and the addition of an accumulation ring. A very challenging part of the project, due to the very high proton beam power, is the target station to produce the neutrino beam. In order to reduce the proton power, a system of four targets/horns is proposed by the project, each to be hit alternatively.

Using a megaton Water Cherenkov detector placed at a distance corresponding at the second oscillation maximum, ESSνSB could cover more than 60% of the CV violating parameter δ_{CP} with a 5 σ confidence level.

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