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The ESSνSB Project for Leptonic CP Violation Discovery based on the European Spallation Source Linac

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Abstract

In addition to the world's most intense pulsed spallation neutron source, the European Spallation Source linac with 5 MW proton power has the potential to become the proton driver of the world's most intense neutrino beam. The physics performance of that neutrino Super Beam in conjunction with a megaton Water Cherenkov neutrino detector installed 1000 m down in a mine at a distance of about 500 km from ESS has been evaluated. In particular, the superior potential of such a neutrino experiment placed at the 2nd oscillation maximum to discover the lepton CP violation in order to explain the matter–antimatter asymmetry in Universe is presented. In addition, the choice of such detector will extent the physics program to proton–decay, atmospheric neutrinos and astrophysics searches. The ESS proton linac upgrades, the accumulator ring needed for proton pulse compression, the target station optimization and the physics potential are described. The ESS neutron installations will be fully ready by 2023 at which moment the upgrades for the neutrino facility could start. In this scenario data taking for neutrino physics could start around 2030.

Keywords: ESSnuSB, neutrino, CP violation, neutrino oscillations, ESS

1. Introduction

The majority of the long baseline projects proposed to discover CP violation in the leptonic sector has been optimised assuming low θ_{13} value. The measurement of θ_{13} in 2012 [1, 2, 3] revealed that the value of this angle is relatively high ($\sim 8°$).

For large θ_{13} values it has been shown [4] that operating at the second maximum of the oscillation $\nu_\mu \rightarrow \nu_e$ is significantly less sensitive to systematic errors. It can also be shown [5] that the neutrino/anti–neutrino asymmetry in the vacuum is approximately equal to $0.30 \sin \delta_{CP}$ at the first oscillation maximum while for the second oscillation maximum this value becomes $0.75 \sin \delta_{CP}$. This clearly shows that experiments at the second oscillation maximum have significantly higher sensitivity to δ_{CP} than those placed at the first oscillation maximum.

The drawback of going to the second oscillation maximum comes from the significant decrease of statistics compared to the first oscillation maximum for the same neutrino energy, due to the needed higher distance from the neutrino source to the detector location. Instead of increasing the distance to go to the second oscillation maximum one could decrease the neutrino energy. This also has a drawback coming from the rapidly decreasing neutrino cross–sections, especially below 1 GeV. Therefore, a very intense neutrino beam is needed in order to go to the second oscillation maximum keeping competitive statistics.

A neutrino Super Beam has been proposed based on the very intense proton beam of the European Spallation Source (ESS) under construction in Lund, Sweden [6]. Thanks to the power of the proton beam, this project called ESSνSB [7] can operate at the second oscillation maximum providing very competitive performance on CP violation discovery in the leptonic sector. The ESS proton linac will have an energy of 2 GeV and a mean

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power of 5 MW, an order of magnitude higher than the present proton beams used by neutrino experiments.

The construction of ESS neutron facility has started in September 2014. The first beam is foreseen for 2019 while the whole facility with full power and energy will be ready by 2023.

2. The ESS proton beam

The ESS is a European facility under construction to provide slow neutrons to research institutes and to the industry. The neutrons are produced in a tungsten target hit by a 5 MW and 2 GeV proton beam. The high intensity proton pulses will be delivered by a linac running at 14 Hz (Fig. 1). Future proton linac upgrades could bring the proton energy up to 3.6 GeV using the empty space left in this linac. The main characteristics of this linac are given in Table 1. The number of protons on target per year (208 days) is of the order of 2.7×10^{23}. The proton pulse duration is 2.86 ms.

Table 1: Main ESS facility parameters of the proton beam.

Parameter	Value
Average beam power	5 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
Maximum accelerating cavity surface field	45 MV/m
Maximum linac length (excluding contingency and upgrade space)	352.5 m
Annual operating period	5000 h
Reliability	95%

The linac's duty cycle for neutron production is only 4%. This low duty cycle can be raised to 8% for simultaneous neutron and neutrino production. The average beam power can thereby be raised from 5 MW to 10 MW. To achieve this, the pulse frequency of the linac can be raised from 14 Hz to 28 Hz (other scenarios are also under study). In this way, it can be sent alternatively, one proton pulse on the neutron target and one on the neutrino one.

The proton pulses for neutrons are too long to be directly sent to the hadron collector (horn) for neutrino production. Indeed, 2.86 ms with a frequency of 14 Hz is not affordable by the horn used as hadron collector. The necessary current to be sent to the horn in order to well focus the charged pions, coming out of the target, towards the neutrino detector, is of the order of 350 kA. Due to this very high current the proton pulses sent to the neutrino facility target must be as short as possible in order to leave enough time to dissipate the power send to the horn before the next pulse.

3. Extra installations needed for the neutrino beam production

To have short pulses of the order of few μs, an accumulation ring is necessary. This also implies the acceleration of H^- instead of protons in order to avoid space charge effects during the entrance in the ring. Doubling the linac power, accelerating H^- and designing an accumulator ring will be the main subjects of a design study.

In order to fit in the already allocated ESS area, it has been decided to consider an accumulation ring with a circumference of 400 m. This accumulator will shorten the proton pulses to about 1.5 μs, very suited to the horn operation. These pulses can also be used by neutron users [8], in which case the proton source in the linac can be replaced by a common H^- source.

Each pulse from the ESS linac will contain 1.1×1.0^{15} protons. This will lead to severe space–charge problems. In case of significant problems with one–ring accumulator, a way to reduce this effect would be to use 4 superimposed rings located in the same tunnel, each ring receiving 1/4 of the bunches during a multi–turn injection. Enough space between the bunches in the bunch train from the linac must be created to permit the beam distribution system to inject from one ring to the next one. Experience already exists from the CERN PS Booster [9] of using 4 superimposed rings.

During the entrance in the accumulator ring the H^- ions coming from the linac have to be stripped using a laser–stripping device. Due to the very high beam power, a foil stripping will probably be impossible to use because the foil would not resist. Both possibilities will be studied.

As for all neutrino beams, a target/horn station will also be needed. The pion decay tunnel length is of the order of 25 m, long enough to allow charged pions to decay into neutrinos and muons, but also short enough to avoid muon decays (producing electron neutrinos) polluting the muon neutrino beam.

Fig. 2 shows a layout of the ESS installations and the extra facilities necessary for the neutrino beam production. Together with a far detector, a near detector is also foreseen in order to mainly measure the relevant neutrino cross–sections.

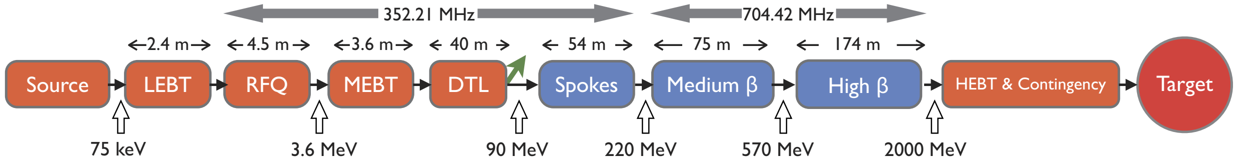

Figure 1: Schematic view of the ESS proton linac.

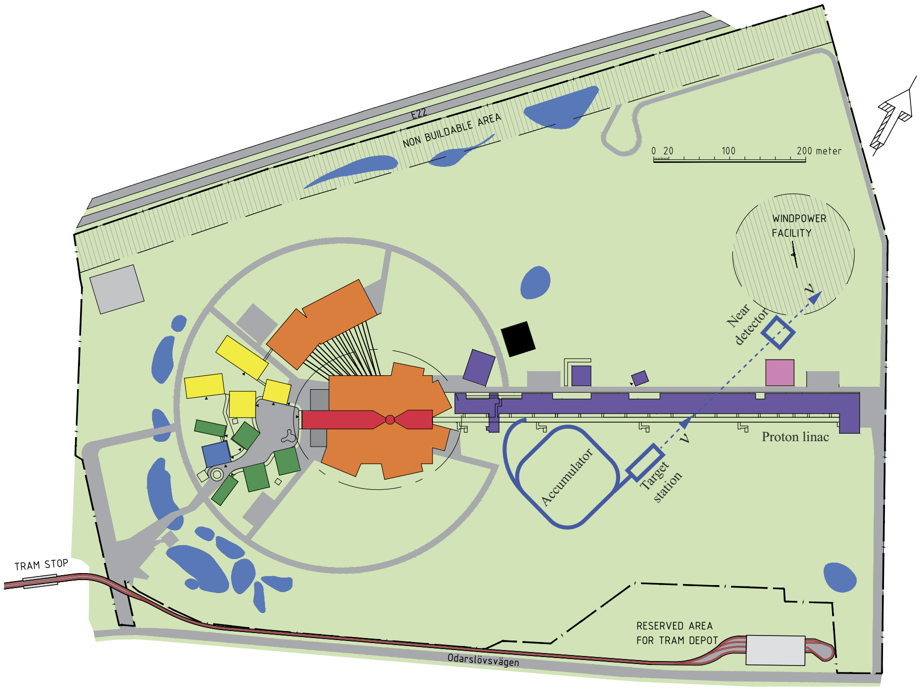

Figure 2: Layout of the ESS installations.

Due to the very high power of the proton beam, the solution proposed by the FP7 Design Study EUROν [10, 11] of using 4 targets/horns pulsed one after the other has been adopted by ESSνSB. A particular care has to be taken for the target and horn cooling. Here also the EUROν choices have been adopted. A target of titanium spheres of few mm diameter with cold helium gas cooling is proposed. The design of horn pulse generator can be found in [12].

4. Neutrino Beam

The shape of the horn has been optimised in order to maximise the discovery probability of CP violation. Fig. 3 presents the neutrino beam composition obtained using the ESS 2 GeV proton beam. In order to compare neutrinos with anti–neutrinos and to have about the same statistics for both species, it is planed to run 2 years with neutrinos (positive polarity in the horn) and 8 years with anti–neutrinos (negative polarity).

The mean neutrino energy is of the order of 400 MeV. The ν_μ ($\bar{\nu}_\mu$) beam contains about 0.5% ν_e ($\bar{\nu}_e$) contamination. These electron neutrinos could be used by the near detector to measure the neutrino cross–sections at the same energies than the electron neutrinos detected by the far detector. No measurements of these cross–sections exist at these neutrino energies. These measurements will help to significantly reduce the systematic errors of this project.

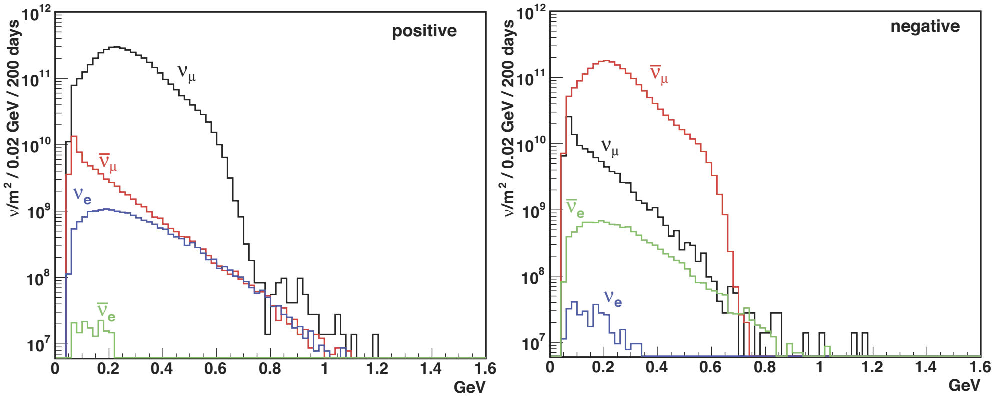

Figure 3: Neutrino energy distribution at a distance of 100 km on–axis from the target station, for 2.0 GeV protons and positive (left, neutrinos) and negative (right, anti–neutrinos) horn current polarities, respectively.

5. Underground Far Detector

The far detector will be a megaton Water Cherenkov similar to MEMPHYS [13, 14]. Its volume would be of the order of 500 kt fiducial volume. A Water Cherenkov detector is well suited at these relatively low neutrino energies.

Several active mines in Sweden have been investigated which could house the far detector. Some of these mines are more interesting than others, these are Zinkgruvan and Garpenberg located at 360 km and 540 km, respectively from Lund. Another interesting mine (Kongsberg) is located in Norway near Oslo at 500 km. To choose the best one several parameters are taken into account as the situation of the mine itself in order to minimise the civil engineering and increase the physics performance to discover CP violation in the leptonic sector according to the final proton beam energy.

It has to be said that resolving the mass hierarchy problem is a secondary physics subject although a 5 σ discovery significance can be reached for normal (NH) and inverted (IH) mass hierarchy [7]. We believe that this problem will be solved before these next generation long baseline projects.

The same far detector can also be used to observe proton decays and to study cosmological neutrinos (from supernova explosions, solar and atmospheric neutrinos etc.)

6. Physics Performance

In order to find the best distance to place the far detector, the discovery probability of CP violation has been studied as a function of the baseline. Fig. 4 presents the fraction of the full parameter δ_{CP} range as a function of the baseline for 3 σ and 5 σ CP violation discovery significance. If the proton energy remains at 2 GeV (present design), the best baseline is around 400 km, close to Zinkgrouvan mine (360 km). Garpenberg mine (540 km) has a better potentiality in case the proton energy goes above 2.5 GeV and can cover up to 60% of the δ_{CP} range for a 5 σ significance. This performance is obtained assuming an unknown mass hierarchy and 5% systematic error on signal and 10% on background. At this baseline ESSνSB fully covers the second oscillation maximum, the first oscillation maximum being around 180 km with significantly less δ_{CP} coverage.

Fig. 5 presents the detected neutrino beam composition in case the far detector is placed in Garpenberg mine. It has been assumed that the MEMPHYS detector is used as far detector and its detection efficiencies have been taken into account [14]. In 10 years running (2 years with neutrinos and 8 years with anti–neutrinos) it is expected to detect about 200 ν_e's and 160 $\bar{\nu}_e$'s. In order to show how well this configuration covers the second oscillation maximum, Fig. 6 presents the detected ν_e spectrum by MEMPHYS superimposed on the oscillation probability for several δ_{CP} values and both mass hierarchies.

As said above, the ESSνSB performance is calculated assuming an unknown mass hierarchy. For the considered baselines matter effects are not expected to play a significant role. Fig. 7 [15] presents the δ_{CP} coverage for Zinkgrouvan mine as a function of the exposure. The upper limit of the bands corresponds to the case where the mass hierarchy is known while the lower limit in case it is unknown. It can be clearly seen that the width of this bands is limited clearly showing the

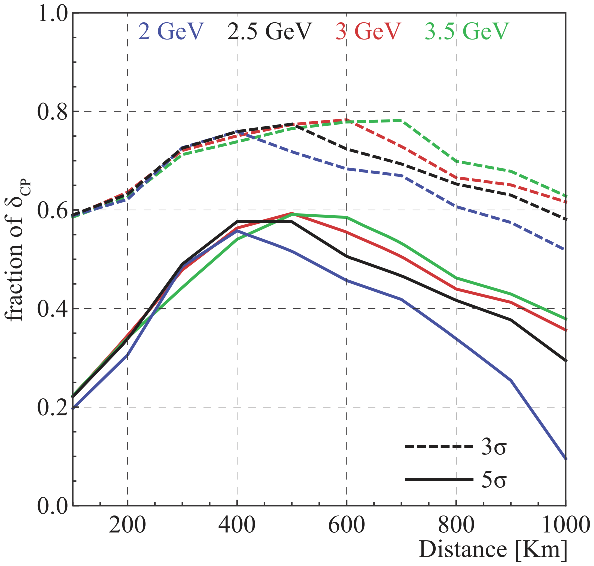

Figure 4: The fraction of the full δ_{CP} range as function of the baseline. The lower (upper) curves are for CP violation discovery at 5 σ (3 σ) significance.

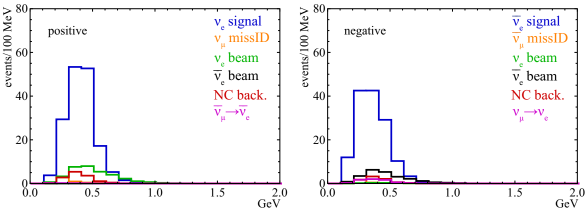

Figure 5: Energy distributions of the detected electron neutrinos (positive) and anti–neutrinos (negative) including background contribution as reconstructed by MEMPHYS detector for two years of neutrino running (left) plus eight years of antineutrino running (right) and a baseline of 540 km (2.0 GeV protons, $\delta_{CP} = 0$).

small influence of the mass hierarchy on ESSνSB CP violation discovery performance. The systematic errors assumed are those mentioned in [16], "default" values, mainly assuming 7.5% systematic errors for the signal and 15% for the background. Fig. 8 [15] shows the same distribution than Fig. 7 with the difference that the width of the bands comes from different systematic errors. The lower limit is the one obtained making the same assumptions than in Fig. 7 while the upper limit is obtained assuming the "optimistic" case mentioned in [16] (mainly assuming 5% systematic error for the signal and 10% for the background). It can be seen that for double exposure (20 years running) the δ_{CP} coverage, at 5 σ discovery significance, can go up to 72%.

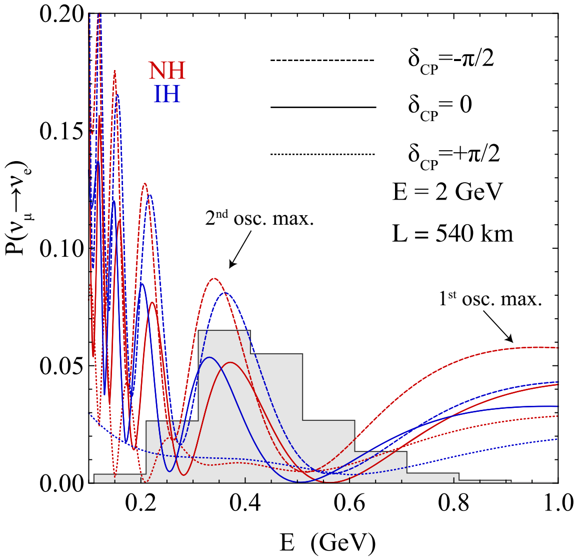

Figure 6: $\nu_\mu \rightarrow \nu_e$ oscillation probability as a function of the neutrino energy. The solid lines are for normal hierarchy (NH) while the dashed ones are for inverted hierarchy (IH). The shaded distribution is the energy distribution of electron neutrinos detected by MEMPHYS far detector.

7. Conclusion

The ESSνSB project proposes to use the ESS installations under construction and mainly its proton linac to produce a very intense neutrino beam in order to discover CP violation in the leptonic sector. This project fully profites of the developments done in previous European Design studies as EUROν and LAGUNA. A new Design Study in the frame of Horizon 2020 is now submitted to study how to built the new neutrino facility on top of the neutron one.

For this new facility upgrades of the proton linac are needed to be able to accelerate H^-. An accumulator ring is also needed to shorten the ESS linac pulses from 2.86 ms to few μs, affordable by the neutrino hadron collector. The design of the target station for neutrino production is also needed with a very good starting point from what has already been done in EUROν.

A Water Cherenkov far detector like MEMPHYS is considered, placed in one of the already investigated mines. A near detector for neutrino cross–section measurements is also under study.

For 10 years data taking, ESSνSB expects to reach up to 60% δ_{CP} coverage at 5 σ CP violation discovery significance.

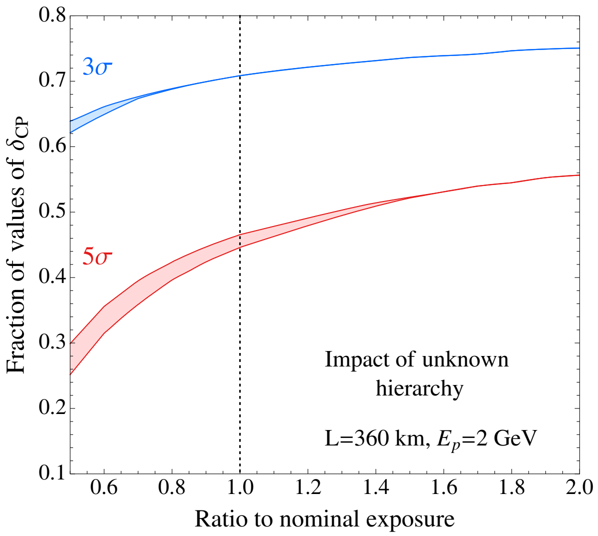

Figure 7: δ_{CP} coverage as a function of the exposure for known and unknown mass hierarchy, 1 being for 10 years, in case the MEPHYS detector is placed in Zingrouvan mine (360 km) and for 2 GeV protons.

8. Acknowlegments

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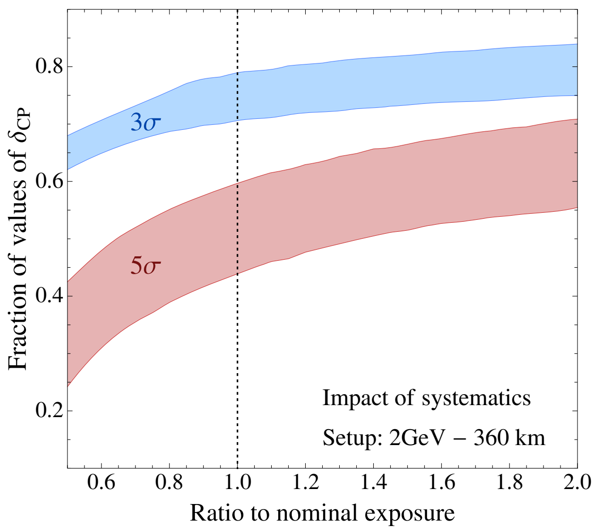

Figure 8: δ_{CP} coverage as a function of the exposure for different systematic errors, 1 being for 10 years, in case the MEPHYS detector is placed in Zingrouvan mine (360 km) and for 2 GeV protons.

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