The ESS neutrino facility for CP violation discovery

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Abstract. The comparatively large value of the neutrino mixing angle $\theta_{13}$ measured in 2012 by neutrino reactor experiments has opened the possibility to observe for the first time CP violation in the leptonic sector. The measured value of $\theta_{13}$ also privileges the 2nd oscillation maximum for the discovery of CP violation instead of the usually used 1st oscillation maximum. The sensitivity at the 2nd oscillation maximum is about three times higher than at the 1st oscillation maximum implying a significantly lower sensitivity to systematic errors. Measuring at the 2nd oscillation maximum necessitates a very intense neutrino beam with the appropriate energy. The world's most intense pulsed spallation neutron source, the European Spallation Source, has a proton linac with 5 MW power and 2 GeV energy. This linac also has the potential to become the proton driver of the world’s most intense neutrino beam with very high potential for the discovery of neutrino CP violation. The physics performance of that neutrino Super Beam in conjunction with a megaton Water Cherenkov neutrino detector installed ca 1000 m down in a mine at a distance of about 500 km from ESS has been evaluated. In addition, the use of such a detector will make it possible to extent the physics program to proton decay, atmospheric neutrinos and astrophysics searches. The ESS proton linac upgrade, the accumulator ring needed for proton pulse compression, the target station optimization and the physics potential are described. In addition to the production of neutrinos, this facility will also be a copious source of muons which could be used to feed a low energy nuSTORM facility, a future neutrino factory or a muon collider. The ESS linac, under construction, will reach full operation at 5 MW by 2023 after which the upgrades for the neutrino facility could start.

1. Introduction

To understand the matter-antimatter asymmetry in the Universe other CP Violation sources are investigated beyond those already observed in the hadronic sector. Indeed, the CP Violation observed in the hadronic sector is by several orders of magnitude insufficient to explain the dominance of matter in the Universe. After observing a relatively high $\theta_{13}$ mixing angle in neutrino oscillations a possible CP Violation in the leptonic sector became a good candidate to explain (under some conditions) the matter–antimatter asymmetry in the Universe.

Few next generation accelerator neutrino projects propose to observe a CP Violation in the leptonic sector using very intense neutrino beams. One of these projects, ESS$\nu$SB [1], proposes to use the very powerful proton linac under construction of the European Spallation Source (ESS) [2] to produce a high intensity muon neutrino beam, sent towards a megaton Water Cherenkov detector, to observe a neutrino CP Violation on the second oscillation maximum. The advantage of placing the far detector on the second oscillation maximum compared to the first one is an enhanced sensitivity to a possible CP Violation [3].
2. ESS as Neutrino Facility
The ESS neutron facility is under construction in Lund, Sweden, since 2014. The proton linac used to produce the spallation neutrons of the facility has a duty cycle of only 4% (pulse duration of 2.86 ms). By doubling the pulse frequency from 14 Hz to 28 Hz (other operation scenarios are also possible) and thus doubling the mean proton power from 5 MW to 10 MW, this facility could be used at the same time to produce neutrons and neutrinos.

The extracted from the linac proton beam can be sent to a target to produce muon neutrinos from decaying pions. The decaying pions can be focused towards the far neutrino detector using a classical magnetic horn. The very high current (∼350 kA) pulses sent in the horn to produce the necessary magnetic field to bend the pions coming out of the target to go in the forward direction, must be relatively short (< 100 μs) for power dissipation reasons. For mainly these reason the proton pulse duration has to be reduced from 2.86 ms to few μs. To perform this, a proton accumulation ring of a circumference of about 400 m is needed. In this case, in order to be able to inject protons inside the ring while already other protons circulate in, H− are needed to be injected in the proton linac and striped at the entrance of the ring.

A target station can be placed just after the accumulation ring followed by a short decay tunnel (∼25 m length). At the end of the decay tunnel a beam dump has to be installed to stop all remaining particles, mainly protons and pions. A near detector (to monitor the unoscillated neutrino beam and to measure the relevant neutrino cross-sections) can be installed at about 500 m from the neutrino target.

Fig. 1 presents a schematic view of the ESS neutron and neutrino facility while Fig. 2 presents the neutrino spectrum which can be obtained at an arbitrary distance of 100 km for one year running.

3. Physics Performance
Using a megaton–class Water Cherenkov detector [4] at a distance of 540 km placed near the active mine of Garpenberg (Sweden), in 10 years data taking, ESSνSB would collect about 300 electron neutrinos (2 years running) and 250 electron antineutrinos (8 years running) coming from muon neutrino oscillations. Fig. 3 presents the $\nu_\mu \rightarrow \nu_e$ oscillation probability as a function of the neutrino energy together with neutrino energy distribution of detected by the far detector neutrinos. This shows that the ESSνSB facility operates almost exclusively on the second
oscillation maximum. Fig. 4 presents the fraction of the full $\delta_{CP}$ range as function of the exposure (1 corresponds to 10 years). The width of the curves is induced by the unknown neutrino mass hierarchy. After 10 years running, ESS$\nu$SB could cover up to 60% of $\delta_{CP}$ values at 5 $\sigma$ discovery level or more than 75% at 3 $\sigma$.

![Figure 3](image.png)

**Figure 3.** $\nu_\mu \rightarrow \nu_e$ oscillation probability as a function of the neutrino energy. The shaded distribution is the energy distribution of electron neutrinos as they would be detected by the far detector.

**Figure 4.** The fraction of the full $\delta_{CP}$ range as function of the exposure (10 years correspond to 1) for an unknown mass hierarchy. The lower (upper) curve is for CP violation discovery at 5 $\sigma$ (3 $\sigma$) significance.

4. Muon Facility

At the level of the beam dump of the neutrino facility a huge number of muons can be collected (produced together with neutrinos from pion decays) for other applications. The mean momentum of these muons is of the order of 0.46 GeV. With an adequate collecting device, more than $4 \times 10^{20}$ muons per year can be extracted. These muons can be used for a “low” nuSTORM neutrino experiments [5] and for R&D for 6D muon cooling for a possible future muon collider. It has been shown that a Higgs Factory based on an ESS muon collider could produce more than half a million Higgs bosons per year [6], enough to study in details this particle.

5. acknowledgements

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References

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