Neutrino CP Violation with the European Spallation Source neutrino Super Beam project

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Abstract. After measuring in 2012 a relatively large value of the neutrino mixing angle $\theta_{13}$, the door is now open to observe for the first time a possible CP violation in the leptonic sector. The measured value of $\theta_{13}$ also privileges the 2$^{\text{nd}}$ oscillation maximum for the discovery of CP violation instead of the usually used 1$^{\text{st}}$ oscillation maximum. The sensitivity at this 2$^{\text{nd}}$ oscillation maximum is about three times higher than for the 1$^{\text{st}}$ oscillation maximum inducing a lower influence of systematic errors. Going to the 2$^{\text{nd}}$ 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 (ESS), will have a proton linac with 5 MW power and 2 GeV energy. This linac, under construction, also has the potential to become the proton driver of the world’s most intense neutrino beam with very high potential to discover a neutrino CP violation. The physics performance of that neutrino Super Beam in conjunction with a megaton underground Water Cherenkov neutrino detector installed at a distance of about 500 km from ESS has been evaluated. 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. In addition to neutrinos, this facility will also produce at the same time a copious number of muons which could be used by a muon collider. The ESS neutron facility will be fully ready by 2023 at which moment the upgrades for the neutrino facility could start.

1. Introduction
The neutrino mixing angles $\theta_{12}$ and $\theta_{23}$ have been measured in several experiments and are both found to be large [1]. The third angle, $\theta_{13}$, first expected to be much smaller than the other two, was recently measured to be about $8^\circ$ [2]. The unexpectedly large value of $\theta_{13}$ significantly increases the possibilities of measuring the CP violation effects in neutrino oscillations. The discovery also represented a shift in how to optimally design long baseline neutrino experiments, since, with the measured value of $\theta_{13}$ and assuming the same level of systematic uncertainties, the sensitivity for measuring the CP term at the second oscillation maximum is about three times higher than at the first maximum [3].

The goal of the European Spallation Source (ESS) neutrino Super Beam project (ESS$\nu$SB) is to assess the possibility of generating a uniquely high intensity, cost effective and high performance neutrino Super Beam in Lund in Sweden, profiting from the presence of the proton linear accelerator at the ESS. The ESS is currently under construction and planned to be operational in 2023. The uniquely high intensity of the ESS linac would allow ESS$\nu$SB to measure neutrino oscillations at the second maximum, contrarily to the two currently leading
Table 1: The design parameters of the ESS (left) and ESSνSB (right).

| Parameter            | ESS  | νSB |
|----------------------|------|-----|
| duty cycle [%]       | 4    | 8   |
| beam power [MW]      | 5    | 10  |
| particles            | protons | H⁻-ions |
| pulse rate [Hz]      | 14   | 28  |
| kinetic energy [GeV] | 2.0  | 2.5 |
| pulse length [ms]    | 2.86 | ~0.0013 |
| pulse current [mA]   | 62   | 50  |

long baseline experiments, DUNE [4] and Tokai-to-Hyper-Kamiokande (T2HK) [5], both of which were optimized on the assumption of a small $\theta_{13}$ and so aim to measure the CP term at the first oscillation maximum.

2. From ESS to ESSνSB

Table 1 compares the design parameters of the ESS linac with the ones used in the ESSνSB studies. With the ESSνSB the linac would double its pulse rate thus increasing the total beam power from 5 MW to 10 MW allowing 5 MW to be used for neutrino production while retaining 5 MW for spallation neutron production. From the linac a transfer line is needed to guide the beam to a ~380 m circumference accumulator. The accumulator reduces the duration of the proton pulses to about 1 µs, a requirement set by the target stations. Due to charge effects in the injection of the beam into the accumulator ring one would need to accelerate $H^{-}$-ions, thus necessitating a separate $H^{-}$ source at the beginning of the linac as well as methods for stripping the ions at the entrance of the accumulator. Finally a target switch yard is needed to transfer the beam from the accumulator to the target station. The target station will consist of four targets and four horns, each target taking 1.25 MW of the beam power. The magnetic horns will focus the produced mesons towards the decay tunnel, which will be ~25 m long to allow for the mesons to decay.

The expected flux of neutrinos/anti-neutrinos 100 km on-axis from the target using 2 GeV protons during 200 days is shown in Figure 1. The beam is expected to be very pure in muon (anti-)neutrinos with a contamination of electron (anti-)neutrinos of less than 1%. The expected energy distribution of the neutrinos will be between 0.2 and 0.6 GeV. In this range the main background will be charge current quasi-elastic scattering, while the deep inelastic resonant scattering backgrounds are strongly suppressed [6]. Neutrino cross-sections at these energies have not been measured in any experiment before and it will be a particular important task for the near detector to measure these accurately to reduce the systematic uncertainties.

Figure 1: The neutrino (left) and anti-neutrino (right) beam fluxes 100 km on-axis from the target using 2 GeV protons during 200 days.
3. The Near and Far Detectors

The baseline design of the near detector in ESSνSB consists of two parts. First, with respect to the incoming neutrino beam, there will be a 3D plastic scintillation detector built up of several millions $1 \times 1 \times 1$ cm$^3$ plastic scintillator cubes. Three orthogonal holes are drilled in each cube to accommodate wave length shifting fibers used for readout. The isotropic detector geometry will be particularly important given that the final state leptons from charge current interactions of low energy neutrinos are expected in large scattering angles compared with neutrino interactions at higher energies. The detector will have a mass of 5 tonnes and operate in a magnetic field of 0.5 Tesla. The scintillation detector in ESSνSB will be based on the same technology as developed for the Super Fine Grained scintillation Detector (SuperFGD) as part of the near detector upgrade (ND280) of the T2K collaboration [7, 8]. Several prototypes of such a detector have already been tested at CERN and are currently being studied. Upstream of the scintillation detector there will be a 250 tonne, 10 m long and 5 m in radius, water Cherenkov detector, which main purpose will be to provide flux monitoring and event rate measurements using the same technology as in the far detector. Due to restrictions of the ESS site the near detector will be placed somewhere between 250 and 500 m from the target station.

The design of the far detector is based on the MEMPHYS Far Detector evaluated by the EUROν project in 2011 [9]. It will consist of two cylindrical shaped detector modules, with a total fiducial volume of more than 500,000 metric tonnes. At distances corresponding to the second oscillation maximum there are two existing mines for which a far detector can be located: i) Zinkgruvan ($\sim 360$ km from ESS) and ii) Garpenberg ($\sim 540$ km from ESS). The proposal is to put both detector modules in the same location (i.e. either in Garpenberg or Zinkgruvan) or to place one detector module in Garpenberg and the other in Zinkgruvan.

4. Systematic Uncertainties

The impact of the level of systematic uncertainties on the $5\sigma$ discovery reach of $\delta_{CP}$ in ESSνSB has been studied using five different scenarios: i) Def., ii) Opt. and iii) Cons., listed in the table in Figure 2a, in addition to two more extreme cases. The individual uncertainties on the neutrino cross-sections and the $\nu_e/\overline{\nu}_e$ fluxes have been shown to have the largest impact on the $\delta_{CP}$ reach of ESSνSB and thus would need to be measured very precisely [10]. Figure 2b shows the fraction of $\delta_{CP}$ values which can be reached at a given significance for the various scenarios of the systematic uncertainty. This study shows that, assuming the most optimistic scenario, more than 60% of $\delta_{CP}$ space can be covered with a significance of $\geq 5\sigma$ [10].

5. Conclusions

Benefiting from the worlds most powerful proton linear accelerator, already under construction at the ESS, as well as the measurement of a relatively large $\theta_{13}$ ESSνSB aims at measuring the CP violation parameter in neutrino oscillations at the second maximum. Here the effect of systematic uncertainties is three times smaller than at the first oscillation maximum and so makes ESSνSB more sensitive to $\delta_{CP}$ than any other competing experiment. Figure 3 shows the precision which can be achieved in the measurement of $\delta_{CP}$ for different locations of the ESSνSB far detector compared with the DUNE and T2HK experiments, clearly demonstrating the strengths of the ESSνSB project.

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Figure 2: The table in (a) lists the size of the various sources of systematic uncertainties in each of the scenarios considered in the sensitivity studies of ESS_{\nu}SB described in the text [11]. In (b) the level of significance for different fractions of the $\delta_{CP}$ values are shown for the various scenarios of the systematic uncertainty [10].

| Systemsatics | SB Opt. | SB Def. | SB Cons. |
|-------------|---------|---------|----------|
| Fiducial volume ND | 0.3% | 0.5% | 1% |
| Fiducial volume FD | 1% | 2.5% | 5% |
| (incl. near-far extrap.) | | | |
| Flux error signal $\nu$ | 5% | 7.5% | 10% |
| Flux error background $\nu$ | 10% | 15% | 20% |
| Flux error signal $\bar{\nu}$ | 10% | 15% | 20% |
| Flux error background $\bar{\nu}$ | 20% | 30% | 40% |
| Background uncertainty | 5% | 7.5% | 10% |
| Cross sect $\times$ eff. QE\* | 10% | 15% | 20% |
| Cross sect $\times$ eff. BES\* | 10% | 15% | 20% |
| Effic. ratio $\nu_e$/QE | 3.5% | 11% | -- |
| Effic. ratio $\nu_e$/BES\* | 2.7% | 5.4% | -- |
| Effic. ratio $\bar{\nu}_e$/BES\* | 2.5% | 5.1% | -- |
| Matter density | 1% | 2% | 5% |

Figure 3: The expected precision of the measurements of $\delta_{CP}$ in ESS_{\nu}SB compared with the prospects of DUNE and T2HK assuming 10 years of data taking and a systematic uncertainty at the level of 3%.

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