OVERVIEW OF THE ESS NEUTRINO SUPER BEAM PLUS PROJECT

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Abstract

The ESS neutrino Super Beam (ESSνSB) project aims to produce an intense neutrino beam optimized for measurement at the second neutrino oscillation maximum, providing an enhanced capability to discover CP violation in the lepton sector and to measure the CP violating phase with high precision. ESSνSB will be integrated into the ESS accelerator facility, which is originally designed to deliver a 2.0 GeV, 5 MW proton beam for neutron production, and will accelerate the additional pulses required for the neutrino production. By using interleaved pulses in ESS proton linac, the power will be effectively increased from 5 to 10 MW. This project has received funding from EU in the framework of Horizon Europe 2020 (2018-2022) and Horizon Europe (2023-2026) to carry out feasibility studies. Initial design studies- covering all parts from the upgrade of the ESS proton linac up to the location of the neutrino far detector- are documented in the Conceptual Design Report (CDR). A continuation of this work, ESSνSB+, aims to enable neutrino-nucleus cross-section measurements and sterile neutrino searches. It proposes two low-energy facilities; nuSTORM, which produces neutrinos from muons decays in a storage ring, and LEMNB, low energy monitored neutrino beam, which monitors the neutrinos by tagging the muons associated with these neutrinos from the decay of the pions. An updated overview of the project will be given in this work.

INTRODUCTION

Reactor-based neutrino experiments have provided crucial information in the search for the Charge Party (CP) violation in the leptonic sector [1]. In particular, the precise measurement of the third neutrino mixing angle, θ_{13}, opened the possibility of discovering the Dirac CP violating phase, δ_{CP} , requires high-intense neutrino beams.

To achieve high-intense neutrino beam, the European Spallation Source neutrino Super Beam (ESSνSB) project has been proposed to use the powerful 5 MW,2 GeV proton beam of ESS proton linear accelerator, located near Lund in Sweden [2]. In a future upgrade of ESS, the facility could simultaneously deliver protons for both neutron and neutrino production without interfering with main mission of ESS. This would involve doubling the linac power and increasing the linac pulse rate from 14 Hz to 28 Hz. In addition, the background reduction at the far detector requires compressing the proton pulses length from 2.86 ms to 1.2 μs, which can be accomplished by using a proton accumulator ring. Accumulator ring requires that H^- acceleration in the linac and electron stripping at the injection into the ring. To ensure efficient beam accumulation while minimizing beam losses, a design for a laser stripping injection scheme is under study, with this method a much cleaner injection with H^- can be achieved [3]. In parallel, a Liouvillian Injection Optimization method is also being studied to avoid the need of a more complex linac design. This method would allow direct proton injection with 4D multiturn accumulation whiteout H^- stripping. It allows the beam to be distributed in both horizontal and vertical planes using a tilted septum [4]. Finally, a target station design incorporates four targets and four magnetic horns to handle the high-power proton beam and produce neutrinos to the near and far detectors.

The high neutrino beam power enables operation at the second neutrino oscillation maximum, where the sensitivity to CP violation and violating parameter, δ_{CP}, is significantly higher compared to facilities operating at the first oscillation maximum [5, 6]. The ESSνSB has been designed with both near and far detector complexes. The near detector complex, located at ESS site, includes a water Cherenkov detector, a super fine-grained scintillator detector, and an emulsion detector. The far detector complex consists of a large water Cherenkov detector with two 270 ktons tanks, be installed in the Zinkgruvan mine in northern Sweden, approximately 360 km from the source at a depth of about 1 km. [7].

The design study of ESSνSB project has carried out in the framework of the European Union H2020 program to assess the feasibility of integrating a neutrino super beam facility with the ESS neutron source. This study approved and conducted between 2018 and 2022, focused on the precision measurement of the CP violating phase using long-baseline (LBL) neutrino experiments and explored additional physics opportunities enabled by the large neutrino detectors, including supernova explosions, proton decay, and solar neutrino studies. The design study and the physics performance of experiment have been compiled in the Conceptual Design Report published in 2022 [8].

The study demonstrates strong sensitivity to CP violation measurement, as shown in Fig. 1 [8]. The results assume a 5 % normalization uncertainty and a total running of 10 years, divided equally between neutrino and antineutrino modes. The left panel shows the CP violation discovery sensitivity as a function of true value of δ_{CP}, reaching up to about 12 σ for maximal the CP violation ($\delta_{CP} \sim \pm 90°$). The middle panel demonstrates that the ESSνSB will cover more than 70% of the δ_{CP} values with a significance exceeding 5 σ, to reject the no-CPV hypothesis. The right panel shows that the expected precision on the measured value of δ_{CP} will be better than 8° over the full parameter range.

As a second-generation long–baseline neutrino facility, ESSνSB, offers high-precision measurement of CP violation phase, providing valuable constraints for phenomenological models of CP violation. A comparison with DUNE and

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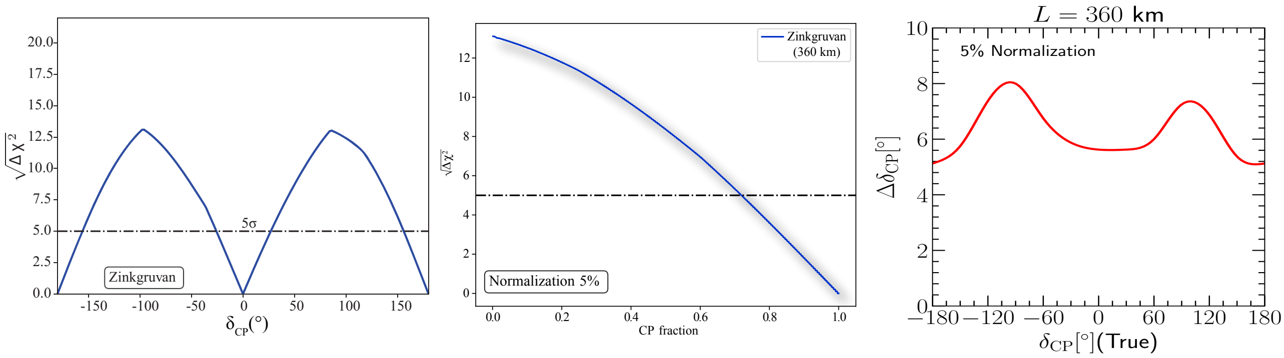

Figure 1: (Left) CP Violation discovery sensitivity of ESSνSB as a function of true δ_{CP} for various level of systematic uncertainty. (Middle) The fraction of true values of δ_{CP} for which CP violation can be discovered at 5 σ. (Right) The precision on the measurement of δ_{CP} .

T2HK, the two under construction long-baseline projects, is shown in Fig. 2.

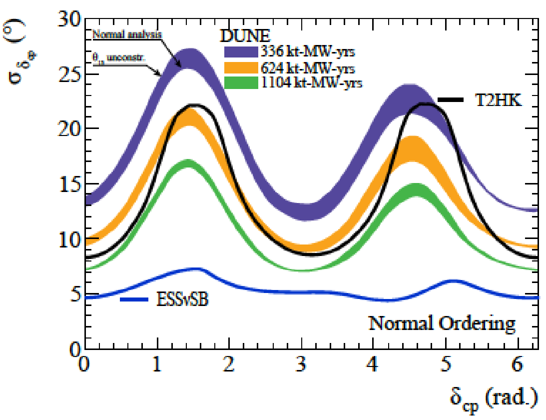

Figure 2: Precision on the ESSνSB measurement on δ_{CP} versus δ_{CP}, compared to the under construction long baseline projects DUNE and T2HK..

ESSνSB+ PROJECT

Limited knowledge of neutrino cross sections below 600 MeV/c leads to systematic uncertainty in neutrino oscillation studies. While this represents the largest contribution in the systematic uncertainty in CP-violation measurements at ESSnuSB, achieving higher precision in this direct remains important. The ESSνSB+ [9], which is an extension phase of ESSνSB project, funded by the European commission under the Horizon Europe program for the period 2023-2026, is undertaken to focus on measuring the neutrino cross-section in the energy range of 200–600 MeV. To achieve this, a dedicated detector station supported by two intermediate facilities is proposed. The first is a Low Energy nuSTORM setup [10] (LEnuSTORM), in which pions generated in the secondary hadron beam will be extracted and transported to a low energy muon storage ring. The second is a Low Energy Monitored Neutrino Beam (LEMNB) [11] , which generates a precisely monitored neutrino beam from pion decays without requiring high beam power or short pulse operation, using a decay tunnel. Fig. 3 shows the layout of the ESSνSB/ESSνSB+ accelerator and the near detector complex.

Both facilities constituted the first and second phases of staging of the ESSnuSB complex. Achieving high precision in CP violation measurements requires reducing the main source of systematic uncertainty for the neutrino interaction cross sections in water for both electron and muon neutrinos. To address this, a simpler target station has been under design as well as a new near-near detector, called the Low Energy neutrino from stored Muons and Monitored beam Near Detector (LEMMOND). The decay of muons in the straight sections of LEnuSTORM racetrack ring will provide clean beams, with equal amounts of muon neutrinos (antineutrinos) and electron antineutrinos (neutrinos), depending on the muon charge. At the same time, the LEMNB will produce clean neutrino and antineutrino beams from pion decays. These high-quality neutrino beams will be used with the LEMMOND detector to precisely measure low energy neutrino cross sections in water.

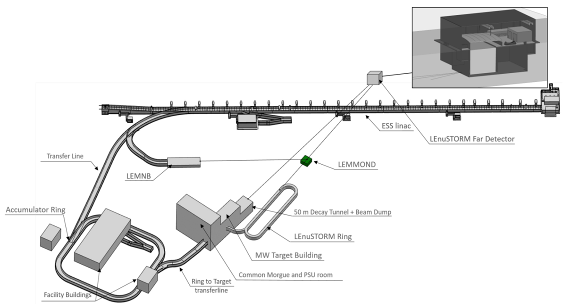

Figure 3: Layout of the ESSνSB and ESSνSB+

LEMNB

The Low Energy Monitored Neutrino Beam (LEMNB) is a facility designed to measure the neutrino cross sections in the 200-600 MeV energy region using a neutrino tagged technique that improves flux normalization. Muons originating from pions in the decay tunnel are monitored at the single particle level, enabling precise cross-section measurements in low energy range by constrain the neutrino flux at the neutrino detector. Thus, this technique, with conventional beam diagnostics, is expected to reduce the overall flux uncertainty to 1%.

A key advantage of the LEMNB is that it doesn't require short proton pulses, so the measurements could be performed prior to the construction of the accumulator ring by using the proton extraction line, decay tunnel, and with a compact dedicated target station. This construction is stage I of the facility of ESSνSB+. The designed detector, based on high granularity fast tracker device such as Micromegas or picosecond Micromegas, offers a better performance compared to the sampling calorimetric technology proposed in ENUBET at CERN. Placing an iron shield in front of the first detector layer reduces the muon peak rates significantly compared to the benchmark scenario without shielding. In addition, optimizing the number of protons per pulse ensures to have a proper detector operation. Also, a good discrimination between signal muons and background pions based on differences of particle tracks in the detector improves the signal-to-noise ratio to enable precise cross section measurements.

LEnuSTORM

The LEnuSTORm facility, similar to LENMB, is designed to perform neutrino cross section measurements in the 200-600 MeV energy range. Pions produced at the ESSνSB target station and collected by a magnetic horn are efficiently injected into a racetrack muon storage ring. In the first straight section of the ring, which is oriented towards the near detector LEMMOND, most of the pions decay into muons that be stored in the ring for a several turns using the bending at the end of straight section, while the remaining pions are led into a beam dump. The circulating muons decay in the straight section, producing well-defined muon and electron neutrino beam to be used for cross-section measurements and also sterile neutrino searches. LEnuSTORM ring is considered stage II of the project, as it requires the compression of the proton beam.

A detailed magnetic lattice and beam optics design of the muon storage ring is under study and will be used as input for simulation studies, especially for sterile neutrinos. The ring design uses iron-dominated magnets to reduce complexity, and a compact FODO lattice to maximize neutrino production by allowing a large transverse acceptance [12].

The racetrack–shaped storage ring lattice consists of two long straight sections connected by two short 180-degree arcs. As the stored muon intensity is well controlled, it is possible to determine absolute neutrino cross sections at the low neutrino energy range by measuring both the electron and muon neutrinos using the same detector, therefore reducing systematic uncertainties. An additional advantage of LEnuSTORM is to search for sterile neutrinos with higher masses than those in any other experiments because of the low energy of the stored muons. For these studies, the near detector, LEMMOND is in progress for both LEnuSTORM and LEMNB facilities.

CONCLUSION

A comprehensive design study of ESSnuSB has proved the feasibility of a long baseline neutrino setup to precisely measure the CP violating phase. The proposed design includes a near detector suite comprised a water Cherenkov, a Super fine grained detector, and an emulsion detector, with a large underground far water Cherenkov detector. The design study of theextension project, ESSνSB+ has been initiated, being motivated by the lack of high precision neutrino cross section measurements on water in the neutrino energy range of the ESSνSB beam, and intends to precisely measure the neutrino cross sections, and hence decrease the systematic uncertainties. To achieve this, two intermediate facilities have been proposed. The first is a low energy monitored neutrino beam (LEMNB) design for precise measurements of muon neutrino cross sections. The second is low energy nuSTORM (LEnuSTORM), a racetrack muon storage ring that enables measurements of both muon and electron neutrinos cross sections. In addition, LEnuSTORM combined with a near-near detector (LEMMOND) and the near detector of the Long Baseline setup, ESSνSB+ will provide the existence of sterile neutrinos. More analysis techniques, physics performance, and the cost of all stages of the proposed neutrino facility will be presented in a new Conceptual Design Report at the conclusion of the ESSνSB+ project.

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