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THE EUROPEAN SPALLATION SOURCE NEUTRINO SUPER BEAM*

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On behalf of the ESSνSB+ project

Abstract

The discovery of neutrino Charge–Parity Violation (CPV) became an important candidate to explain the matter dominance in the Universe. The goal of the ESSνSB project is to discover and measure neutrino CPV with unprecedented sensitivity. The construction of the European Spallation Source, ESS, the world's most intense proton source, represents an outstanding opportunity for such project to take place. ESSνSB has been granted from EU in the framework of H2020 (2018–2022) and Horizon Europe (2023–2026) to make Design Studies. The aim of the first Design Study was to demonstrate that the ESS linac can be used to generate an intense neutrino beam by doubling its average beam power and that a megaton water Cherenkov detector can be constructed in a mine 360 km from ESS providing detection of neutrinos at the 2nd neutrino oscillation maximum. A CDR has been published in which it is shown the high physics performance to discover CPV and precisely measure the violating parameter δ_{CP}. For this, the modification for neutrino generation to compress the proton pulse length from 2.86 ms, to 1.3 µs has been studied. The second, ongoing, Design Study, ESSνSB+, is devoted to neutrino cross–section measurements relevant to the CPV discovery. Two facilities are proposed, a low energy nuSTORM (muons decaying to neutrinos in a race–track storage ring) and low energy ENUBET (pions decaying to a muon and a neutrino, allowing the neutrino beam to be monitored by detection of the decay muon).

INTRODUCTION

The European Spallation Source (ESS) [1] which construction is almost finished in Lund (Sweden) uses a linac proton driver to deliver a 5 MW 2 GeV proton beam to produce neutrons for neutron scattering applications. A first European Design Study in the framework of Horizon 2020, called ESSνSB (European Spallation Source neutrino Super Beam) [2] took place between 2018 and 2022. Its aim was to investigate the possibility to add, on top of the neutron facility, a neutrino Super Beam devoted to the discovery and precise measurement of CPV in the leptonic sector, which could help to explain the matter dominance in the Universe.

At the end of this project a Conceptual Design Report [3] has been published in which the physics performance is also reported. It is proposed to double the proton linac power in order to have 5 MW for neutron production and the equivalent for neutrino production. To shorten the proton linac pulses from 2.86 ms to less than 1.5 µs necessary for the neutrino programme it is proposed to use an accumulator with a circumference of less than 400 m. The presence of the accumulator obliges to accelerate in the linac H^- instead of protons. A target station is also proposed with four targets/horns pulsed alternatively to share the very powerful proton pulses. A far water Cherenkov detector placed at a distance 360 km it is foreseen for these neutrino oscillation studies.

Figure 1 presents the coverage fraction of the violating parameter δ_{CP} versus the confidence level for CPV discovery. More than 70% of δ_{CP} can be covered at 5σ confidence level, while the expected precision on δ_{CP} is lower than 8° for all δ_{CP} values (Fig. 2).

Following this study proving the feasibility of the proposed facility and the very promising physics performance, a second EU Design Study has been proposed. This second project, which started beginning of 2023 with a duration of four years, studies the possibility to stage the construction of the neutrino facility previously proposed by adding two intermediate stages with a muonic "colour".

Neutrino cross–section uncertainty is the main systematic error for the discovery of CPV in ESSνSB. In the two stages of the new project, ESSνSB+, the neutrino cross–sections at the relavant neutrino energy range will be measured. In the first stage, it is proposed to build a low energy ENUBET [4], called Low Energy Neutrino Monitored Beam (LENMB), not needing short proton pulses and high power proton beam.

A low energy nuSTORM facility [5] (LEnuSTORM) will be added in a next stage. In this second stage a search of sterile neutrinos will also be performed.

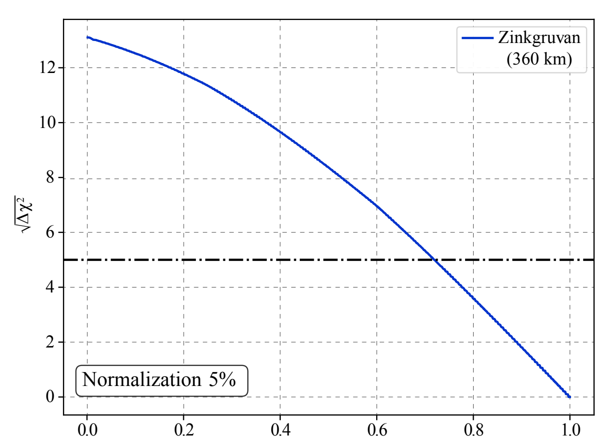

Figure 1: Confidence level versus fraction of values of δ_{CP} for which CP violation could be discovered.

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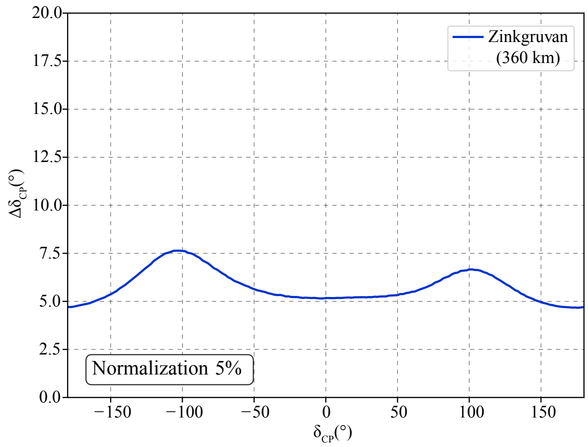

Figure 2: Precision on the ESSνSB measurement on δ_{CP} versus δ_{CP}.

THE ESSνSB+ PROJECT

In striving for high precision, it is essential to reduce both the relative and absolute sizes of the systematic errors by accurately measuring the electron and muon neutrino interaction cross-sections in water. In this stage a simpler target station will be used than the one proposed for the full ESSνSB project. The role of this target station is to produce charged pions using just one target and one horn (1/4th of the full proton power) to feed LENMB and LEnuSTORM.

This study also includes the design of a common detector for the Low Energy nuSTORM and for the Low Energy Monitored Neutrino Beam sub-projects for measurement of the neutrino cross-sections of interest.

Figure 3 presents the proposed facility layout inside the ESS allocated area. In this figure it is seen together the ESSνSB facility for CPV measurement together with the ESSνSB+ subprojects LEMNB and LEnuSTORM. This layout is still preliminary and could vary following further optimisations of the whole project.

LENMB

This promising new technique using tagged neutrinos can be utilised to measure precisely neutrino cross–sections. A high energy version has already been proposed and financed by an ERC grant. Here, in this ESSνSB+ proposal, we include a “low” energy version able to measure cross–sections in the energy region where the whole ESSνSB and ESSνSB+ projects will be operated.

The ENUBET-like Low Energy Monitored Neutrino Beam (LEMNB), instead of kaon decays used by the high energy version, will use pion decays to produce neutrinos. In Phase 1 of this study, a preliminary design of the ca 30 m long LEMNB decay tunnel will be made on the basis of the H2020 ESSνSB Design Study and ERC ENUBET project. Muons from pion decays, which are produced with an average emission angle of order 50 mrad at 1 GeV, are monitored at the single–particle level using sampling calorimeters for muon/pion separation. These detectors will be used to count the number of leptons produced by pion decays and by the decay–in–flight of muons. In this case, the neutrino beam normalization is monitored by measuring the muon that accompanies the muon neutrino in the pion decay. The combination of the muon rate with conventional diagnostics (full beam-line simulation, hadroproduction data, beam monitors) is foreseen to reduce the overall uncertainty on the flux down to 1%.

Thanks to the additional sample of electron neutrinos originating from the decay in flight, the ESS monitored neutrino beam will be able to assess also the electron neutrino versus muon neutrino difference of cross–sections below 1 GeV. During the final two years (Phase 2) of the Design Study, a more elaborated scheme will be proposed optimising all stages in order to obtain the highest statistics in as short period as possible, for neutrino cross-sections measurements to satisfy the ESSνSB needs.

In a synergetic way, the target station proposed for all phases of the project will also be used by this subproject. The advantage of this technique is that there is probably no need to have short proton pulses, so it could start before the accumulator ring is constructed using the proton extraction line and the ESSνSB target station. If it is confirmed that the ESS long proton pulses (2.86 ms) can be used, this part of ESSνSB+ could be the first to be built and operated at a moderated cost to be defined during this study.

LEnuSTORM

The Low Energy nuSTORM (LEnuSTORM) will be used for cross–section measurements in the region of 200–600 MeV in order to reduce the dominant systematic uncertainty in the determination of CPV. LEnuSTORM will also be used to search for sterile neutrinos.

This study includes the design of the muon decay ring and the injection of pions coming from the target station. The racetrack muon storage ring will allow muons to decay and give a well–defined muon and electron neutrino beam. The shape and dimensions of this storage ring which are designed as part of the ESSνSB+ study, are constraint by the available space and the physics performance.

The main deliverable of this part of the project is the design of the LEnuSTORM racetrack muon ring, including an estimate of its cost. A magnetic lattice and beam optics scheme for this new ring under design will be used as input into simulation studies of its performance. In addition, the particle transfer lines before and after the target station and the ring injection are studied.

The study has, as an early priority task, to propose the layout of the ring on the ESS site in order to allow civil engineering studies to start in good conditions. At an early point in the second stage, a first estimate of the flux of neutrinos and their energy spectrum will be provided in order to asses the physics performance of the facility.

The essential point is that LEnuSTORM will make it possible to measure both the electron and the muon neutrino cross–sections at the low neutrino energy range of the ESSνSB neutrino beam. An important additional feature

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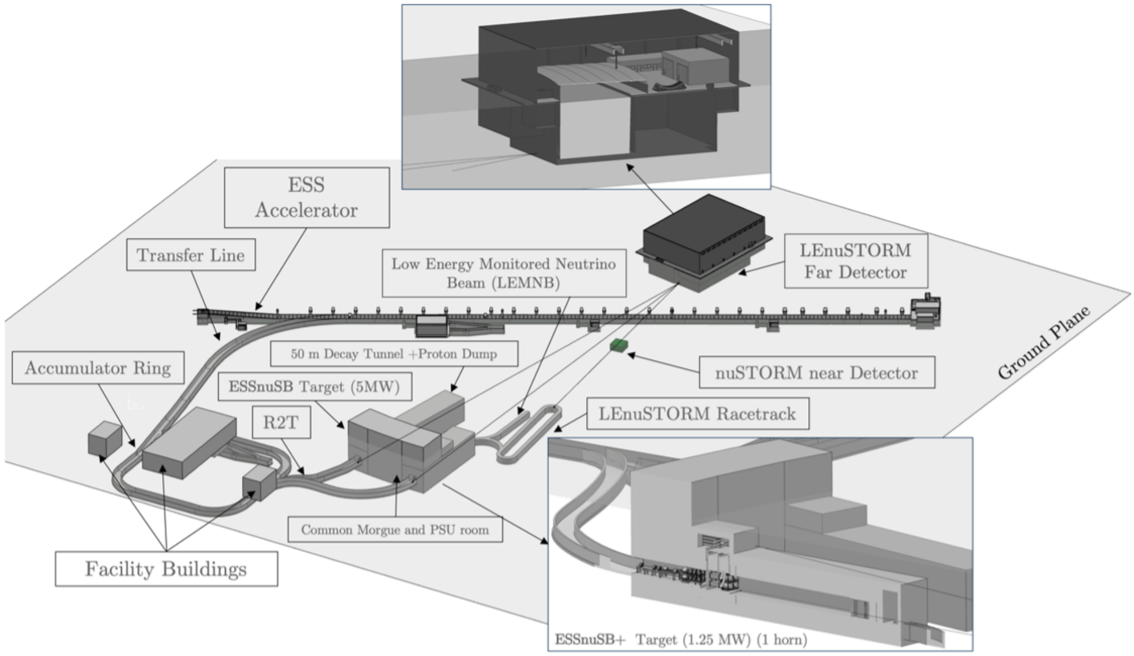

Figure 3: Layout of the ESS neutrino Super Beam facility. It is shown the ESSνSB beam extraction line, the ESSνSB accumulator ring and the ESSνSB+ LEnuSTORM racetrack, the ESSνSB and ESSνSB+ target stations. Also indicated are the positions of the LEMNB decay tunnel close to the LEnuSTORM race track, the LEnuSTORM near detector, and the ESSνSB near detector (dimensions in mm).

of LEnuSTORM is that it will enable searches for sterile neutrinos of higher masses than in any other experiments because of the low energy of the muons to be fed into the LEnuSTORM ring. For these searches the utilisation of the LEnuSTORM detector (considered as near detector), under design, and the ESSνSB near detector (considered as far detector), already designed, is under investigation.

The lattice and beam optics design of the LEnuSTORM racetrack muon ring is elaborated from the existing higher energy proposals. During the first phase of the project, shape and dimensions of the racetrack ring and the overall layout are established. A preliminary parameter range for the injected and collected beams will be determined and used in the initial design work, which will result in an updated neutrino spectrum to be used to explore the physics potential.

The ring lattice design must incorporate large aperture combined function magnets and effective beam control methods to avoid large beam losses due to the very large spread in momentum and transverse phase space among the stored muons. The updated lattice will be used as input to simulations to assess the performance of the storage ring. In the second phase, several lattice types, as well as the injection method, will be evaluated based on the injection and storage efficiency, as well as on the final neutrino flux. The study will include the transfer lines from the ESSνSB complex to the target and from the initial capture an extraction up to the injection point in the ring.

CONCLUSION

After the first successful European Design Study proving that the European Spallation Source can also be used for CPV discovery in the leptonic sector and that this neutrino facility can precisely measure the amount of this violation, a second EU feasibility study, ESSνSB+, is undertaken proposing to stage the operations towards the final neutrino facility. To precisely measure the relevant for this project neutrino cross–sections in order to further decrease the systematic errors, two intermediate subprojects are proposed. The first is the installation of a low energy ENUBET to measure ν_μ cross–sections and the second one is a low energy nuSTORM to measure ν_μ and ν_e cross–sections. ESSνSB+ will also investigate the possibility to perform sterile neutrino searches.

At the end of this project a new Conceptual Design Report will be produced also including the physics performance and the cost of all stages of the proposed neutrino facility.

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