PoS PROCEEDINGS OF SCIENCE

The ESSνSB project

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The ESSνSB project aims to produce a neutrino beam of unique intensity for a long-baseline oscillation measurement of CP-violation in the leptonic sector. The project, supported within the H2020 framework programme of the European Union, is currently in a conceptual design study phase, and work is ongoing within the project to develop viable solutions for the upgrade of the linear accelerator of the European Spallation Source (ESS), for the associated ring accumulator and the high-power target stations, as well as to establish solutions for the near and far detectors. The unique strength of the project lies in the capability to produce a neutrino beam that is intense enough to place the far detector at the second oscillation maximum. Such a placement will reduce the sensitivity of the experiment to systematic errors, which, due to the recently established value of the neutrino mixing angle θ_{13}, is now known to limit the measurement precision at the first oscillation maximum. In this paper we outline the basic components of the project and discuss the status of the ongoing conceptual design study.

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1. Introduction

The currently known CP-violation in the weak interaction of the quarks, as described by the Cabibbo-Kobayashi-Maskawa matrix, is several orders of magnitude too small to adequately explain the observed matter-antimatter asymmetry in the Universe if it is assumed that our Universe was created in a Big Bang scenario governed by the Standard Model with presently established parameters [1]. If CP-violation is present in the leptonic sector it would provide an additional mechanism that via sphaleron processes could transform an uneven lepton-antilepton distribution into the observed baryon asymmetry [2]. Long-baseline neutrino oscillation experiments, that investigate the $\nu_\mu \rightarrow \nu_e$ oscillation, and its anti-particle counterpart, provide a path to discover and measure leptonic CP-violation. However, recent measurements of the neutrino mixing angle θ_{13} to be $\approx 10^\circ$ [3] give cause for caution when designing the next generation of long-baseline experiments. For this value the atmospheric term in the oscillation formula dominates over the CP-interference term at the first oscillation maximum. On the other hand, at the second maximum the CP-interference term gains in magnitude and becomes comparable in size to the atmospheric term. This enhances the precision with which a non-zero CP-violation phase, δ_{CP}, can be determined in a measurement compared to measurements at the first maximum that often is the focus of other proposals [4, 5]. The drawback of using the second oscillation maximum for a long-baseline experiment comes from the decrease in detectable intensity of the oscillated neutrino beam with distance due to general beam divergence. Consequently, to successfully perform a measurement at the second maximum, a sufficiently intense neutrino beam has to be created.

The ESSνSB project overcomes this challenge by invoking synergies with an existing project and proposes to use the driver accelerator of the ESS neutron scattering facility [6], which when completed in 2025 will provide the world's most intense proton beam suitable for a long-baseline experiment. In order to accomplish this an upgrade of the ESS accelerator would suffice thus avoiding the need for investments in a new facility dedicated to neutrino physics only. Furthermore, by exploiting the results from previous projects supported by the European Union we illuminate how to best benefit from investments already made in order to construct a European long-baseline experiment with world-unique physics potential.

2. Upgrading ESS for the ESSνSB experiment

ESS, currently under construction in Lund, Sweden, will primarily provide neutrons in the cold (<5 meV) and thermal (<80 meV) energy ranges, using a high-power spallation target and moderator system, for neutron scattering experiments in applied physics. The neutron beams at ESS will have unequalled brightness with a peak flux 30 times higher than any reactor-based neutron source and with a power level five times above any other accelerator-based spallation source [6].

Using the high-intensity ESS proton beam for a long-baseline neutrino experiment would also provide an unparalleled opportunity. The ESS baseline, now under implementation, relies on a proton linear accelerator with a beam energy of 2 GeV and a repetition rate of 14 Hz. The average beam current is 62.5 mA and the macro-pulse length is 2.86 ms, which gives an average beam power of 5 MW and 125 MW during the pulse. The machine consists of a normal conducting part with a Radio Frequency Quadrupole (RFQ) stage and a Drift Tube Linac (DTL) that brings the

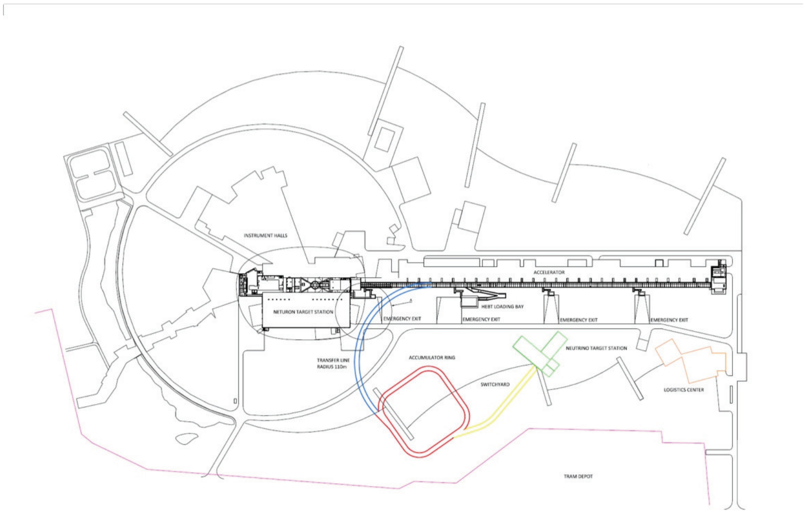

Figure 1: Overview of the upgrade of the ESS accelerator for the ESSνSB project showing the location of the beam transfer line, the ring accumulator and the target stations for neutrino production relative to the ESS baseline. See text for further discussion.

beam energy to 90 MeV in ca 50 m, and a superconducting section that provides the 2 GeV final energy in ca 300 m before the beam impinges on a horizontal rotating segmented tungsten target wheel, with a diameter of 2.5 m, enclosed in a 6000 ton shielding monolith.

The ESSνSB proposal comprises an upgrade of the ESS linac to accelerate an H^+ and an H^- beam in alternating pulses using, to as large an extent as possible, the same accelerator hardware. The strategy of the upgrade is to maintain the beam power for the neutron scattering experiments, while increasing the duty cycle to feed target stations for neutrino production. The long beam pulse at ESS needs to be shortened in order to reduce the length of the current pulse in the magnetic horns used to focus the hadrons from the production target. This can be accomplished by doing multiturn injection into a ring accumulator with subsequent single-turn extraction. The advantage of using an H^- beam comes from improved injection performance for the accumulator. An overview of the facility with the position of the accumulator can be seen in Fig. 1.

The ESS baseline design allows upgrades to higher energy by the addition of superconducting cavities in the final beam transport sections. For the ESSνSB project an upgrade to a beam energy of 2.5 GeV is envisaged. This upgrade allows the average beam current to be reduced from 62.5 mA to 50 mA. Without the energy upgrade the average power needed from the RF system would double, which in turn would require larger changes in the RF installations. With an energy upgrade the increase in average power from the RF system stays at 60%, which should be feasible with limited alterations and within the available space. The lower average beam current of 50 mA would also simplify the acceleration of the H^- beam.

An initial overview of the needed modifications was carried out at an early stage of the project, and has been published as a CERN technical note [7]. Two general scenarios were investigated in that first overview and constitute the baseline for the ongoing upgrade study. In the first scenario the pulse frequency is doubled to 28 Hz and alternating beams of H^+ and H^- ions are accelerated in 2.86 ms and 2.9 ms long pulses, where the longer H^- pulse includes chopping to introduce the temporal gaps necessary for injection into, and extraction from, the accumulator. In the second scenario higher rate pulsing is used. The current baseline for this scenario uses a 70 Hz pulse frequency and four interleaved H^- pulses with lengths $\sim$1.3 ms or $\sim$0.77 ms to give either 30 mA or 50 mA current.

Some of the main modifications that can be mentioned in these scenarios are the introduction of an additional eight cryomodules with associated RF stations and a change of klystron collectors to accept the 60% power increase. Such an upgrade could be coordinated with planned maintenance or upgrades of the RF system to avoid any influence on the neutron scattering programme. On the front-end side the upgrade comprises a new H^- source, where merging of the H^- and proton beams can either be done before the low energy stage or alternatively after a new RFQ and beam transport line just before the DTL stage. Both these options are under study. In addition to the upgraded accelerator hardware, some upgrade of existing power installations are needed for these two approaches. The preliminary cost for the upgrade is estimated to be ca 230 MEuro, if a new low-energy stage is included. This cost can be compared to the overall cost of ESS which has been estimated to be ca 1.8 GEuro.

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2.1 Options for the accumulator and target stations

The purpose of the accumulator is to shorten the pulse length to stay within the current capacity of the conductors of the magnetic horns of the hadron collectors. To accomplish this the pulse needs to be shortened to the μs range from the original ms duration. At the same time a shortened pulse will also improve the signal-to-background ratio in the neutrino detectors. Several accumulator options have been studied. The current baseline is a 384 m circumference ring with a dipole field of 1.33 T and a revolution time of 1.33 μs, using multiturn injection and single turn extraction as mentioned above. One of the major technical issues with capturing and storing the high-intensity beam, where the standard ESS pulse contains 8.9×10^{14} protons, is space-charge effects. This hampers effective injection of a proton beam into the accumulator, and is the reason that injection of an H^- beam with subsequent foil or laser stripping is studied as part of the project. Space charge effects in the accumulator itself can be mitigated using two alternative techniques. A straightforward approach is to use a set of stacked rings, which in the ESSνSB baseline would comprise four stacked rings that would feed four separate target stations. This approach would be similar to the PS booster at CERN. An alternative is to pulse one accumulator ring several times. The initial results of this part of the study show that foil stripping of the injected H^- beam is a viable option under the foreseen conditions.

The design of the ESS target stations is a continuation of the development within the previous EUROν project where a four-horn assembly was studied. The baseline target design consists of a packed-bed of spherical Ti6Al4V beads with helium cooling. The target is located within the forward part of the inner conductor of the respective horn. The material of the horns is suggested to be Al-6061 T6 alloy. Extensive studies of loads and deformation arising from the pulsing magnetic field and from thermal stress has already been made as part of the EUROν project.

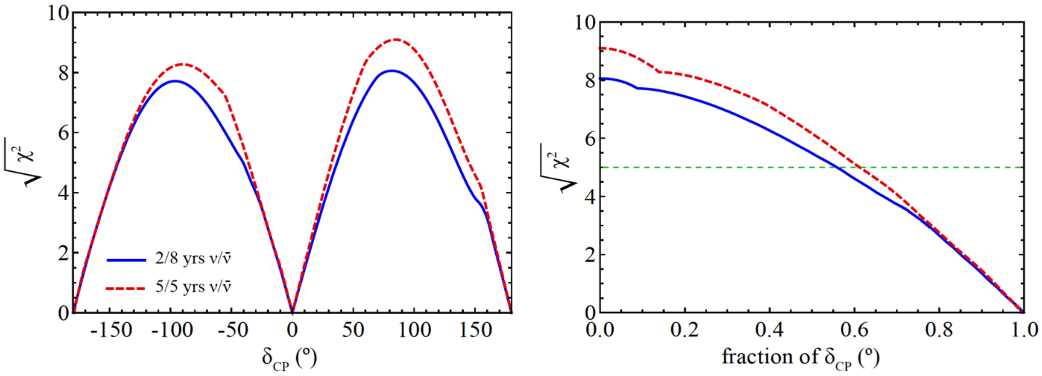

Figure 2: Discovery potential of the ESSνSB experiment given by the significance with which a measurement of a given value of δ_{CP} would exclude the null hypothesis for two different combinations of neutrino and anti-neutrino run times. Left panel: the statistical significance as function of δ_{CP}. Right panel: the fraction of the total angular range that can be covered at a given statistical significance. A discovery of CP-violation at the 5σ significance level can be met over ca 60% of the full angular range with ESSνSB. The graphs were produced for the 2.5 GeV proton beam option and a baseline of 540 km.

3. The near and far detectors

The far detector of the ESSνSB project takes as starting point the MEMPHYS [12] water Cherenkov detector investigated e.g. within the EUROν and LAGUNA EU-FP7 design studies, with the aim of adapting the design to the neutrino spectrum and flux from ESSνSB. The geological situation at the potential host locations are also investigated as part of the ESSνSB project. The MEMPHYS design envisaged two cylindrical detector volumes with a diameter of 65 m, a height of 100 m, and a total fiducial mass of 500 kton. The foreseen optical readout would consist of ca 120 000 photomultiplier tubes of 8 and 10 inch diameter. In order to measure the flux at the second maximum, two sites have been identified for the ESSνSB far detector at this point. The first one is located at the Garpenberg mine 540 km north of ESS, and the second one at the Zinkgruvan mine at 350 km distance, also towards the north. Geological studies of the mines and the surroundings to establish the precise location and design of the detector caverns are ongoing. The current timeline is that the proposal for the site, as part of the design study, will be taken in 2020. Simulations of the detector response is also ongoing using state-of-the-art simulation software based on the GEANT4 [8, 9, 10] and GENIE [11] frameworks.

The near detector is a crucial component of the ESSνSB experiment. The current baseline design consists of a kiloton water Cherenkov detector in combination with a fine grain tracker, of similar type as introduced by other experiments [13], positioned in a magnetic field. The combination of the two detectors will make it possible to perform event rate measurements and flux normalisation and to measure neutrino cross sections in the relevant energy range (60 – 600 MeV), where there currently is very limited knowledge of the cross sections. The tracking detector will be located upstream of the water volume and directly adjacent to it. When a neutrino interacts in the tracker, the event topology is reconstructed and the momenta of the charged particles measured. The charged particles that exit at the downstream side of the tracker enter the water Cherenkov

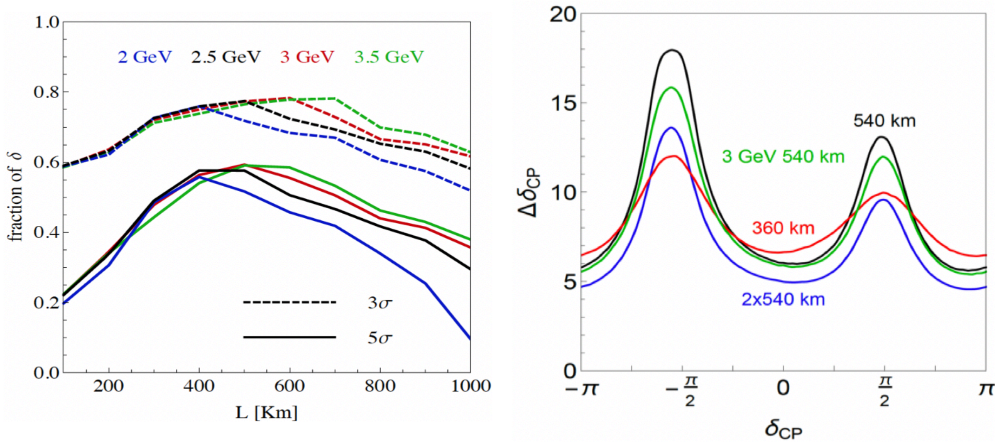

Figure 3: Left panel: the fraction of the angular range of δ_{CP} that can be covered at the 3σ and 5σ levels for different beam energies. Right panel: the precision, $\Delta\delta_{CP}$, with which δ_{CP} can be measured for different baselines. The black and red lines give the precision at 2.5 GeV proton beam energy for the 360 km and 540 km baselines, while the green curve gives the result for a 3 GeV proton beam and 540 km baseline. All results are for five years of neutrino and anti-neutrino beam, respectively, except for the blue line in the right panel which shows the improvement in precision that can be obtained if the measurement time is increased to 20 years.

detector where they will be registered and identified. Using a water Cherenkov detector as part of the near detector suite also has the advantage that cross section differences between the near and far detector material can be neglected for those events that are completely contained in the water volume. This makes it possible to benchmark the reconstruction algorithms in the near and far detector against each other by direct comparisons between simulation results and measurement. This is of interest in order to have a possibility to investigate any potential differences in rates occuring in the ^{12}C of the tracker elements and the ^{16}O in the water volume. Finally, a potential inclusion of a layered water and emulsion detector is also considered as it would provide an additional way to measure the neutrino-water cross section with good accuracy in the energy region of interest.

4. The physics reach

As has been discussed previously [4, 5], and also mentioned above, the placement of the ESSνSB far detector at the second oscillation maximum will increase the sensitivity of the δ_{cp} measurement compared to measurements at the first maximum since the atmospheric term in the oscillation formula dominates over the CP-interference term at the first maximum while they are comparable in magnitude at the second. This improves the precision with which a non-zero δ_{CP} can be established in a measurement. The physics reach of the facility can be determined in several ways. Here we limit ourselves to present preliminary results concerning the discovery potential and precision that ESSνSB will have for a δ_{cp} measurement. The neutrino spectra for this study were produced using a 2.5 GeV proton beam and the target-horn configuration discussed above with a far detector of MEMPHYS type. The analysis was carried out using the GLoBES [14, 15] software and the precision in δ_{cp} was extracted from that analysis. The discovery potential is summarized in Figs. 2 & 3. A 10 year measurement period split either into two periods of 5 years with neutrino and anti-neutrino beam, or with a division in a 2 year and an 8 year period, would reach a 5σ significance level over ca 60% of the full angular range of δ_{CP} (see Fig. 2). This comparison can be carried further by also investigating how the δ_{CP} coverage depends on the proton beam energy and the length of the baseline. The corresponding results are shown in the left panel of Fig. 3. The covered fraction can, at the 5σ level, in an ideal case, reach almost 80% while the maximum coverage moves from a baseline length of slightly more than 400 km, at a proton beam of 2 GeV, to ca 700 km at 3.5 GeV. For the 2.5 GeV proton beam a maximum coverage of ca 70% is predicted for the 5σ significance level. Finally, the precision of the measurement, shown in the right panel of Fig. 3. for different baselines, varies between ca 5° and more than 15° over the full angular range. These results shows that in addition to having excellent discovery potential for leptonic CP-violation, ESSνSB has the potential to provide the first precision measurement of a CP-violation phase over a large range.

5. Conclusion

The ESSνSB project, which currently is in a conceptual design study phase financed by the H2020 program, has as its aim to exploit synergies with the proton driver of the European Spallation Source, and to use experience gained from previous EU-funded design studies for neutrino physics, to propose a concept for a European long-baseline neutrino experiment. The ESS accelerator, providing the most intense proton beam in the world, is planned to come online by 2025. In this paper we have discussed how an upgrade of the facility would provide an unparalleled opportunity for a high-power long-baseline neutrino experiment that would be capable of discovering and measuring a CP-violation phase at the second oscillation maximum, and given preliminary predictions of the discovery potential and measurement precision of such an experiment.

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