PROCEEDINGS OF SCIENCE

# The ESS Based Neutrino Super Beam Experiment (ESS$\nu$SB)

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The European Spallation Source neutrino Super Beam (ESS$\nu$SB) aims to benefit from the high power of the European Spallation Source (ESS) linear accelerator (linac) in Lund-Sweden, to produce the world's most intense second-generation neutrino beam, which will enable measurements to be made at the second neutrino oscillation maximum.

Assuming a ten-year exposure with five years running time in neutrino-mode and five years in antineutrino-mode, CP-invariance violation could be established with a significance of $5\sigma$ over more than 70% of all values of $\delta_{CP}$ and with an error in the measurement of the $\delta_{CP}$ angle of less than 8° for all values of $\delta_{CP}$.

**** Particles and Nuclei International Conference - PANIC2021 ****
**** 5 - 10 September, 2021 ****
**** Online ****

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[†] This project has received funding from the European Union Horizon 2020 research and innovation program under grant agreement No 777419. This work has been in part also funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - Projektnummer 423761110.

[*] Speaker

PoS(PANIC2021)284

## 1. Introduction

In the search for the CP-violation in the leptonic sector, crucial information has been obtained from neutrino experiments [1]. The measurement of the third neutrino mixing angle, $\theta_{13}$, opened the possibility of discovering the Dirac leptonic CP violating angle, $\delta_{CP}$, with intense "super" neutrino beam experiments. Moreover, the T2K experiment has recently reported new results on $\delta_{CP}$, where they disfavored almost half of its possible values at the 99.7% ($3\sigma$) confidence level [2]. In the light of these new findings, an urgent need has arisen to improve the detection sensitivity of the current long-baseline detectors, considering proton driver at MW scale power with MegaTon scale detector, with a key modification to place the far detectors at the second (significantly more sensitive to CP violation), rather than the first, oscillation maximum. Several Super Beam detectors have been proposed, as next-generation long-baseline neutrino experiments, in particular the DUNE experiment in USA [3] and the T2HK in Japan [4]. However, the current plans of these experiments are to place the far detector at the first, rather than, the second oscillation maximum.

## 2. European spallation Source neutrino Super Beam (ESS$\nu$SB) Experiment

The ESS$\nu$SB is a third-generation neutrino long-baseline experiment. It is a European scientific collaboration, gathering scientists from fifteen institutions in eleven European countries [5]. The ESS$\nu$SB aims to produce the world's most intense neutrino beam in order to search and measure, with precision, the CP-violation in the leptonic sector, at significance level in more than 70% of the $\delta_{CP}$ range, using the high power proton beam of the European Spallation Source (ESS) linear accelerator (linac) in Lund-Sweden [6]. Such intense neutrino beam will provide sufficient statistics at a mega-tonne water Cherenkov far detector. The latter will be placed at the second oscillation maximum, where the CP-violating term in the neutrino oscillation probability, proportional to L/E, is significantly larger, by a factor $\sim 3$ at the oscillation peak value, compared to that at the first oscillation maximum. This is of high importance as the accuracy in neutrino-beam measurements is limited by the systematic rather than statistical errors. However, several technological challenges must be precisely studied and simulated before addressing the design of the ESS$\nu$SB experiment. Figure 1 shows the layout of the ESS$\nu$SB facility with all proposed modifications.

### 2.1 ESS$\nu$SB facility

The ESS linac will provide an average proton beam power of 5 MW to the spallation neutron target divided in 14 macro-pulses per second, each with 2.86 ms duration. Interleaved with these pulses there will be another 5 MW of beam power delivered to the accumulator ring and later to the neutrino target. These pulses will also be produced and accelerated at 14 Hz, which means that the linac must be pulsed at 28 Hz. The accumulator has as principal role to compress the long pulses from the linac to single intense beam pulses that are fast extracted and arrive via a beam transport channel to the four targets where the neutrinos are produced [7]. This pulse compression is mandatory for two reasons: a) to overcome the thermal power limitations from the pulsing of the secondary particle focusing device (the magnetic horns) that operates at high current and b) to help reducing the background from atmospheric neutrinos (and other sources) to the far detectors by gating to the beam pulses. Once the proton beam is brought to the neutrino beam direction by the

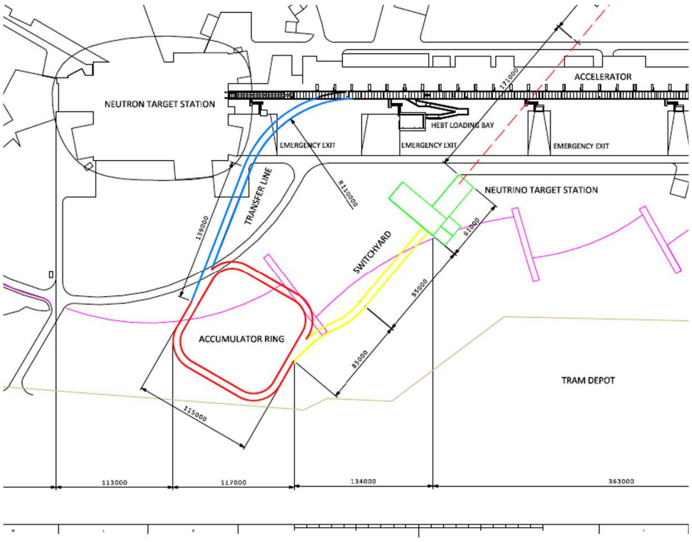

**Figure 1:** ESS$\nu$SB layout.

Ring-to-Switchyard (R2S) beam line, it will be distributed onto four targets by a beam switchyard (BSY), which will also focus the proton beam in a homogeneous shape in the middle of the target. The focusing of the secondary particles produced by the protons impinging on the solid target inside the decay tunnel of the facility is realized by the hadronic collector, which is based on four magnetic horns. The magnetic field inside each horn is produced by a 350 kA current pulse, generated by a Power Supply Unit (PSU), of 100 µs duration, circulating inside the horn body, repeated at 14 Hz. This high current intensity and frequency, as well as the emission of secondary particles, produce a significant amount of power deposition in the horns. The target technology is based on a granular target concept that is able to afford 1.25 MW proton beam power with 2.5 GeV proton kinetic energy. The target geometry consists of a packed bed target of 78 cm long and 3 cm diameter, filled with 3 mm diameter titanium spheres. The canister is drilled with apertures on each side to provide an efficient transverse cooling with helium flow working at 10 bar to extract the 138 kW of deposited power. The 50-meter length of the decay tunnel has been optimised to increase the number of decaying pions, producing muon neutrinos, and keeping the number of decaying muons, producing electron neutrinos, to a limited level. Moreover, a new structure of the beam dump is designed to withstand $\sim$ 850 kW energy deposition from the secondary beam generated by the four targets.

The near detector (ND) will be placed at a baseline of $\sim$ 250 m from the neutrino target, with the aim to monitor the neutrino beam and to measure neutrino interaction cross-sections, especially the electron neutrino cross-sections. The ND complex will be composed of three detectors: 1) a kiloton mass water Cherenkov detector, (WatCh): for event rate measurement, flux normalisation and event reconstruction comparison with the far detector. 2) A magnetized fine-grained tracker (SFGD): for measurements of the poorly known neutrino cross sections in this energy region (60–600 MeV) and 3) an emulsion setup similar to that in the NINJA experiment [8]. The far detector technology has been chosen as a MEMPHYS-like water Cherenkov detector [9] with $\sim$ 538 kt fiducial volume, which location is still under consideration; 1) at the Garpenberg mine, $\sim$ 540 km from ESS, and at 2) Zinkgruvan mine at $\sim$ 360 km from ESS, both locations with $\sim$ 1 km overburden.

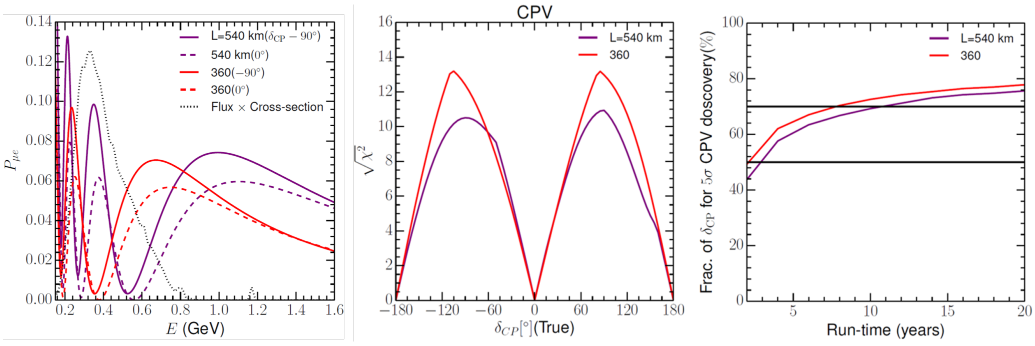

**Figure 2:** (Left) $\nu_e$ appearance probability vs $E_\nu$. (Middle) CP violation discovery sensitivity of ESS$\nu$SB as a function of true $\delta_{CP}$. (Right) the fraction of true values of $\delta_{CP}$ for which CP violation can be discovered at $5\sigma$ as a function of run-time.

## 2.2 ESS$\nu$SB physics potential

Figure 2 (left) shows the $\nu_\mu \rightarrow \nu_e$ appearance probability (and flux × cross-section) as a function of the neutrino energy [10]. It shows that the variation of the oscillation probability with respect to $\delta_{CP}$ is much higher around the second oscillation maximum, at $E_\nu \sim 350\,\text{MeV}$, as compared to the first oscillation maximum. In the middle panel of the figure, we present the CP violation discovery sensitivity of ESS$\nu$SB, for both baseline options, as a function of $\delta_{CP}$ (true). It shows that for maximal values of $\delta_{CP}$ around ±90°, the sensitivity is ca $10\sigma$ for the baseline option of 540 km and ca $13\sigma$ for the baseline option of $\sim 360$ km. In the right panel of the figure, we have plotted the fraction of $\delta_{CP}$ values for which CP violation can be discovered at more than $5\sigma$ as function of run-time. A run-time of t implies, running t/2 years in neutrino mode and running t/2 years in antineutrino mode. The black horizontal lines correspond to the benchmark of 50% and 70% CP coverage for which CP violation can be discovered at more than $5\sigma$, respectively.

## References

[1] F. P. An *et al.*, Phys. Rev. Lett. 108 (17), (2012) 171803.

[2] K. Abe *et al.*, Nature 580, (2020) 339.

[3] J. Strait *et al.* [DUNE], arXiv:1601.05823 [physics.ins-det].

[4] K. Abe *et al.* [Hyper-Kamiokande], arXiv:1805.04163 [physics.ins-det].

[5] https://essnusb.eu/.

[6] R. Garoby *et al.*, Phys. Scr. 93 (2018) 014001.

[7] E. Baussan *et al.* Phys. Rev. ST Accel. Beams, 17 (2014) 031001.

[8] A. Hiramoto *et al.*, Phys. Rev. D 102, (2020) 072006.

[9] L. Agostino *et al.*, [MEMPHYS Collaboration], JCAP 1301 (2013) 024.

[10] A. Alekou *et al.* [ESSnuSB], arXiv:2107.07585 [hep-ex]