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Status of ESSnuSB and summary of workshop

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ESSnuSB is a design study for a future experiment that will measure CP violation in the lepton sector by observing neutrino oscillations at the second maximum. The advantages of measurement at the second maximum are smaller sensitivity on the systematic error and oscillation matter effects. A very intense neutrino beam required for such a measurement will be produced using the uniquely powerful 5 MW European Spalation Source (ESS) linear accelerator. Neutrino oscillation signal will be observed in the large 538 kt fiducial mass far detector. The near detector complex will be used to measure the initial neutrino flux and neutrino interaction cross-sections. A description given of the the advantages of measurement at the second maximum, required upgrades to the ESS site in order to produce neutrino beam, and near and far detector sites. Physics reach using the experimental setup is then presented. There is a short report at the end from the ESSnuSB workshop held at this conference.

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1. Introduction

ESSnuSB is a design study for a future experiment that will measure CP violation in the lepton sector by observing neutrino oscillations at the second maximum. One of the effects CP violation has on neutrino oscillations is a difference between vacuum oscillation probabilities of neutrinos and anti-neutrinos. ESSnuSB aims to measure the difference between probabilities for $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ appearance channels.

The second oscillation maximum offers several advantages for CP violation measurements compared to the first one. CP violation effect is almost three times larger at the 2$^{\text{nd}}$ maximum compared to the 1$^{\text{st}}$ one. More precisely [1, 2]:

$$\frac{\left(P_{\nu_\mu\to\nu_e} - P_{\overline{\nu}_\mu\to\overline{\nu}_e}\right) \text{ @ } 2^{\text{nd}} \text{ osc. max.}}{\left(P_{\nu_\mu\to\nu_e} - P_{\overline{\nu}_\mu\to\overline{\nu}_e}\right) \text{ @ } 1^{\text{st}} \text{ osc. max.}} \sim 2.7\,, \tag{1}$$

where $P_{\overset{(-)}{\nu}_\alpha\to\overset{(-)}{\nu}_\beta}$ are the (anti)neutrino oscillation probabilities for a corresponding channel. In vacuum, this ratio does not depend on PMNS mixing matrix elements. Matter effects, which distort the oscillation pattern, are much less prominent in the 2$^{\text{nd}}$ maximum than in the 1$^{\text{st}}$ one. Matter effects can mimic the CP violation signal in the 1$^{\text{st}}$ maximum if they are not properly accounted for in the analysis. These points are illustrated in Fig. 1.

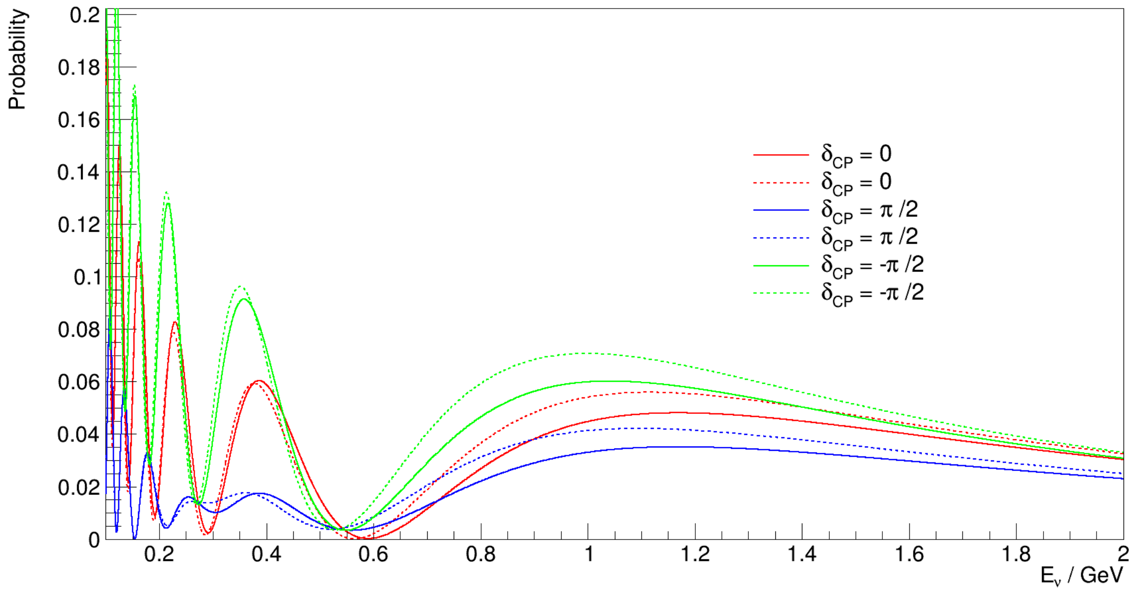


Figure 1: Oscillation probability for $\nu_\mu \to \nu_e$ channel as a function of energy at a distance of 540 km. Solid lines show oscillation probabilities in vacuum, dashed lines show oscillation probabilities with matter effects included. Different colours correspond to different values of δ_{CP} parameter. Taken from [3].

The disadvantage of measuring at the 2$^{\text{nd}}$ maximum is that there will inevitably be less neutrino interactions as compared to the 1$^{\text{st}}$ maximum, resulting in less significant statistical sample of signal events. To move from the 1$^{\text{st}}$ to the 2$^{\text{nd}}$ maximum, one must either position the far detector three times farther away resulting in 9x less interactions, or lower neutrino energy by a factor 3 reducing the event sample by at least three times.

To take full advantage of CP violation measurement at the second maximum, one must have a large enough statistical sample [4]. A sufficiently intense neutrino beam with neutrino energies above the charged-current (CC) interaction threshold in conjuction with a large fiducial mass of far detectors is required to achieve this.

The high intensity neutrino beam will be produced using the European Spallation Source (ESS) linear accelerator [5] (under construction) as a proton driver. Once fully operational, the ESS linac will accelerate protons to 2.0 GeV kinetic energy with an average beam power of 5 MW, which will make it the most powerful accelerator in the world. Since ESS is designed to produce high intensity spallation neutron flux, a number of upgrades will be necessary to concurrently produce a neutrino beam.

A suite of the near detectors will be placed at the ESS site to measure the intensity and flavour composition of the initial neutrino flux, and to measure the relevant neutrino interaction cross-sections. Far detectors will be composed of two large water Cherenkov (WC) tanks with a total fiducial mass of 538 kt and will be used to measure the neutrino oscillation signal.

2. ESS accelerator site upgrades and target station

A number of upgrades to the ESS accelerator are necessary to produce a neutrino beam concurrently with a neutron flux, which are schematically shown in Fig. 2.

The frequency of the ESS linac must be increased from 14 Hz to 28 Hz to obtain additional acceleration cycles which will be used for neutrino production without affecting the neutron program. Proton kinetic energy will be increased to 2.5 GeV, which is more favourable both for neutrino and neutron flux production. During neutrino cycles, H^- ions will be accelerated instead of protons in order to ease the filling of the accumulator ring, which requires an addition of an H^- source to the linac. More details may be found in the talk [6].

The accumulator ring will be built to shorten the ESS pulse from 2.86 ms to about 1 μs. This is necessary for sufficient rejection of external neutrino background in the far detectors by considering only interactions that happen in the short beam time window. The atmospheric neutrino background for 2.86 ms beam pulses would completely drown the CP violation signal, while it can be completely neglected for the short 1 μs pulses. In addition, it would be extremely challenging to design a magnetic horn able to withstand a 2.86 ms 350 kA current pulse. A more detailed description can be found in the talk [7].

The neutrino production target station will be composed of four identical targets enveloped by the magnetic focusing devices (horns). The multi-target design is driven by the very high intensity of the proton beam as it would be difficult to design a cooling system for a single target/horn. The target will be composed of hard packed TiO_2 pebbles. The horns will be used for charge selection and collimation of secondary particles exiting the target (mostly pions at ESSnuSB proton energies) which are then lead into a decay tunnel 50 m long and 4.0 m in diameter to decay in-flight. By selecting the charge of the collimated pions, one can select the primary composition of the beam between neutrinos and anti-neutrinos. The target station is described in the dedicated talk [8].

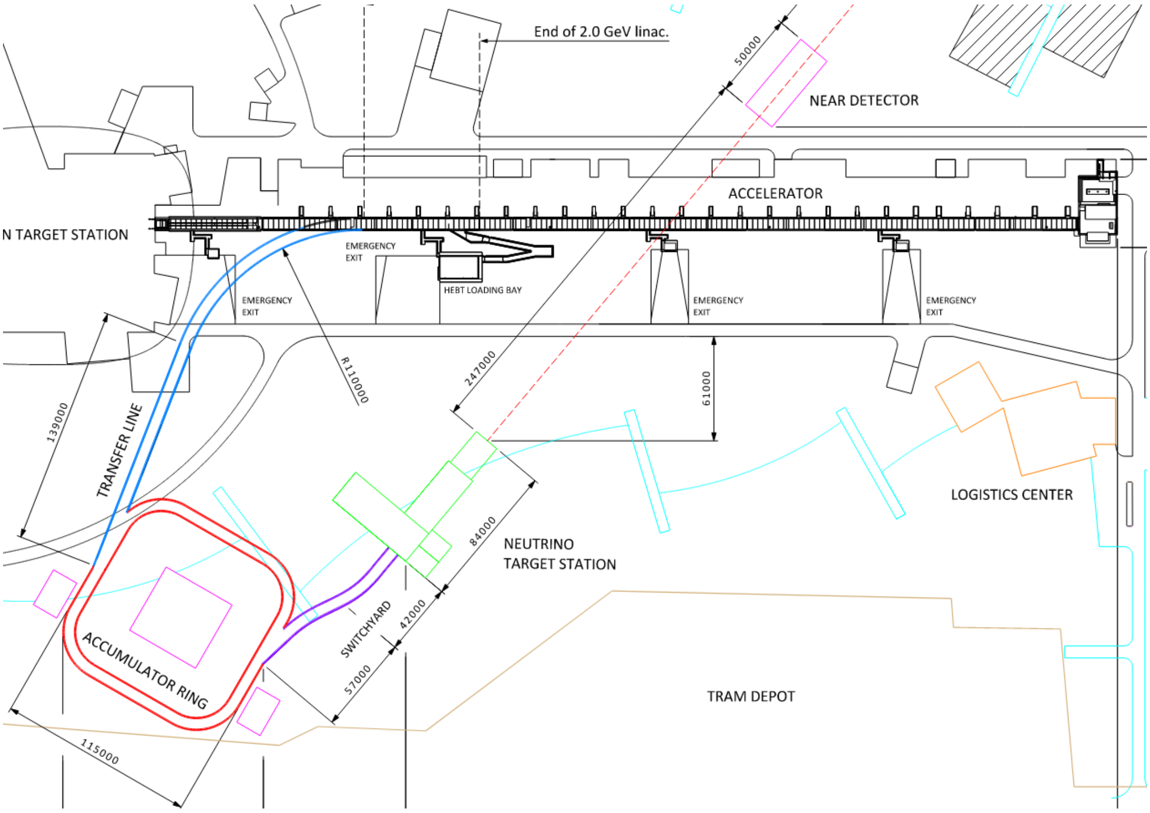


Figure 2: Schematic layout of the required ESS upgrades. The ESS linear accelerator is shown in black, the transfer line from the linac to the accumulator ring is shown in blue, the accumulator ring is shown in red, the switchyard is shown in purple, the target station is shown in green, and the near detector site is shown in magenta.

3. Near detectors

A near detector (ND) hall will be built at the ESS site (see Fig. 2) and will contain a suite of three detectors (in upstream to downstream order): a NINJA-like [9] water-emulsion detector, a 1 t SFGD-like [10] scintillator detector, and a 0.5 kt fiducial mass water Cherenkov detector [11]. The technical drawing of the ND hall is shown in Fig. 3.

The main purpose of near detectors is to measure initial neutrino flux intensity and flavour composition, and to measure neutrino-water interaction cross-section. The cross-section measurement is of particular importance since there is currently very little data on it in the ESSnuSB neutrino energy region of approximately 150 MeV to 450 MeV (see Fig. 51.1 in [12]).

The water Cherenkov detector will record the bulk of neutrino interactions at the ND site due to its large mass. It will use the same technology and target material as the far detector, which will help reduce the systematic errors of the experiment. The trade-off is that its tracking and event reconstruction performance is lower than that of smaller and more fine-grained detectors.

The scintillator detector will have a smaller target mass, but will feature better tracking and event reconstruction abilities. Since it will be magnetized, it will have the ability to determine particle charge and perform momentum spectroscopy. Charged particles originating in this detector

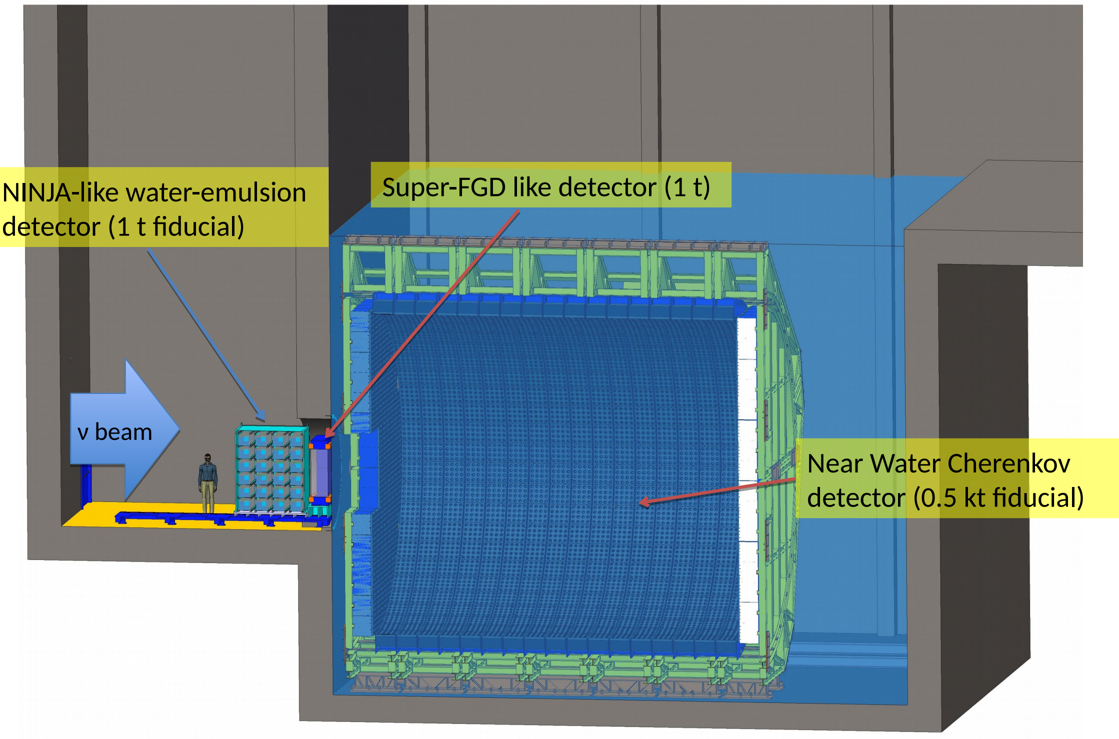


Figure 3: ESSnuSB near detector hall.

and passing downstream into the water Cherenkov detector will provide an opportunity for additional calibration of the two detectors.

The Emulsion detector will have the smallest target mass, but will feature the best tracking and event reconstruction performance. It will be used to study detailed topology of neutrino interaction events and measure various double differential cross-sections.

4. Far detectors

The far detector site of the ESSnuSB experiment will contain two large water Cherenkov tanks containing a 269 kt fiducial mass each, making a total of 538 kt neutrino target mass. The choice of two tanks instead of a single larger one is driven by extreme technical difficulties to excavate a single cavern large enough to hold the entire desired volume of water.

The two candidate sites for the far detector are two active mines: the Zingruvan mine (360 km from ESS) and the Garpenberg mine (540 km from ESS); both sites are located in Sweden. The detectors would be placed about 1000 m underground for each option. The 540 km option covers mostly the second oscillation maximum at the ESSnuSB beam energies, while the 360 km option covers both 1$^{\text{st}}$ and 2$^{\text{nd}}$ maximum and profits from the increased number of expected neutrino interactions.

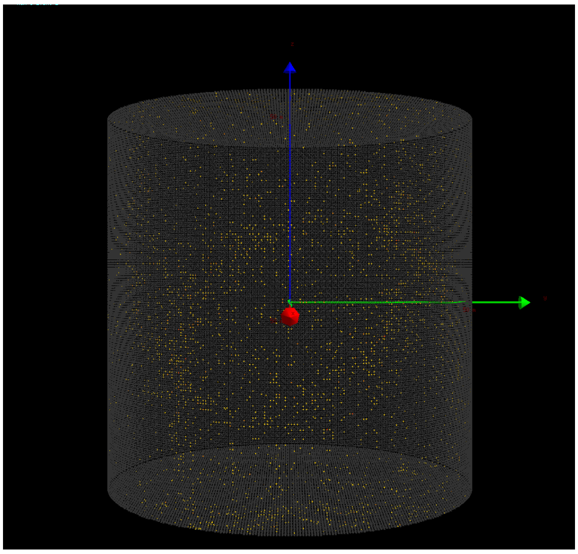


Figure 4: Simulation of a neutrino interaction event in the far detector tank.

The detector performance is described in more detail in the poster [13].

5. Physics reach

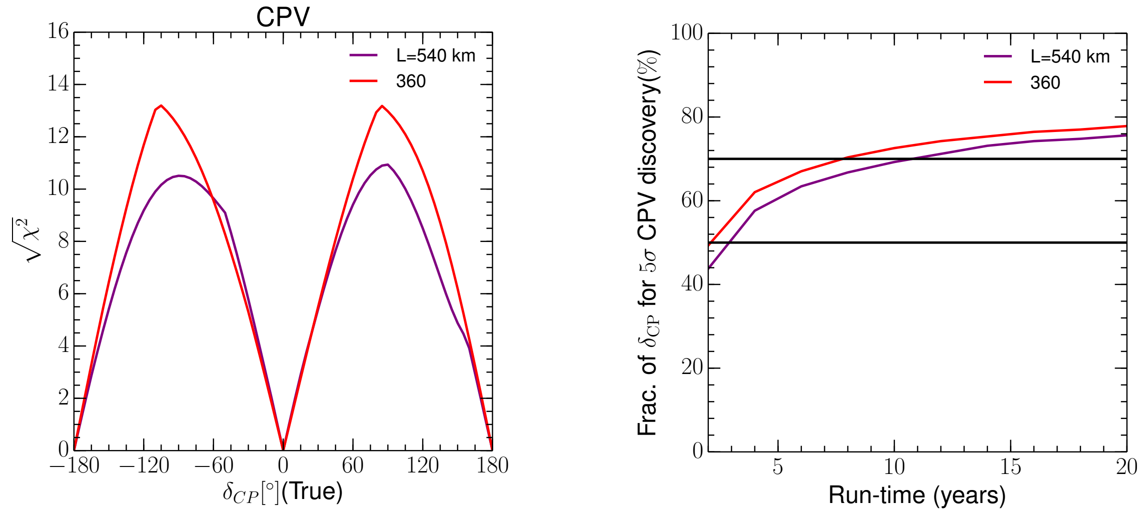
A number of optimizations to maximize the physics reach have been performed since the first iterations [14, 15] of the ESSnuSB project. Most notably, the target station has been optimized using a genetic algorithm to produce a more appropriate flux, and the response of the far detectors has been tuned to the ESSnuSB neutrino energies, significantly increasing the signal selection efficiency while retaining a very high signal sample purity.

The expected physics reach of the ESSnuSB experimental setup after these optimizations has been calculated using the following assumptions: both FD candidate sites are considered separately, 540 km (Garpenberg mine) and 360 km (Zinkgruvan mine); the experiment will run for 5 years in neutrino mode and 5 years in anti-neutrino mode; systematic uncertainty is applied to normalization of the expected interacting neutrino spectra with uncertainties of 5% on signal and 10% on background.

The CP violation discovery potential of the ESSnuSB experiment is shown in Fig. 5. The sensitivity to CP violation is expected to be about 13 σ at 540 km and 11 σ at 360 km for true values of $\delta_{CP} = \pm\pi/2$. The experiment expects to cover 75% of δ_{CP} range with more than 5 σ sensitivity in 11 years of data taking at 540 km and in 6 years at 360 km.

The true strength of the experiment lies in its ability to very precisely measure the value of the δ_{CP} parameter as shown in Fig. 6. For the distance of 360 km, the entire range of the parameter is expected to be measured with a precision of less than 8°. In addition, the experiment will be able to determine (or confirm) the neutrino mass hierarchy with a significance of more than 5 σ for all values of δ_{CP} as shown in Fig. 7.

A detailed description of this analysis can be found in [16]. Current developments on the improvement of the ESSnuSB physics potential analysis were given in a talk [17].



(a) CP discovery potential as a function of true δ_{CP}.

(b) Fraction of the true δ_{CP} range with discovery potential larger than $5\,\sigma$ as a function of total run time. The assumption is that the experiment will run half of that time in neutrino mode and the other half in anti-neutrino mode.

Figure 5: CP violation discovery potential of the ESSnuSB experiment and fraction of δ_{CP} range covered at more than $5\,\sigma$. Figures are taken from [16].

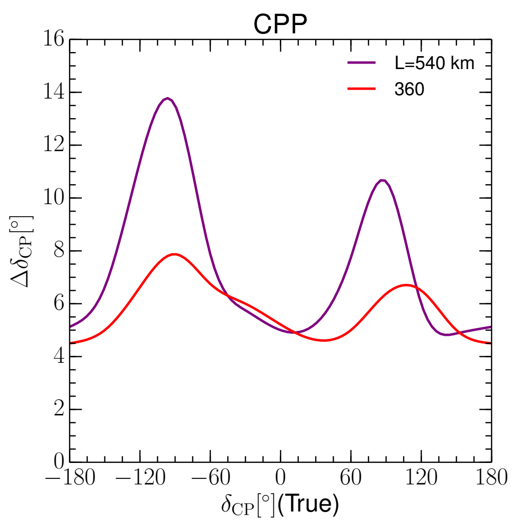


Figure 6: Expected measurement precision of the CP violating parameter δ_{CP} as a function of true δ_{CP}.

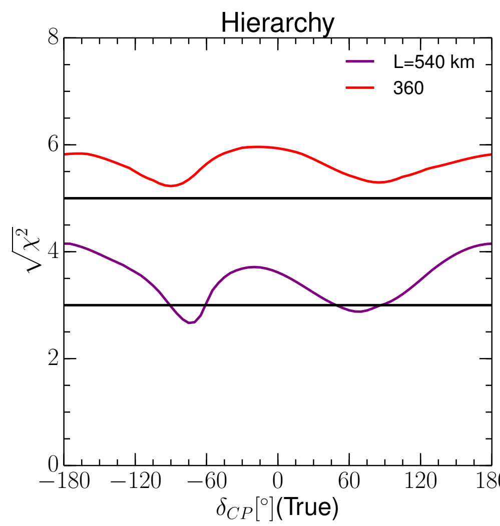


Figure 7: Expected sensitivity to determination of mass hierarchy vs. true δ_{CP}.

6. ESSnuSB workshop

A workshop on current developments and the future of the ESSnuSB project has been organized during this conference. There was an introduction on the future design study program in the context of the joint High Intensity Frontier Initiative (HIFI) [18], followed by talks on civil engineering and safety requirements at the ESS site [19] and at the far detector site [20]. An environmental preservation and societal commitment in context of ESSnuSB was presented in the talk [21]. There were two talks on physics possibilities using proposed ESS upgrades in addition to the main ESSnuSB program: observing decay-at-rest neutrinos and coherent neutrino scattering [22], and the talk on the possibility of an addition of a low energy nuSTORM race-track ring [23]. At the end of the workshop there were two talks regarding the steps required towards a muon colider complex at the ESS: one about upgrades which would be necessary to start testing the technology required for the muon collider [24] and the other on the design and physics reach of the muon collider itself [25].

7. Conclusions

ESSnuSB will investigate CP violation in the lepton sector by observing $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations at the 2$^{\text{nd}}$ neutrino oscillation maximum. The measurement at the 2$^{\text{nd}}$ maximum will be made possible by using a powerful 5 MW ESS linear accelerator as a proton driver for the neutrino beam production and a large 538 kt fiducial mass of the far detector as neutrino target. The CP violation signal in the second maximum is about three times larger than at the first one, making the experiment less sensitive to systematic errors. Additionally, matter effects on the oscillation probability at the 2$^{\text{nd}}$ maximum are very small compared to the signal, while at the 1$^{\text{st}}$ one they need to be carefully taken into account. This will make ESSnuSB very sensitive to CP violation discovery and insensitive to systematic errors. The experiment will also achieve an unprecedented precision for the measurement of the CP violating parameter δ_{CP}, starting a new era of precision of CP violation measurement in the leptonic sector.

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References

[1] H. Nunokawa, S.J. Parke and J.W. Valle, *CP Violation and Neutrino Oscillations*, *Prog. Part. Nucl. Phys.* **60** (2008) 338 [0710.0554].

[2] S. Parke, *Neutrinos: Theory and Phenomenology*, *Phys. Scripta T* **158** (2013) 014013 [1310.5992].

[3] L. Halić, *Expected number of neutrino interactions in the far detectors of the ESSnuSB project*, Master's thesis, University of Rijeka, Rijeka, 2021, [https://urn.nsk.hr/urn:nbn:hr:194:594824].

[4] P. Coloma and E. Fernandez-Martinez, *Optimization of neutrino oscillation facilities for large θ_{13}*, *JHEP* **04** (2012) 089 [1110.4583].

[5] R. Garoby, A. Vergara, H. Danared, I. Alonso, E. Bargallo, B. Cheymol et al., *The European Spallation Source Design*, *Physica Scripta* **93** (2017) 014001.

[6] B. Folsom, *ESSνSB Linac and Transfer Line: Lattice Design and Error Studies*, *Talk at NUFACT 2021, Contribution 43* .

[7] M. Olvegard, *An accumulator ring for the 5 MW beam for the ESSnuSB*, *Talk at NUFACT 2021, Contribution 247* .

[8] L. Lacny, *Status of the ESSνSB Target Station*, *Talk at NUFACT 2021, Contribution 220* .

[9] A. Hiramoto et al., *First measurement of $\overline{\nu}_\mu$ and ν_μ charged-current inclusive interactions on water using a nuclear emulsion detector*, *Phys. Rev. D* **102** (2020) 072006 [2008.03895].

[10] A. Blondel et al., *A fully active fine grained detector with three readout views*, *JINST* **13** (2018) P02006 [1707.01785].

[11] ESSnuSB collaboration, *The ESS neutrino super-beam near detector*, in *European Physical Society Conference on High Energy Physics 2021*, 11, 2021 [2111.05550].

[12] P. Zyla et al., *Review of Particle Physics*, *PTEP* **2020** (2020) 083C01.

[13] O. Zormpa, *ESSnuSB detector performance*, *Poster at NUFACT 2021, Contribution 202* .

[14] E. Baussan et al., *A very intense neutrino super beam experiment for leptonic CP violation discovery based on the European spallation source linac*, *Nucl. Phys. B* **885** (2014) 127 [1309.7022].

[15] E. Wildner et al., *The Opportunity Offered by the ESSnuSB Project to Exploit the Larger Leptonic CP Violation Signal at the Second Oscillation Maximum and the Requirements of This Project on the ESS Accelerator Complex*, *Adv. High Energy Phys.* **2016** (2016) 8640493 [1510.00493].

[16] A. Alekou et al., *Updated physics performance of the ESSnuSB experiment*, *Eur. Phys. J. C* **81** (2021) 1130 [2107.07585].

[17] S. Rosauro Alcaraz, *Physics potential of the ESSnuSB* , *Talk at NUFACT 2021, Contribution 13* .

[18] M. Dracos, *Introduction of the ESSnuSB/HIFI Design Study program 2022-2025*, *Talk at NUFACT 2021, Contribution 319* .

[19] B. Kildetoft, *Civil engineering and safety requirements for ESSnuSB at the ESS site*, *Talk at NUFACT 2021, Contribution 320* .

[20] D. Saiang, *Civil engineering and safety requirements for ESSnuSB at the Far Detector site*, *Talk at NUFACT 2021, Contribution 321* .

[21] C. Carlile, *Environment preservation and societal commitment*, *Talk at NUFACT 2021, Contribution 323* .

[22] J. Conrad, *Prospects for decay-at-rest and coherent neutrino scattering at ESS*, *Talk at NUFACT 2021, Contribution 322* .

[23] M. Olvegard, *Design of a Low Energy (0.4 GeV) nuSTORM race-track ring*, *Talk at NUFACT 2021, Contribution 324* .

[24] T. Ekelof, *Upgrades of the ESSnuSB design required to enable tests of the Muon Collider Proton Complex*, *Talk at NUFACT 2021, Contribution 325* .

[25] C. Rubbia, *A possible ultimate goal: A Muon Collider Higgs Factor based at ESS*, *Talk at NUFACT 2021, Contribution 326* .