The European Spallation Source neutrino Super Beam ESSνSB

Abstract

The European Spallation Source linear proton accelerator will have a uniquely high beam power of 5 MW to be used for spallation neutron production. The beam power can be raised to 10 MW by increasing the accelerator duty cycle from 4% to 8% and the additional 5 MW used to generate a uniquely intense neutrino Super Beam ESSvSB for measurement of leptonic CP violation. ESSvSB is complementary to other proposed Super Beam experiments by the fact that the resulting high neutrino-beam intensity makes it possible to locate the large water Cherenkov neutrino detector that will be used, at the second neutrino oscillation maximum, making the performance of ESSvSB for leptonic CP violation precision measurements highly competitive.

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1. Context

1.1 *The new possibility to discover and measure with high precision CP violation in the leptonic sector.*

The discovery in 1998 of neutrino flavour oscillations opened up the possibility that there be CP violation in the leptonic sector and that this CP violation could be discovered and measured through precision measurements of the oscillations. The oscillation that is potentially the most sensitive to CP violation is that between ν_μ and ν_e. The oscillation probability is approximately equal to the sum of three terms, the atmospheric, the solar and the interference term, see Figure 1[1]. The observation of a CP violating signal requires the interference term to be of measurable magnitude.

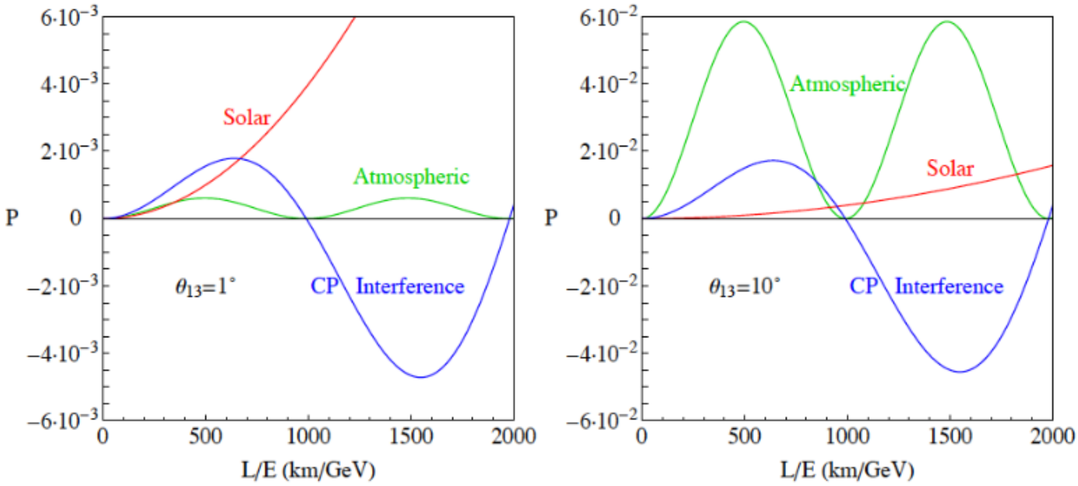

Figure 1: Solar, atmospheric and interference terms of the $\nu_\mu \rightarrow \nu_e$ in vacuum as function of L/E for a small (left) and a large (right) ϑ_{13} value.

The atmospheric term increases with the angle θ_{13} while the solar term increases with L/E where L is the distance between the creation point of neutrinos and the detector and E the neutrino energy. In order to maximize the interference term, and thus the CP violation signal, these two terms should be of similar magnitude. Before 2012 the value of θ_{13} had not been measured but it was thought to be very small, implying that to have the two terms of similar magnitude, the L/E ratio should be approximately 500 km/GeV, corresponding to the position of the first oscillation maximum, as illustrated in the left plot of Figure 1.

In 2012 the reactor experiments Daya Bay, RENO and Double Chooz published results of measurements of the mixing angle θ_{13} of around 9°. This value actually saturates the upper bound set by the already measured values of the other two angles and the unitarity of the mixing matrix and has thus turned out to be as large as we could have hoped for. Its relatively large value opened up the possibility to measure the CP violating parameter δ_{CP} (CP is violated if the value of δ_{CP} is neither 0 nor π). Before 2012 the feasibility of measuring δ_{CP} was uncertain, but the measured large value of θ_{13} indicated that it may well be within reach. Moreover, to compensate for the unexpectedly large value of θ_{13}, the value of L/E needs to be increased by approximately a factor 3, which is realized by relocating the detector from the first to the second neutrino oscillation maximum, at which the atmospheric and solar terms are of the similar order as illustrated in the right plot of Figure 1.

This type of optimization under the new paradigm of a large θ_{13} value is crucial in order to obtain the interference term as high as possible, thereby avoiding to be severely limited by the systematic uncertainties of the other two terms. The ESSνSB setup already incorporates this novel feature: the 540 km baseline and ca 0.35 MeV mean energy of the neutrino energy of ESSνSB implies an L/E value of 1500 km/GeV centred at the second oscillation maximum. Moreover, the asymmetry between the neutrino and anti-neutrino appearance probability at the second oscillation

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[1] Optimization of neutrino oscillation facilities for large θ_{13}, P. Coloma, E. Fernandez-Martinez, JHEP 1204 (2012) 089, DOI: 10.1007/JHEP04(2012)089, e-Print: arXiv:1110.4583 [hep-ph]

maximum is of the order of $0.75\sin\delta_{CP}$[2] while on the first oscillation maximum is only $0.30\sin\delta_{CP}$. For these reasons and considering the limitations imposed by systematic errors, the ESSνSB setup provides, as confirmed by Monte Carlo simulations, a better sensitivity to CP violation than similar setups which were designed before 2012 to have their neutrino detector placed at the first oscillation maximum and which have not been able to re-optimize their experimental design subsequent to the discovery of the large value of θ_{13}.

While current neutrino oscillation facilities such as T2K and NOνA, which measure at the first neutrino oscillation maximum, may develop some sensitivity to δ_{CP}, which for T2K currently is at the 2 to 3 standard deviations level, new experimental facilities with more powerful accelerators and larger fiducial-mass neutrino-detectors will be necessary for a discovery at the 5 standard deviations level. As to the future experiments Hyper-K and DUNE, proposed already before 2012, they were designed under the assumption of a very small value of θ_{13}, for which case the relative CP violation signal at the fist oscillation maximum would be significantly larger than at the second. For the now known larger value of θ_{13}, the situation is thus reversed with a relative CP violation signal that is about 3 times larger at the second maximum as compared to that at the first maximum (see above). This now implies, for equal performance at the first and the second oscillation maximum, the requirement of a three times smaller systematic errors when measuring at the first maximum as compared to the second. It also implies that, in order to keep the statistical errors on a level comparable to the systematic errors, a very intense neutrino beam is needed for the measurement at the three times more distant second oscillation maximum. With ESSνSB this requirement is satisfied by the use of what is to become the world's most powerful proton accelerator, the European Spallation Source linear accelerator (linac)[3].

1.2 The performance for CP violation discovery of the three proposed future long baseline experiments

In Figure 2 is presented the physics performance of the three different proposed long baseline neutrino experiments **assuming the same level of systematic errors of about 3% for all three in order to make a comparison on an equal footing**. The left plot shows the resolution in the measurement of δ_{CP} versus the value of δ_{CP}, the middle plot shows the discovery significance for CP violation versus δ_{CP}, and the right plot the significance as function of the covered fraction of δ_{CP}. In the figure caption more details about the plots are given. These plots clearly demonstrate that ESSνSB has a higher resolution in the measurement of the CP violating angle δ_{CP} and a large reach for CP violation discovery than the other two experiments.

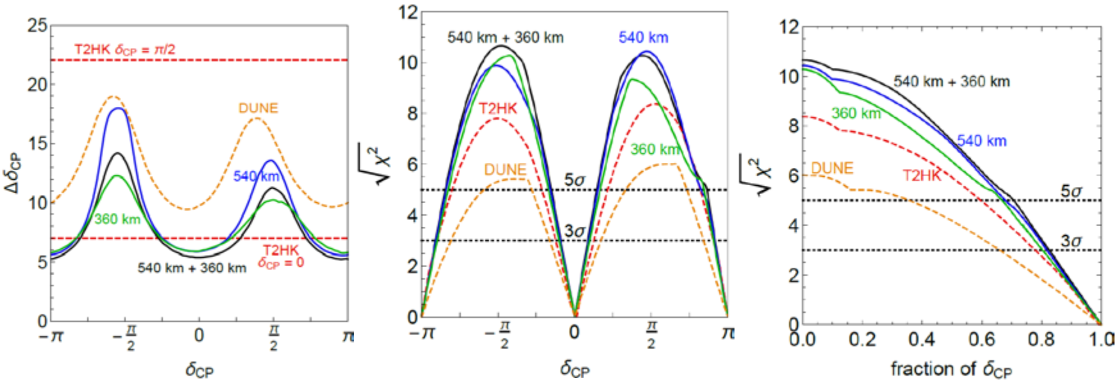

Figure 2: Resolution in the CP violating angle δ_{CP} (left) and the CP violation discovery reach in terms of standard deviations (middle) versus δ_{CP}, and the discovery reach versus the fraction of the δ_{CP} range covered (right), for the three different experiments Hyper-K, DUNE and ESSνSB. For the ESSνSB three cases are shown, one 500 kt detector in the Garpenberg mine (540 km baseline, blue curves), one 500 kt detector in the Zinkgruvan mine (360 km baseline, green curves) and two 250 kt detectors, one in the Garpenberg mine and one in the Zinkgruvan mine (black curves). The Hyper-K curve in the middle and right plots and the two resolution values in the left plot for $\delta_{CP} = 0$ and $\delta_{CP} = \pi/2$, indicated by the two dotted horizontal lines, are those presented by Hyper-K at the Neutrino 2018 conference. The

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[2] Neutrinos: Theory and Phenomenology, S. Parke, Phys.Scripta T158 (2013) 014013, FERMILAB-CONF-13-453-T, DOI: 10.1088/0031-8949/2013/T158/014013

[3] The European Spallation Source, http://europeanspallationsource.se/, *ESS Technical Design Report*, Release 1.0, Nov. 2012.

DUNE curves have been derived using the public GLoBES file released by the DUNE collaboration with its Conceptual Design Report in 2016. Performance predictions for DUNE, assuming 7 years of data taking, were shown by the DUNE collaboration at the Neutrino 2018 conference. For the comparison, in this plot the same simulations were repeated, assuming 10 years of data taking to be in line with the assumptions made for the Hyper-K simulations. The ESSvSB curves have been derived setting the systematic errors to 3% to be in line with the systematic error levels set by DUNE and Hyper-K. The $\sin^2 2\vartheta_{13}$ *and* ϑ_{23} *values for DUNE and ESSvSS have been set to the same values as those used by Hyper-K, again to compare the three experiments on the same footing.*

The conclusion that ESSvSB has, by making the measurement at the second oscillation maximum, a superior δ_{CP} resolution is not new. Figure 3, which was published as a conclusion of the Neutrino Working Group[4] during the US 2013 *Snowmass* process to define the US particle physics roadmap, presents the δ_{CP} accuracy that can be reached by the proposed main future facilities. As seen in Figure 3, ESSvSB, at that time far from being optimised, is significantly more performant for CP violation precision measurement than the other two proposed facilities, LBNE (a predecessor to DUNE) and T2HK. Of course, the Low Energy Neutrino Factory (IDS-NF)[5] attains an even higher performance, but at a much higher investment cost and with severe technological problems still unsolved. The Neutrino Factory facility can be considered as a possible further, second stage, of the ESSvSB project when the full statistics measurements have been made, in case CP violation is only hinted at by then or to measure δ_{CP} with higher precision. High precision measurements of the PMNS mixing matrix elements will allow a precision test of the unitarity of the PMNS matrix. This is a crucial point as a deviation from unitarity would be an important indicator of new physics.

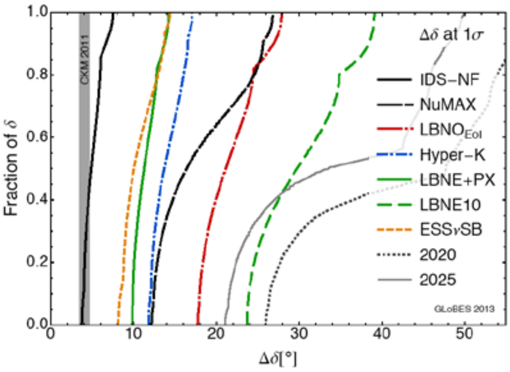

Figure 3: Expected precision of a measurement of δ_{CP} *at present and future long-baseline oscillation experiments*[4]*. Results are shown as a function of the fraction of possible values of* δ_{CP} *for which a given precision (defined as half of the confidence interval at 1 σ, for 1 d.o.f.) is expected.*

For the determination of the mass hierarchy, a 3 σ significance is reached by ESSvSB for nearly all δ_{CP} values. In the proposed optimization studies, the ESSvSB consortium will endeavour to bring this performance to the level of more than 5 σ for all δ_{CP} values by including in these studies the results of the detection of atmospheric neutrinos, which will also be copiously recorded by the ESSvSB MEMPHYS-type detector[6] (this possibility was studied by the LAGUNA collaboration). However, it is very likely that this measurement will be done during the coming 10 years by other experiments like, e.g., JUNO and PINGU/ORCA[7], before the next generation of long baseline neutrino experiments including ESSvSB, will start taking data.

1.3 The ongoing construction of the ESS linac which is to become the world's most powerful proton accelerator

The ESS linac will have an average beam power of 5 MW, which is nearly an order of magnitude higher than any other

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[4] *Working Group Report: Neutrinos, Intensity Frontier Neutrino Working Group Collaboration* (A. de Gouvea et al.). Oct 16, 2013. FERMILAB-CONF-13-479-E, Conference: C13-07-29.2, e-Print: arXiv:1310.4340 [hep-ex].

[5] *Understanding the performance of the low energy neutrino factory*, P. Ballett and S. Pascoli, Phys. Rev. D 86, 053002 (2012).

[6] "MEMPHYS: A Large scale water Cerenkov detector at Frejus", hep-ex/0607026.

[7] *Quantifying the sensitivity of oscillation experiments to the neutrino mass ordering*, M. Blennow, P. Coloma, P. Huber, T. Schwetz, Nov 7, 2013, JHEP 1403 (2014) 028, e-Print: arXiv:1311.1822 [hep-ph].

currently operating proton accelerator in the world. It will deliver a beam of 2 GeV protons to a Tungsten target to produce neutron beams from spallation. ESS is currently well into its construction phase and will deliver first beams in 2021 and be at full specification in 2025. It will be a major European user facility where researchers from universities, national laboratories and industry from all the world will investigate scientific questions relating to material science, molecular biology and other sciences and a broad spectrum of applications.

2. Objectives

2.1 The precision measurement of the CP violating angle δ_{CP}

The implications of the discovery and precise measurement of δ_{CP} are far reaching, leading to the inference that neutrino interactions may in fact be responsible for that a small residual fraction of matter survived the massive annihilation of the matter and antimatter created in the Big Bang, a residual that is what presently makes up the matter of the Universe. The neutrino may also have played a crucial role in the birth and evolution of the Universe itself, in view of its enormous abundance. An understanding of the contribution of neutrinos in these areas requires precise measurements of the parameters governing neutrino oscillations, in particular δ_{CP}.

A measurement of δ_{CP} could also imply the discovery of a completely new source of CP violation. The quark mixing matrix provides a consistent description of the quark CP violation amount observed so far, which can be encoded in the reduced Jarlskog invariant $J = (3.0 \pm 0.2)\cdot 10^{-5}$. This value has been shown to be far too small to account for the observed Baryon Asymmetry of the Universe (BAU). The recent measurement of θ_{13} indicates that the corresponding quantity in the neutrino sector $J=0.3\cdot\sin\delta_{CP}$ is potentially four orders of magnitude larger. A measurement of δ_{CP} could thus, as already discussed, provide very illuminating information on the origin of the BAU.

2.2 The measurement of supernova neutrinos

The ESSνSB MEMPHYS type detector can also be used, simultaneously with neutrino beam operation, for astroparticle physics. In 1987, 12 neutrinos emitted from a supernova explosion in the Large Magellan Cloud near our galaxy were detected by the Kamiokande detector. Such detection of the neutrinos emitted in supernova explosions help to understand the supernova explosion mechanism. With its 500 kton large fiducial mass, the ESSνSB detector will record about $5x10^4$ neutrinos from a supernova explosion at 10 kiloparsec distance in our galaxy which would provide very detailed and highly interesting information on the mechanism of the explosion.

There is a diffuse flux of neutrinos emitted from all the supernova explosions that have occurred in the universe. The measurement of this flux is important for the understanding of stellar birth and death, the production of chemical elements, neutron stars and black holes. Their diffuse neutrino energy spectrum is below 20 MeV and therefore difficult to detect. Adding Gadolinium to the water in the ESSνSB detector will increase the sensitivity to low energy anti-neutrinos.

2.3 Search for proton decay

The ESSνSB detector can also be used, simultaneously with the neutrino detection, for proton lifetime measurements. Proton decay is not allowed by the SM. On the other hand, Grand Unified Theories (GUT) predict proton decay. Its discovery would again reveal the existence of a more fundamental theory beyond the SM. The present lower limit of the half-life for the decay $p\rightarrow\pi^0e^+$ is $1.6x10^{34}$ years set by Super-Kamiokande[8] employing the same Water Cherenkov detector technique as ESSνSB is planning to use, but with a detector volume 20 times smaller than that of the ESSνSB detector. If the proton life-time is below 10^{35} years, then proton decays would be observed after 10 years of data taking with the ESSnuSB detector. If not, on the other hand, no proton decays would be observed, this would impose a stringent limit on GUT.

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[8] *Search for nucleon decay into charged antilepton plus meson in Super-K*, H. Nishino et al., Phys. Rev. D 85, 112001 (2012).

3. Methodology

3.1 The development of the ESS linac upgrade required to deliver a 10 MW beam

In order to achieve a sufficiently intense neutrino beam for measuring the appearance of a large enough numbers of electron neutrinos and antineutrinos at the second maximum, a proton beam of about 5 MW average power will be required. The ESS linac currently under construction will be used to accelerate protons to the energy of 2 GeV in 2.86 ms long 62.5 mA pulses at 14 Hz pulse frequency to be used for spallation neutron production. The low duty cycle of 4% of the ESS linac makes it possible to accelerate 14 additional pulses of H^- ions, interleaved with the proton pulses, to be used for the proposed production of a uniquely high-intensity neutrino beam.

The modifications, that will have to be undertaken to increase the ESS linac power from 5 MW to 10 MW, have been studied by F. Gerigk and E. Montesinos and documented in a CERN report[9]. To increase the average power by 5 MW will require the installation of 3 new electric substations and new high voltage cables, of 8 more accelerating modules to raise the beam energy from 2.0 GeV to 2.5 GeV, of new klystron collectors to sustain the increased averaged klystron current, of more capacity chargers for the modulators to allow the increase in pulse frequency, of a H^- sources and the doubling of the very first accelerating elements of the linac.

The conclusion of the authors is that "*no show stoppers have been identified for a possible future addition of the capability of a 5 MW* H^- *beam to the 5 MW* H^+ *beam of the ESS linac built as presently foreseen*." The proposed modifications will be studied in more detail during the current Design Study. Another problem that will be studied is the effect of higher order modes induced in the linac accelerating cavities by the 100 ns gaps in the 2.86 ms long H^- pulse that need to be created in the linac in order to have a 100 ns gap in the circulating beam in the accumulator during which the field of the accumulator extraction kicker will be raised.

3.2 The development of an accumulator ring capable of compressing the ESS linac pulses to about 1.3 microseconds

The very high current (350 kA) pulse needed in the hadron collector (magnetic horn) which focuses the produced pions in the forward direction, causes a high heat dissipation in the thin walls of the hadron collector. The flat top of the current pulse can for this reason not be longer than the order of a few microseconds. The 2.86 ms length of the pulses from the ESS linac will therefore be compressed by about three orders of magnitude to about 1.3 µs using a ca 400 m circumference accumulator ring.

As a first step in the design of this ring, the magnetic lattice of the accumulator ring of the US Spallation Neutron Source (SNS) in Oak Ridge, USA, has been adapted to the higher energy of the ESS beam, using simulations to study different H^- stripping schemes and the accumulator beam stability including space charge effects. With a 2.86 ms pulse length and a 62.5 mA current the number of H^- per pulse will be 11×10^{14}. This first study showed that this high number causes problems with stripping-foil heating and space charge effects. The study has therefore been continued making the assumption that only 1/4 of the total number of particles in one linac pulse is accumulated in the ring. This can be achieved using either 4 stacked accumulator rings, with a beam switching system at injection to distribute the linac beam pulse into the different accumulator rings, or one ring receiving sequentially 4 times more linac pulses, each of a length that is 1/4 of the linac pulse length. The latter option (which is currently the baseline option) requires create three 100 µs gaps in the pulse at the beginning of which the accumulator ring will be emptied and during which the magnetic horn capacitors will be recharged or to increase the linac pulse frequency to 70 Hz and acceleration of four times more H^- pulses, each of 1/4 length. Some preliminary feasibility considerations of increased linac frequency have already been documented by F. Gerigk and E. Montesinos in the already mentioned document.

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[9] F. Gerigk and E. Montesinos, *Required modifications of the ESS accelerator architecture for ESSnuSB* , CERN-ACC-NOTE-2016-0050, July 2016

Space charge simulations will be made to find out whether the effect of the very short linac bunches (a few ps) on the beam behaviour will imply the need for more equipment, like cavities with phase shift and/or momentum shift in the accumulator to modify the microstructure of the beam coming from the linac.

The beam transfer line from the linac to the accumulator, the multi-turn injection, including the H^- stripping system, the extraction kicker for single turn ejection and the beam switchyard that splits the beam up on the four targets, will be developed using simulations. The current baseline technology for H^- stripping is foil-stripping, but laser stripping will also be studied as a longer-term option. The problem with foil stripping is that the high H^- intensity incident on the foil heats the foil to a temperature that may be too high for the foil to withstand. So far, laser stripping of H^-, which does not present this problem, has been used for H^- pulses of only a few µs length. The possibility of making experimental tests of laser striping for longer pulses, using existing set-ups at the SNS in the US, will be investigated.

Spallation neutron users of the ESS have expressed a keen interest in having pulses significantly shorter than 2.86 ms, like 100 µs long pulses, such that the proton pulse length and the neutron moderating time are matched and the neutron peak brightness maximised. Such pulses could be achieved with the proposed accumulator ring using slow extraction, an option that will be included in the present Design Study. The synergy between the two uses opens up the perspective of eventually sharing the investment and operation costs for the H^- beam and the accumulator with the spallation neutron users.

3.3 The development of a target station for a 5 MW proton beam for neutrino production

The Target Station includes the target itself, the hadron collector, the decay tunnel and the beam dump. The design of a target for neutrino production capable of withstanding the heat load of a 5 MW beam seems not feasible. In order to reduce the heat-load there will be four targets, which will be hit in sequence by the proton pulses, thereby reducing the beam power hitting each target to 1.25 MW. Following the EUROv studies[10], a packed bed of titanium spheres cooled with helium gas has become the baseline design for a Super Beam based on a 2-5 GeV proton beam with a power of up to 1.3 MW per target. The continued studies for ESSvSB include modelling of the vibration of the spheres and their possible degradation at the contact points and further development of instrumentation to monitor the performance.

The ESSvSB proton beam will thus need to be divided up on four beam lines, using a beam switchyard, with four separate targets, each with a separate hadron collector. The hadron collectors will have to be pulsed more frequently than in current neutrino projects and withstand an average beam power of 1.25 MW, which is twice as high as in current neutrino projects. This represents a considerable challenge for the design of the hadron collector and its power supply. A first design was produced during the EUROv studies, demonstrating on paper that the requirements can be satisfied[11,12]. Studies will be made to further elaborate the design of the hadron collector and its power supply to the specific ESSvSB conditions, in particular for the two pulsing frequencies 14 Hz and 70 Hz.

Alternative designs of the hadron collectors, which would allow a continuous powering and for which the hadron collector therefore would not need proton pulse compression, are also being studied. Such a solution, if proved feasible, would significantly reduce the capital cost of the project.

The Target Station includes a ca 25 m long decay tunnel and a beam dump. Particular care will be taken in the design of these elements to preserve a possible future utilisation of the charged muons produced at the same time as the neutrinos for other facilities such as a low-energy nuSTORM facility, a Neutrino Factory and/or a muon collider.

3.4 The development of a near detector for the high intensity, low energy ESSvSB neutrino beam

A near detector located in the beam a few hundred meters downstream from the target station is required to monitor the neutrino flux, to measure neutrino cross sections and to study background channels. For ESSvSB the study of cross sections will be particularly important as there are till now very few such measurements for the relatively low neutrino

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[10] *A High Intensity Neutrino Oscillation Facility in Europe,* European Commission Framework Program 7 Design Study: EUROnu, Project No. 212372

[11] "*Neutrino super beam based on a superconducting proton linac*", E. Baussan et al., Phys. Rev. ST Accel. Beams 17, 031001 (2014), arXiv:1212.0732v1 [physics.acc-ph].

[12] "*Study of the pulse power supply unit for the four-horn system of the CERN to Fréjus neutrino super beam*", E. Baussan et al., JINST 8 (2013) T07006.

energies 0.2-0.6 GeV of the ESSνSB beam. It is important that these cross-section measurements be made with the same target material as in the Far Detector, i.e. with a water target. The relatively high beam flux of the ESSνSB beam at the level of the Near Detector will make high statistics measurement of the neutrino cross-sections feasible. On the other hand, the ESSνSB low neutrino beam energy implies that the resonant scattering background, which, compared to the quasi-elastic scattering signal, becomes of significant above 0.6 GeV, and the deep inelastic scattering background, which becomes significant above 2 GeV, are strongly suppressed compared to what will be the case at Hyper-K, which uses a 0.3-0.9 GeV neutrino beam, and in particular compared to what will be the caser at DUNE, which uses a 1.2-6 GeV neutrino beam.

A first simulation study of a cylindrical water Cherenkov near detector of 10 m diameter and 10 m length, large enough to contain the ESSνSB beam and the tracks of the produced muons, has already been made. Additional detectors will be needed to measure the topology of the events and to identify the different neutrino interaction channels. The experience already available from the construction and operation of the T2K near detector, for which an improvement program is currently under way, will provide valuable input to the ESSνSB near detector design work. As there are important differences in both the neutrino energy and the neutrino flux between the two experiments, the near detector design for T2K will have to be studied in detail to fit the ESSνSB requirements. We have gained useful experience by participating in the beam tests at CERN of the Baby MIND detector in 2017 and the SuperFGD detector prototype in 2018, both of which are intended for use in the T2K and Hyper-Kamiokande near detectors.

3.5 The design of an underground megaton water Cherenkov far detector

The far detector shall detect and identify the ν_μ and, in particular, the ν_e and provide a measurement of their energy with an as large as possible fiducial target mass and identify background events caused by cosmic rays by the use of an outer detector layer. The starting point for the ESSνSB far detector design is the detailed MEMPHYS Far Detector design produced and evaluated by the EUROν project. This detector has 500 kt fiducial mass divided up on two cylindrical detector volumes, 65 m in diameter and 100 m high, and was intended for installation in the Féjus tunnel in the French alps for detection of the neutrinos in a Super Beam generated with the previously planned 4.5 GeV CERN Super Proton Linac. A detailed study was also made of the design of the Fréjus underground cavern in which the detector would be installed. The experience of the Super-Kamiokande detector design work on the excavation, the detector enclosure and the water cleaning system, transparency monitoring and addition of Gadolinium salt, as well as the new studies of these items made for Hyper-Kamiokande, represents a very valuable input to the ESSνSB far detector design work. There has also been detailed and well documented studies made for the LAGUNA LBNO project of underground caverns for large neutrino detectors, made for installation in the Pyhäsalmi mine in Finland. The latter is of particular interest as the geology of the bedrock in Finland is similar to that in Sweden.

The Garpenberg mine, located at 540 km from ESS, is currently the prime candidate location for the MEMPHYS type detector of ESSνSB. At this mine there is a 900 m deep shaft, which since two years is no longer needed by the mining activities for ore hoisting and which can thus be employed to hoist up the one million cubic meters of rock debris from the detector cavern excavation. The underground mine surroundings will be studied in detail collecting geological and rock mechanics information by making core drillings, core logging, rock strength testing and rock stress measurements of the bedrock at 1000 m depth. The technical part of this task will be subcontracted to the Mining and Rock Engineering Division of Luleå Technical University and a specialised rock engineering company, with which we have been working since 4 years. We already have some preliminary results from one core drilling out to the granite zone outside the Garpenberg mine syncline which look very promising. A memorandum of understanding (MoU) has already been signed between Uppsala University and the mine owner Boliden Group Inc and preliminary civil engineering and logistics reports are favourable.

The Zinkgruvan mine, located at 360 km from ESS, is currently the second option for the location of the Far Detector. Zinkgruvan is, like Garpenberg, located near the second neutrino oscillation maximum and approximately on the same straight line from ESS as Garpenberg. At Zinkgruvan there is only one main transport shaft, which is fully used by the mining activities for ore hoisting, so a new transport shaft for the hoisting of the ESSνSB excavation debris may have to be made. No core drilling outside the syncline has so far been made at Zinkgruvan. In Figure 2 are shown the performance with both MEMPHYS type detector cylinders in Garpenberg, with one of the detector cylinders in Garpenberg and one in Zinkgruvan and with both detector cylinders in Zinkgruvan. The CP violation discovery reach is similar for the three cases where as the resolution in δ_{CP}, is higher for Zinkgruvan compared to the other two.

As to the design of the far detector photo-detectors, more efficient and less costly designs, like that of the MCP photomultipliers produced for JUNO, have appeared on the market, replacing the classical Venetian-blind-dynode-amplified photomultiplier and making a higher photo-detection efficiency and larger photodetector coverage possible with no increase in detector cost. The development of further progress in this field will be followed closely.

4. Readiness

4.1 The ESSνSB consortium is actively working with the EU supported ESSνSB Design Study

The concept of using the ESS linac to generate a uniquely intense neutrino beam to enable measurements at the second oscillation maximum was first presented in a seminar at CERN in 2012 and later published as E. Baussan et al., "Neutrino super beam based on a superconducting proton linac" in Phys. Rev. ST Accel. Beams 17, 031001 (2014). In 2015 the ESSνSB consortium received a ca 0.3 MEUR allocation from the EU COST Association for the period 2016-2019 to set up a European network, EuroNuNet[13], with the purpose of "Combining forces for a novel European facility for neutrino-antineutrino symmetry-violation discovery". The COST grant is currently used for financing travel and scientific missions of neutrino scientists between the 13 participating countries.

In 2017 the ESSνSB consortium received 3 MEUR funding from the H2020 program to finance a Design Study of the ESSνSB project of a total cost of 4.7 M€, during the period 2018-2021[14]. The 17 member institutes of the ESSνSB H2020 INFRADEV-1 Design Study are: Centre National de la Recherche Scientific (**CNRS)** France (two institutes), Uppsala University (**UU)** Sweden, Royal Institute of Technology (**KTH)** Stockholm Sweden, European Spallation Source (**ESS)**, Cukurova University Adana (**CU)** Turkey, Universidad Autonoma de Madrid (**UAM)** Spain, Demokritos Center (**NCSR)** Athens Greece, Istituto Nazionale di Fisica Nucleare (**INFN)** Italy (two institutes), Rudjer Boskovic Institute (**RBI)** Croatia, Sofia University St. Kliment Ohridski (**UniSofia)** Bulgaria, Lund University **(LU)** Sweden, University of Science and Technology (**AGH)** Krakow Poland, European Organisation for Nuclear Research (**CERN)**, University of Geneva (**UniGe)** Switzerland and University of Durham (**UDUR)** UK.

The ESSνSB Design Study is coordinated by CNRS. The ESS linac power upgrade design work (WP2) is led by ESS with UU and CERN as collaborators. The accumulator design (WP3) is led by UU with CERN and CRNS as collaborators. CNRS and AGH work on the neutrino target station design (WP4) with AGH leading the work. The ESSνSB detector work (WP5) is led by UniSofia with LU, RBI, NCRS, CU and UU as collaborators, with UniGe playing a leading role in the T2K detector test beam work at CERN and with INFN working on a special proposal for electron neutrino cross-section measurements. The ESSνSB physics performance (WP6) is led by UAM with KTH and UDUR as collaborators. A significant fraction of the ESSνSB funding is being used to recruit and finance young postdocs to contribute in the design work. A first annual meeting of ESSνSB was held in Strasbourg in November 2018. The results of the now ongoing Design Study will be published in a Conceptual Design Report (CDR) in 2021.

The plan is that the ESSνSB INFRADEV-1 Design Study 2018-2021 will be followed by an INFRADEV-2 Preparatory Phase 2022-2024 resulting in a Technical Design Report (TDR). As from 2024, the TDR will be used as a basis for seeking financial support from European governments to enable the start of ESSνSB construction work around 2026-2029. By that time the ESS baseline infrastructure with the proton linac, the neutron spallation target and 15 neutron instruments will already have been built up and started operation. It is foreseen that the build-up of the neutrino production infrastructure at ESS and the neutrino detector will be going on for ca 7 years leading up to the start of data taking some time in the period 2033-2036. A first task for ESSνSB will be to discover leptonic CP violation and measure δ_{CP} with high precision. In subsequent updates and according to the physics needs, this neutrino Super Beam could be transformed to a muon facility to serve a nuSTORM facility, a Neutrino Factory or/and a muon collider.

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[13] https://www.cost.eu/actions/CA15139#tabs|Name:overview

[14] http://essnusb.eu/

5. Expected challenges

5.1 The handling of the very high-power H^- beam in the linac, in the accumulator ring and in the target station

The particles to be accelerated in the ESS linac and injected into the accumulator will be H^- ions. If the electrons of the H^- are lost due to different kinds of perturbations in the accelerator and beam transfer line from the H^- ion source to the accumulator injection point, the resulting proton will hit the beam pipe walls of the linac and transfer line and induce radioactivity in the surrounding equipment. Currently, a proton beam loss of 0.1 W/m is foreseen for proton acceleration in the linac. An increase in the loss of up to 1 W/m due to increased beam loss with H^- acceleration and transfer could probably be tolerated. There are however a number of conditions on the linac and the transfer line that need to be fulfilled to avoid a higher loss. One such condition is that the beam optics in the linac be such as to minimize losses. Another is that the radius of curvature of the beam transfer line must be kept above a certain limiting value. These conditions are being carefully studied.

5.2 The design of the large far detector caverns in the Nordic granite bedrock

As already mentioned there have already been very detailed engineering design studies of the required very large volume to be excavated at ca 1000 m depth in the bedrock within the previous LAGUNA project in Finland and the Hyper-Kamiokande project in Japan. The pressure under ca 1000 m of bedrock is very high and the stability of the walls of the excavated volume is critically dependent on the strength of the rock, the geometry of the excavated volume and the various techniques used to strengthen the walls. However, a necessary input to any, even only conceptual, design of such an excavation is to have information of the rock pressure and rock strength at the location where the excavation is planned, in our case at 1000 depth near the Garpenberg and/or Zinkgruvan mines in Sweden. Such investigations require a number of ca one-kilometer-long holes of a few centimetres diameter to be drilled into the bedrock to measure the pressure and to bring out samples of the bedrock material for strength measurements. The ESSνSB collaboration has access to sufficient technical expertise to work out a conceptual design of the required excavation of 2 caverns of order half a million m^3 each, provided results of such measurements can be made available. However, the drillings are costly (order 100’000 EUR per hole) and could not been included in the request for funding from EU/H2020. We are therefore currently seeking to acquire external funding for the drillings.

5.3 ESSνSB will need continued EU funding to enable the preparation of a Technical Design Report

In its Strategy Session in 2013 the CERN Strategy Council stated as part of its ‘European Strategy for Particle Physics’ that there is “a strong scientific case for a long baseline neutrino program exploring CP violation and the mass hierarchy in the neutrino sector”. The Council recommended that “CERN should develop a neutrino program to pave the way for a substantial European role in future long-baseline experiments”, which CERN has since then in part done with the development of the CERN Neutrino Platform. This Platform has predominantly been used to support the US DUNE Liquid Argon detector project and to some extent the T2K and Hyper-Kamiokande near detector projects. The Council also recommended that “Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan”.

After this recommendation was made in 2013 the construction of the ESS began in 2014 and a Design Study of the use of the ESS linac to create a uniquely intense neutrino beam enabling measurements at the second oscillation maximum started. In view of the outstanding opportunity for precision neutrino experimentation offered by this use of the ESS linac, the European COST Association provided ca 0.3 MEUR to be used for networking for this project as from 2016 and the EU2020 program provided 3 MEUR for the financing of the Design Study as from 2018. This has enabled a vigorous start to the study of the specific possibilities for a world-leading and complementary long-baseline neutrino project.

In order to demonstrate in the form of a Technical Design Report the feasibility and performance of ESSνSB as a precision experiment, having in the longer term perspective a very significant muon-physics potential, the ESSνSB consortium will need continued support from EU as from 2022 in the form of Preparatory Phase funding. A formal requirement for ESSνSB to be in a position to apply for EU Preparatory Phase funding at the end of the ESSνSB Design Study in 2021 is that ESSνSB be included in the 2021 ESFRI list. The European Strategy for Particle Physics will represent one of the significant inputs for the ESFRI committee when it will decide in 2021 on the ESFRI list update. In view of this we propose that the CERN Strategy Council should include, in its upcoming 'European Strategy for Particle Physics', the opportunity, new since 2013, of the ESSνSB Collaboration producing a thorough Technical Design Study of the proposal to use the European Spallation Source linac to drive a uniquely intense Long Baseline neutrino beam.

5.4 The unique scientific potential of the ESSνSB project will make possible a further successive build-up of a forceful scientific collaboration around the ESSνSB project

Europe has had a strong tradition of neutrino-beam physics for many decades with the discovery of neutral currents in the 1970s, detailed measurements of deep inelastic neutrino scattering in the 1980s and the CERN Neutrino beam to Gran Sasso (CNGS) in the 2000s. The decision by CERN to close down the CNGS beam and not to build the proposed CERN neutrino beam to the detector location in the Fréjus tunnel in France, nor to build the proposed CERN neutrino beam to the detector location in the Pyhäsalmi mine in Finland, left the members of the large European neutrino community with the option of joining either the US or the Japanese neutrino beam programs. When the measurement of the larger than expected θ_{13} mixing angle had been published in 2012 and the construction of ESS was definitely decided, this lead to the publication of a first conceptual proposal in 2014 to use the uniquely powerful ESS proton linac to generate an equally uniquely intense neutrino beam that would enable measurements at the second neutrino oscillation maximum. At that time, many of the neutrino physicists in Europe had, as a consequence of CERN's earlier decisions referred to above, already committed themselves to the US or Japanese programs. The mission of the ESSνSB project is to demonstrate experimentally the existence of leptonic CP violation and to make precision measurement of the leptonic CP violating angle at the second oscillation maximum where sensitivity is greater than at the first oscillation maximum making the project complementary to the other two. The present ESSνSB Consortium is confident that the high potential of the ESSνSB project, unique both by its ca 3 times smaller dependency on systematic errors for the CP violation measurement and by its future potential, in a longer perspective, for high intensity muon physics, will lead to a further successive build-up of a strong and productive scientific collaboration around the ESSνSB project.