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The ESSνSB Project

Elian Bouquerel, Eric Baussan, Marcos Dracos∗†
IPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France
E-mail: marcos.dracos@in2p3.fr

Tord Ekelöf
Department of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden

Aysel Kayis Topaksu

Faculty of Arts and Science, Physics Department, Çukurova University, 01330 Adana, Turkey

After measuring in 2012 a relatively large value of the neutrino mixing angle θ_{13}, the door is now open to observe for the first time a possible CP violation in the leptonic sector. The measured value of θ_{13} also privileges the 2nd oscillation maximum for the discovery of CP violation instead of the usually used 1st oscillation maximum. The sensitivity at this 2nd oscillation maximum is significantly higher than for the 1st oscillation maximum also inducing a lower influence of systematic errors. Going to the 2nd oscillation maximum necessitates a very intense neutrino beam with the appropriate energy. The world's most intense pulsed neutron source, the European Spallation Source, will have a proton linac with 5 MW power and 2 GeV energy. This linac, under construction, also has the potential to become the proton driver of the world's most intense neutrino beam with very high potential to discover a neutrino CP violation. The physics performance of that neutrino Super Beam in conjunction with a megaton underground Water Cherenkov neutrino detector installed at a distance of about 500 km from ESS has been evaluated. In addition, the choice of such detector will extent the physics program to proton–decay, atmospheric neutrinos and astrophysics searches. The ESS proton linac upgrades, the accumulator ring needed for proton pulse compression, the Target Station and the physics potential are described. In addition to neutrinos, this facility will also produce at the same time a copious number of muons which could be used by other physics applications. The ESS linac will be fully ready by 2023 at which moment the upgrade process for the neutrino facility construction could start.

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∗Speaker.

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1. Introduction

After measuring a relatively high value for the third mixing angle θ_{13}, the observation of CP violation in the leptonic sector is now in reach of future neutrino Super Beam projects. This observation could, under certain conditions, help to understand the observed matter-antimatter in the Universe (disappearance of antimatter).

For this observation, high intensity neutrino beams are needed. Also, a better understanding of systematic uncertainties has to be achieved during the coming years. T2K [1], after many years of data taking pushed down the signal systematic error at the level of 6%. Further improvement needs a huge effort, while preliminary work, before the next generation experiments start data taking, has to take place.

Not being sure at which level these uncertainties will go down during the coming years, ways to mitigate their effect on CP violation observation have to be found. One of these ways is to operate the neutrino facilities on the second oscillation maximum (SOM) of the $\nu_\mu \to \nu_e$ oscillation. Indeed, on the SOM, for a high θ_{13} value, the effect of systematic uncertainties is less while the sensitivity to the CP violating phase δ_{CP} is significantly higher than on the first oscillation maximum (FOM) [2, 3, 4]. This would not be the case for lower values of θ_{13}. For this reason, facilities designed before the measurement of θ_{13}, had to re-optimise their design in the limit of their possibilities.

In order to operate a neutrino facility on the SOM a very intense proton beam is needed to compensate for the three times higher distance compared to the FOM. After the measurement of θ_{13} and the approval of the European Spallation Source (ESS) [5], the project ESSνSB has been proposed [6]. Indeed, the ESS neutron facility, under construction in Lund (Sweden), will have by 2023 a very powerful 2 GeV proton linac of 5 MW, which can also be used, on top of the neutron production, to produce neutrinos using a specific target.

2. The ESS facility

The ESS is a neutron facility using neutron scattering for many applications. To produce neutrons, a very high power proton beam is used hitting a massive spallation target. The protons are produced and accelerated in a linac with a cycle of 14 Hz. The proton pulse duration is relatively large, 2.86 ms, but still inducing a duty cycle of 4% only. The facility power will be 5 MW, making the ESS linac the most powerful accelerator in the world in the coming years. Table 1 gives the main ESS linac parameters while Fig. 1 shows a schematic view. An empty space in the linac allows to upgrade the facility from 2 GeV protons to 3.5 GeV.

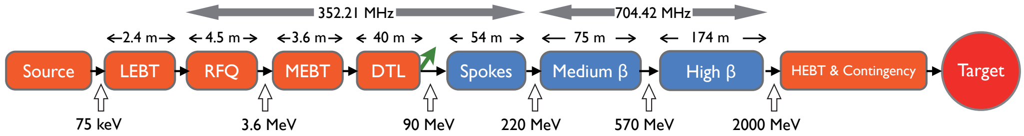

Figure 1: Schematic view of the ESS proton linac.

The construction of the ESS facility started in 2014 and will be fully ready by 2025 with all neutron stations available.

Table 1: Main ESS linac parameters compared to those in case of the presence of the neutrino facility (ESSνSB).

Parameter	Value	
	ESS	ESS+ESSνSB
Ion	p	H$^-$
Average beam power	5 MW	10 MW
Kinetic energy	2.0 GeV	2.5 GeV
Average macro–pulse current	62.5 mA	30-60 mA
Macro–pulse length	2.86 ms	>2.9 ms
Sub-pulse length	N/A	∼0.72 ms
Pulse repetition rate	14 Hz	28 Hz
Linac length	352.5 m	352.5+∼70 m
Annual operating period	5000 h	5000 h

3. The neutrino facility

In order to upgrade the ESS facility to a neutrino facility, while being operated at the same time as a neutron facility, few modifications have to be performed. These modifications mainly concern the doubling of the linac frequency and the shortening of proton pulses from 2.86 ms to few μs. Indeed, the ESS proton pulses for neutron production are too large for the neutrino production because of limitations in the hadron collector of the neutrino Target Station. Table 1 presents a comparison of the linac parameters between the neutron facility alone and after the presence of the neutrino one.

To shorten the proton pulses a proton accumulator is needed after the linac. The size of this accumulation ring has to fit in the already ESS allocated area while at the same time it must not be too small in order to avoid very strong charge effects inside the accumulator. A good compromise is an accumulator with a circumference of about 380 m [7]. In order to accumulate all protons, H$^-$ ions have to be accelerated in the linac and injected in the accumulator with an electron stripping at the entrance. This stripping can be performed by a carbon foil or using a laser system. Both methods are under study.

The acceleration of H$^-$ in the linac necessitates the addition of an H$^-$ source on top of the proton one [8]. There is also the possibility to abandon the proton source by the neutron facility and only use the short pulses produced for the neutrino facility as it is the case for SNS (Spallation Neutron Source, USA) [9, 10]. Fig. 2 shows two possible implementation schemes of the H$^-$ source together with the proton one.

A previous preliminary study [11] has not identified showstoppers at the level of the proton driver for all these modifications neither incompatibilities with the present neutron utilisation. This study strongly recommends to increase the proton kinetic energy from 2 GeV to 2.5 GeV, mainly to decrease the space charge tune shift in the accumulation ring, and reduce the average current in the linac for the same power and same neutrino flux. This energy increase also benefits to the physics performance of the neutrino facility (see below).

Several pulsing schemes of the proton linac and the accumulator have been studied. The

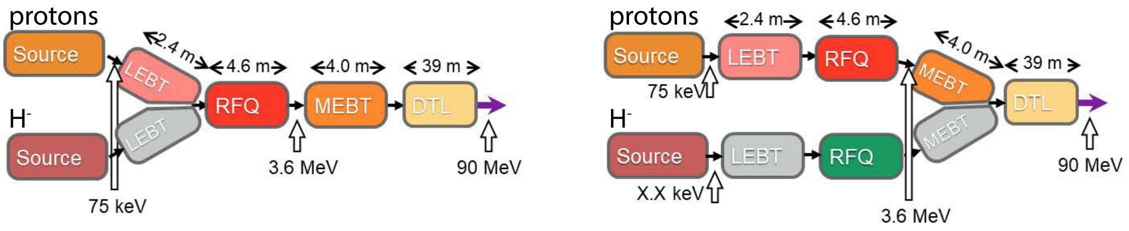

Figure 2: Schematic view of the H$^-$ source implementation in the ESS linac.

present considered scheme is the one depicted by Fig. 3. A pulsing scheme where the total energy consumption is reduced, while the efficiency of neither the linac nor the ring is compromised, is chosen as the baseline pulsing scheme. Four H$^-$, sub-pulses are interleaved between the proton pulses for neutron production. The duration of these sub-pulses is 0.65 ms. A 100 μs gap is foreseen between the H$^-$ sub-pulses to allow the proton extraction without losses from the accumulator towards the Target Station. Finally, the extraction from the accumulator will be done every 0.75 ms.

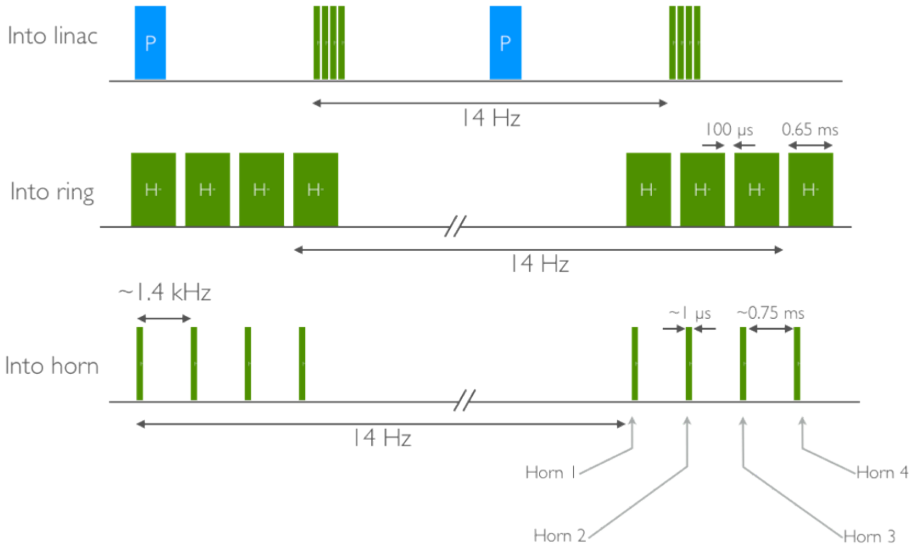

Figure 3: Baseline pulsing scheme of the proton linac and accumulator. Blue (p) pulses are for protons for neutron production and green (H$^-$) pulses are for neutrino production.

The Target Station [12] has been borrowed from the previous Design Study EUROν [13]. To mitigate the very high power of the proton beam and in accordance with the linac and accumulator pulsing scheme, the Target Station has four targets and four corresponding hadron collectors (horns). Each target/horn is pulsed each time by one fourth of the total proton power providing better operation conditions with respect to vibrations, heating dissipation and reliability. Fig. 4 presents the Target Station layout while Fig. 5 shows the horn with the target inside. Because of the relatively low energy protons, the decay tunnel length is only 25 m long. This tunnel is followed by a beam dump stopping all remaining protons, pions and muons.

The proposed target is also the one defined in EUROν composed of few millimeters titanium spheres placed in a canister. A monolithic target could suffer from vibrations and from cooling issues, while the proposed target could be cooled using a He gas flow going through the spheres.

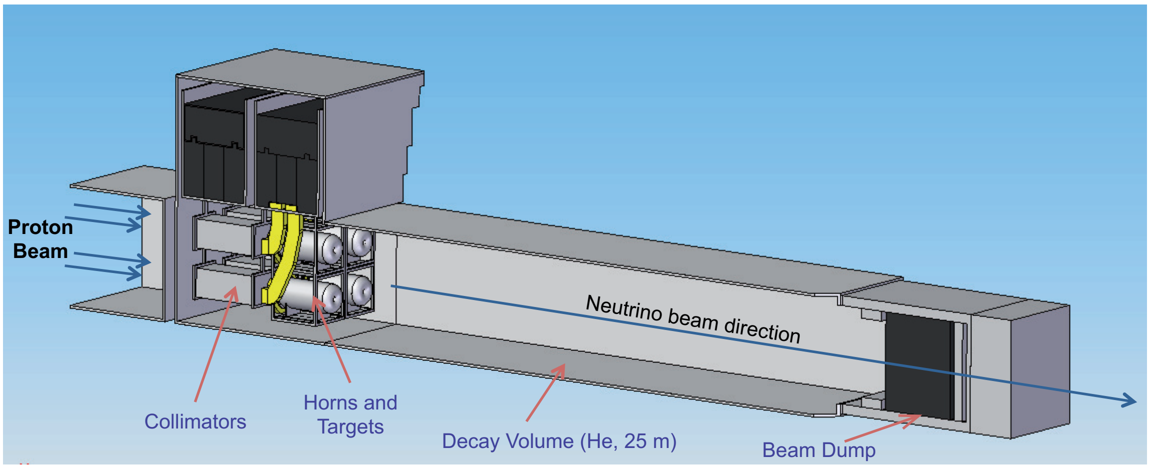

Figure 4: Layout of the Target Station including the decay tunnel and the beam dump.

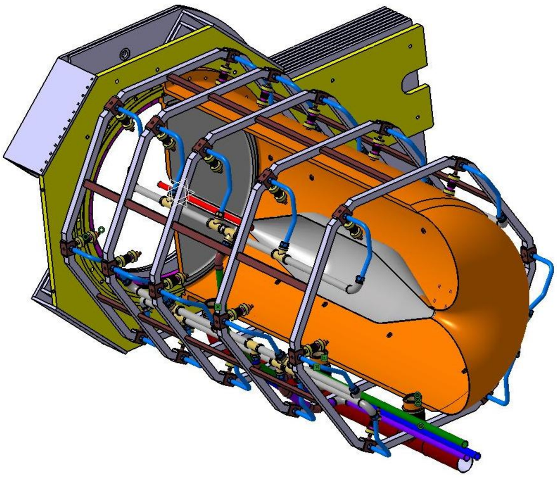

Figure 5: One of the four horns with the target (red) inside, the cooling system and the strip lines.

A near detector [14], placed at around 500 m from the neutrino target will have the role to monitor the neutrino beam and measure the relative neutrino interaction cross–sections in water. This detector could be composed of electronic detectors as Super–FGD [1] and a passive nuclear emulsion detector as NINJA [15]. The nuclear emulsion detector could measure the neutrino beam topological characteristics and composition.

Finally, Fig. 6 shows a possible implementation of the neutrino facility on the ESS site. It is seen the H^- extraction line from the linac, the accumulation ring, the switchyard to share the beam among the four targets/horns, the Target Station and the near detector.

As far detector, ESSνSB will use a MEMPHYS-like [16] water Cherenkov detector. This detector, of 500 kt fiducial mass, can be installed in an active mine at a distance corresponding to the SOM. Two mines are now under investigation, Garpenberg, at a distance of 540 km from

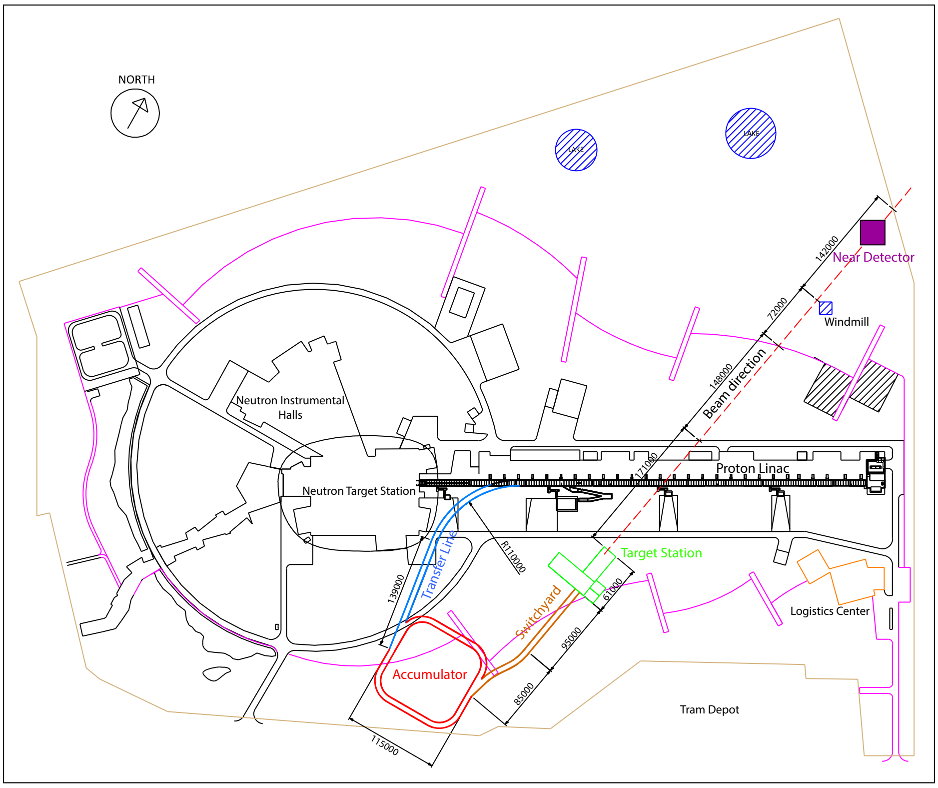

Figure 6: Layout of the neutrino facility on top of the neutron one, showing the extraction line from the linac (in blue), the accumulator (in red) the beam switchyard (orange), the Target Station (in green) and the location of the near detector (in purple).

Lund and Zinkgruvan, at a distance of 360 km. As mentioned below, each baseline has its own advantages. Especially, Garpenberg is better for CP violation discovery while Zinkgruvan has better performance for measuring δ_{CP}. This detector, thanks to its large volume, will also have a rich astroparticle physics program including detection of super nova explosion neutrinos and atmospheric neutrinos. It can also be used for proton lifetime studies.

4. The physics performance

Using the above configuration and 2.5 GeV kinetic energy protons the neutrino energy distributions exhibited by Fig. 7 for neutrino (positive current in the horn) and for antineutrino (negative current in the horn) runs, would be obtained with the current Target Station optimisation. Table 2 presents the neutrinos per year (200 days) and per m^2 crossing a surface perpendicular to the beam axis and placed at an arbitrary distance of 100 km from the target. The primary ν_μ beam has a very high purity of 97.9% with very low ν_e contamination of 0.3%. For $\bar{\nu}_\mu$ runs, the $\bar{\nu}_\mu$ purity is of the order of 94.5%, while the $\bar{\nu}_e$ contamination remains at the level of 0.2%. The electron neutrino contamination can be used to measure ν_e and $\bar{\nu}_e$ cross–sections at the level of the near detector.

To find the best distance from Lund to place the far detector, the potential to discover CP violation in the leptonic sector has been studied versus the distance. Fig. 8 presents the fraction of δ_{CP} covered at 3 σ and 5 σ significance to reject 0° and π. This study has been done for several

Table 2: Number of neutrinos per m^2 crossing a surface placed on–axis at a distance of 100 km from the target station during 200 days for 2.5 GeV protons and positive/negative horn current polarities.

	positive		negative	
	N_ν $(\times 10^{10})$/m^2	%	N_ν $(\times 10^{10})$/m^2	%
ν_μ	583	97.5	23.9	6.6
$\bar{\nu}_\mu$	12.8	2.1	340	93.2
ν_e	1.9	0.3	0.08	0.02
$\bar{\nu}_e$	0.03	0.01	0.8	0.2

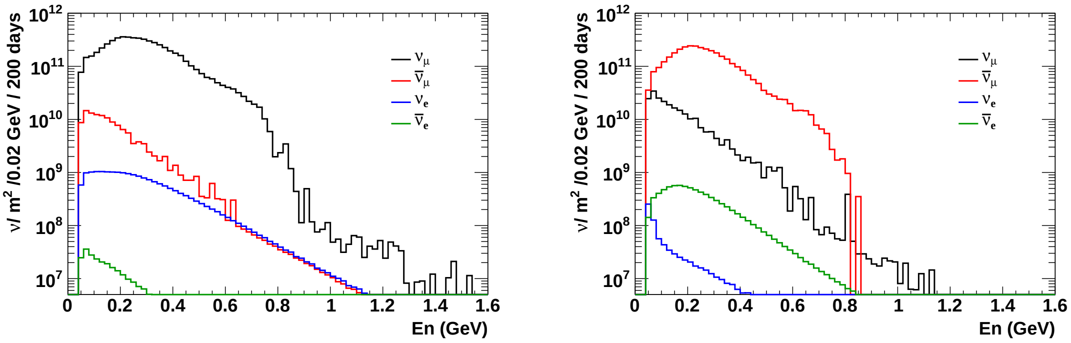

Figure 7: Neutrino energy distributions for neutrino (positive current in the horn, left) and antineutrino (negative current in the horn, right) runs. These on–axis distributions are given per m^2 at the arbitrary distance of 100 km from the target and for one running year (200 days).

proton energies from 2 GeV to 3.5 GeV, in case of future ESS linac upgrades. In all the cases, the fraction of covered δ_{CP} values exhibits a plateau between 400 km and 600 km, reaching 60% for 5 σ significance and 75% for 3 σ significance, for 10 year-run. It can also be seen that increasing the proton energy improves the physics performance of the facility.

Fig. 9 presents $\Delta\delta_{CP}$ versus δ_{CP} for several cases. It is seen that placing the detector in Garpenberg mine (540 km) is better for CP violation discovery because the precision achieved near 0° and π is better than the one obtained by placing the detector in Zinkgruvan mine (360 km). The resolution at 360 km is better elsewhere placing Zinkgruvan mine in better position for δ_{CP} precision measurement. It can also be seen that by increasing the proton energy to 3 GeV improves $\Delta\delta_{CP}$. By doubling statistics (20 years, 2×540 km) $\Delta\delta_{CP}$ near 0° and π goes below 5°.

More information about the ESSνSB physics performance can be found in [17].

5. The ESSνSB potentiality

Together with the neutrino production, the ESSνSB facility would also produce from pion decays a huge number of muons. These muons could be collected at the level of the beam dump using specific devices and used for other applications. The mean momentum of the muons is of the order of 0.46 MeV. A magnet and a collecting device could be placed at the level of the beam

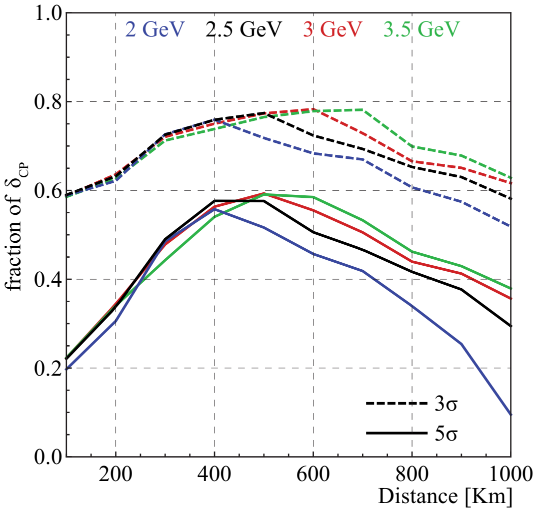

Figure 8: The fraction of the full δ_{CP} range as function of the baseline. The lower (upper) curves are for CP violation discovery at 5 σ (3 σ) significance.

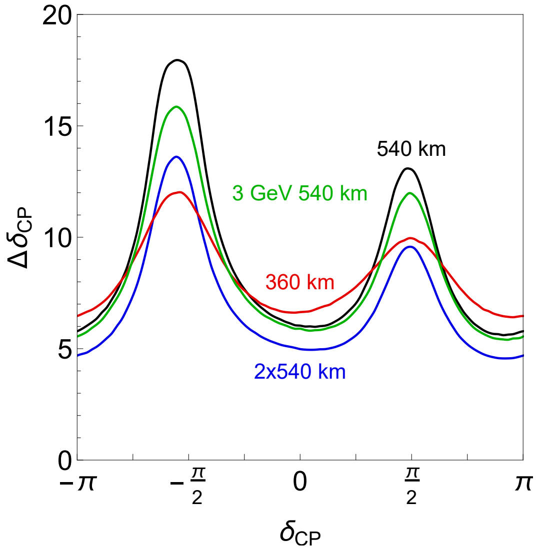

Figure 9: Precision on δ_{CP} versus δ_{CP} for 10-year run (half neutrino and half antineutrino run). Also, the performance for proton energy for 3 GeV is shown while 2×540 stands for 20-year run.

dump to deviate and collect a significant fraction of these muons. Preliminary calculations show that more than 4×10^{20} muons per year can be extracted. These muons can be used for a "low" nuSTORM neutrino experiment [18], for sterile neutrino searches, cross-section measurements and for R&D for 6D muon cooling. Using a solenoid instead of a horn, the whole facility can be used to produce μ^+ and μ^- for a Neutrino Factory [13] (considered as the ultimate neutrino facility) or/and a Muon Collider [19].

6. Conclusion

Neutrino long baseline experiments have for many years tried to reduce the systematic errors. Also, an ongoing program will try if possible to reduce them further. In order to be less dependent on systematic uncertainties and taking into account the relatively large value of the last measured mixing angle θ_{13}, it is more advantageous to operate the future long baseline neutrino experiments for CP violation discovery and δ_{CP} parameter measurement, on the second oscillation maximum. For this, a high intensity proton driver is needed. The ESSνSB project proposes to use the 5 MW ESS proton linac to produce a very intense neutrino beam, and place the far detector in a distance corresponding to the second oscillation maximum.

By using a 500 kt fiducial mass Cherenkov detector, ESSνSB can reach, for 10-year running, 60% δ_{CP} coverage with a 5 σ significance. After discovering CP violation in the leptonic sector, ESSνSB can measure relatively precisely δ_{CP}.

This project has a high potential for future upgrades by using the muons produced at the same time than the neutrinos or by using another target station to collect both signs μ^+ and μ^- to be used by a future Neutrino Factory or/and a Muon Collider.

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