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THE EUROPEAN SPALLATION SOURCE NEUTRINO SUPER BEAM DESIGN STUDY*

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Abstract

The discovery of oscillations and the latest progress in neutrino physics will make possible to observe for the first time a possible CP violation at the level of leptons. This will help to understand the disappearance of antimatter in the Universe. The ESSνSB project proposes to use the proton linac of the European Spallation Source currently under construction to produce a very intense neutrino Super Beam, in parallel with the spallation neutron production. The ESS linac is expected to deliver 5 MW average power, 2 GeV proton beam, with a rate of 14 Hz and pulse duration of 2.86 ms. By doubling the pulse rate, 5 MW power more can be provided for the production of the neutrino beam. In order to shorten the proton pulse duration to few µs requested by the neutrino facility, an accumulation ring is needed, imposing the use and acceleration of H^- ions instead of protons in the linac. The neutrino facility also needs a separate target station with a different design than the one of the neutron facility. On top of the target, a hadron magnetic collecting device is needed in order to focus the emerging charged hadrons from the target and obtain an intense neutrino beam directed towards the neutrino detector. This project is supported by a COST Action and an EU H2020 Design Study.

INTRODUCTION

The European Spallation Source (ESS) [1] under construction in Lund (Sweden) will use for the production of neutrons a very powerful proton linac. The kinetic energy of these protons is 2 GeV while the power is 5 MW.

This linac could also be used to produce a very high intensity neutrino beam for neutrino oscillation experiments. The proposed here neutrino facility can be used to understand the matter-antimatter asymmetry observed in the Universe. This can be done by observing a possible difference between neutrino and antineutrino oscillations. Such a difference has already been observed at the level of hadrons but not enough to explain the antimatter disappearance.

The very high power of the ESS proton linac and the high intensity neutrino beam produced allows to compare neutrino-antineutrino oscillations on the second oscillation maximum. While losing statistics because of the higher baseline compared to the first oscillation maximum, this possibility allows to be more sensitive to a possible CP violation in the leptonic sector decreasing at the same time the importance of systematic errors [2–4]. This is what is proposed by the ESSνSB project [5].

To make a design study and prepare a Conceptual Design Report (CDR) a proposal has been submitted to EU in 2017. This proposal has been accepted with a total cost of 4.7 M€, 3 M€ provided by EU, and 17 participating institutes [6]. The CDR is expected to be delivered by the end of 2021. An R&D phase with a preparation of a Technical Design Report is expected to follow.

THE ESS FACILITY

The main components of the ESS neutron facility are a proton linac, a target station and the neutron instruments. A schematic view of the proton linac is shown by Fig. 1. The principle parameters of this linac are given by Table 1. The proton kinetic energy will be 2 GeV with the possibility to go up to 3.5 GeV in future upgrades, thanks to the empty space left inside the linac tunnel. The linac pulse repetition rate is 14 Hz with a pulse length of 2.86 ms leading to a duty cycle of only 4%. This leaves enough room for extra pulses.

Table 1: Main ESS and Proposed ESS+ESSnuSB Facilities Parameters of the Proton Beam

Parameter	**ESS**	**ESS+ESSνSB**
Ion	p	p+H^-
Average beam power	5 MW	10 MW
Proton kinetic energy	2.0 GeV	2.5 GeV
Macro–pulse current	62.5 mA	50 mA
Macro–pulse length	2.86 ms	>2.86 ms
Pulse repetition rate	14 Hz	28 Hz
Beam duty cycle	4%	8%
Linac length	352.5 m	352.m m+70 m
Annual operating period	5000 h	5000 h

The construction of the facility started in 2014 and is expected to finish in 2023 with the proton linac at full power.

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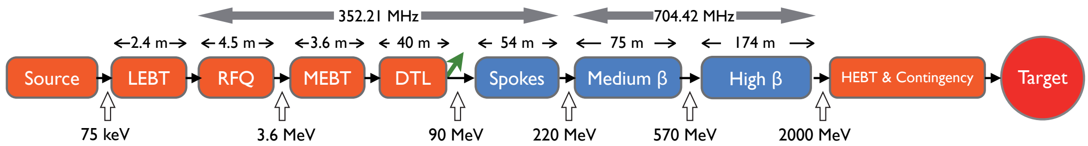

Figure 1: Schematic view of the ESS proton linac.

THE NEUTRINO FACILITY

To add, on top of the neutron facility, the proposed neutrino facility, without disturbing the neutron users, the following modifications are planned (Fig. 2):

- Increase the proton kinetic energy from 2 GeV to 2.5 GeV and the frequency from 14 Hz to 28 Hz. This will decrease all space charge effects. Table 1 shows the linac parameters proposed for the upgraded facility (ESS+ESSνSB). As mentioned below, protons have to be replaced by H^- ions in which case an H^- source has to be added.

- Add an accumulation ring with a circumference of about 380 m reducing the proton pulses duration to about 1.3 µs and fitting in the already allocate ESS area. This proton pulse compression is necessary because of the presence of the hadronic collector in the Target Station in which a very high pulsed current of the order of 350 kA is injected. Too long pulses could not be afforded due to very high Joule effect heating too much this device. Because of the compression in the accumulation ring, H^- ions need to be injected from the linac with a stripping at the entrance of the accumulator. The electron stripping could be done using a carbon foil. In order to avoid heating problems with the foil a laser stripping is also under study.

- As for the neutron production a neutrino Target Station is needed. This target station, in order to mitigate the proton beam high power, will have four targets and four magnetic horns [7]. To share the proton beam over the four targets/horns a switchyard is used at the ejection point of the proton beam from the accumulator. For the decay of the mesons produced inside the target made of TiO_2, the target station has a 25 m decay tunnel followed by a beam dump stopping all remaining particles with the exception of neutrinos. The decay tunnel length is optimised in order to leave enough time to pions to decay into neutrinos and muons, and not enough time to muons to decay and produce electron neutrinos contaminating the primary muon neutrino beam.

- For the neutrino detection near and far detectors are needed. The near detector will be used to monitor the neutrino beam and measure neutrino cross-sections while the far detector will detect the oscillated neutrino beam. Two active mines in Sweden could host the far detector. A MEMPHYS–like detector (megaton Water Cherenkov) [8] can be used for this purpose. The first mine, Zinkgruvan, is located at about 360 km from Lund while the distance from the second one, Garpenberg is of the order of 540 km. This megaton far detector also has a rich astroparticle physics program and could have a significant contribution to proton lifetime searches.

Concerning the compatibility between the present neutron facility design and the upgrade to a neutrino facility a special study has been performed by CERN experts [9] concluding that no showstoppers have been identified and giving recommendations about the linac modifications and the design of the accumulator.

Spallation neutron users 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 utilisations opens up the perspective of sharing the investment and operation costs for the H^- beam and the accumulator with the spallation neutron users.

In case of short proton pulses and using the massive neutron target absorbing all pions and muons, decay at rest experiments can also be performed. The neutrinos emitted by the decay of pions and muons at rest could be used to measure neutrino cross-sections at around 30 MeV, needed for supernova neutrino measurements.

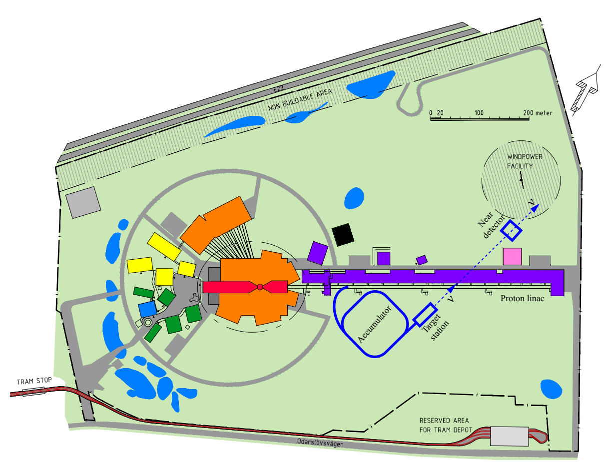

Figure 2: Layout of the ESS installation with a possible neutrino facility implementation in blue (accumulator, target station, near detector).

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PHYSICS PERFORMANCE

The neutrino oscillation to be studied and used for a CP violation discovery is $\nu_\mu \rightarrow \nu_e$. In this case, the initial neutrino beam must have a very low electron neutrino component. The energy distribution of the produced neutrino beam is given by Fig. 3 at an arbitrary distance of 100 km from the target in forward direction. The covered energy range corresponds to the second oscillation maximum for the considered baseline.

The neutrino beam is composed by more than 97% muon neutrinos with a very small electron neutrino component of about 0.5%. This signal contamination, to be precisely measured by the near detector, could be used to measure the electron neutrino cross-sections with water (as the target used by the far detector) at the energies relevant to this project and not yet measured.

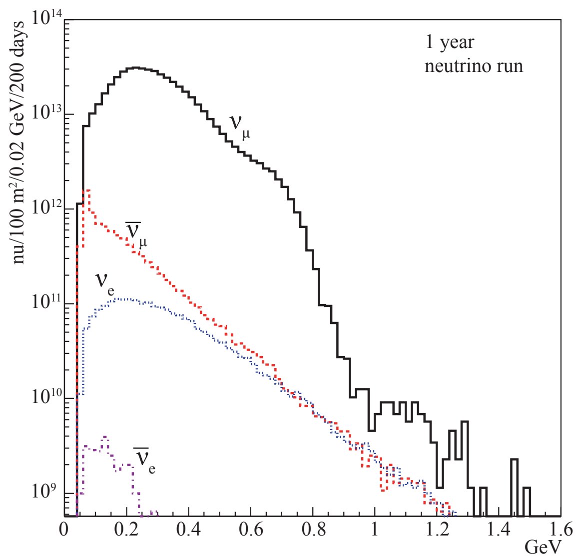

Figure 3: Neutrino energy distribution at an arbitrary distance of 100 km on–axis from the target station, for 2.5 GeV protons and positive horn current polarity.

Fig. 4 [10] summarises the physics performance of the proposed facility to discover CP violation in the leptonic sector. It presents the discovery significance as a function of the CP violation parameter δ_{CP}. Two baselines have been used corresponding to the two candidate mines, Zinkgruvan and Garpenberg. For about 60% of the values of δ_{CP} more than 5σ confidence level is obtained after 10-years data taking for both baselines. At this level, the statistical uncertainty still dominates the systematic errors. In case CP violation is not discovered after the first ten years or if more precision on δ_{CP} is needed, more data can be taken without necessitating further upgrades of the facility. For these studies the systematic errors reported in [11] have been used. For the signal 5% systematic error has been considered.

TOWARDS A MUON FACILITY

Together with the neutrino production muons are also produced with about the same amount [12]. More than 10^{20} muons could be collected per year. These muons, having a mean energy of about 0.5 GeV, could be extracted at the level of the beam dump and used by other projects as a low energy νSTORM [13] for neutrino cross-section measurements and sterile neutrino studies. The same muons can also be used by a Neutrino Factory in case high precision is needed on neutrino oscillation parameters.

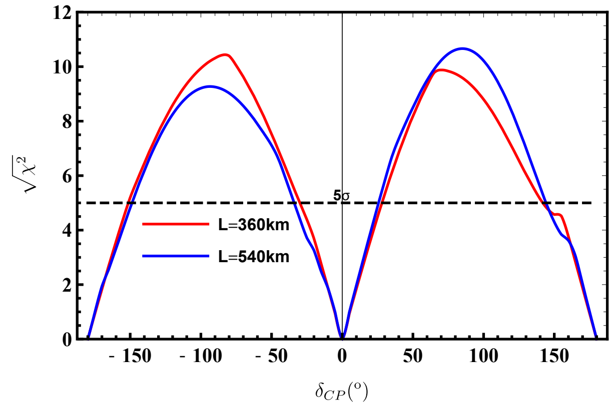

Figure 4: CP violation discovery significance versus δ_{CP} for two baselines, 360 km and 540 km corresponding to the two active mines Zinkgruvan and Garpenberg, respectively.

In a second stage, the ESS muons could be used to feed a muon collider which can be used in a first phase as a Higgs Factory. It has been shown recently that about 200k Higgs bosons can be produced per year and per interaction point, enough to well study this Standard Model particle [14]. These very "clean" events can be used to well study the Higgs boson and search for new physics beyond the Standard Model.

CONCLUSION

The ESS neutron facility is now well under construction and will be ready in 2023. An upgrade to a neutrino facility is proposed using the very powerful proton linac. This unprecedented proton power allows to operate the neutrino facility on the second oscillation maximum, position more sensitive to matter-antimatter asymmetry and less sensitive to systematic errors than for the first oscillation maximum.

A Design Study, ESSνSB, supported by EU has started since beginning of 2018 and will last for four years. During this feasibility phase the modifications of the ESS linac will be studied. These studies also include the addition of an accumulation ring to compress the ESS proton pulses to less than 1.5 µs, a neutrino target station and the corresponding near and far detectors. This period will be followed by a Technical Design Report preparation.

The expected physics performance is very high, covering after 10 years data taking about 60% of the CP violation parameter δ_{CP}. This performance can be increased by just extending the data taking period.

A second upgrade could transform the neutrino facility to a muon facility for neutrino studies or/and going towards a muon collider.

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