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# ESSvSB: A NEW FACILITY CONCEPT FOR THE PRODUCTION OF VERY INTENSE NEUTRINO BEAMS IN EUROPE

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## Abstract

A new project for the production of a very intense neutrino beam has arisen to enable the discovery of leptonic CP violation and neutrino mass hierarchy. This facility will use the proton linac of the European Spallation Source (ESS) in Lund to deliver the neutrino super beam. The ESS linac is expected to be fully operational at 5 MW power by 2022, producing 2 GeV and 2.86 ms long proton pulses at a rate of 14 Hz. An upgrade of the mean power to 10 MW and a frequency of 28 Hz, in which half is for the neutron beam, is necessary for the production of the neutrino beam. The primary proton beam-line completing the linac will consist of switchyards and accumulator rings. The secondary beam-line producing neutrinos will consist of a four-horn/target station, decay tunnel and beam dump. To detect the produced neutrinos a far megaton scale Water Cherenkov detector will be placed at a baseline of about 500 km in one of the existing mines in Sweden. The elements of the primary and secondary beam-lines and all the possible scenarios impacting the design of the ESSvSB facility as well as the safety issues due to the high irradiation produced are presented and discussed in this paper.

## INTRODUCTION

The ESSvSB (standing for European Spallation Source Neutrino Super Beam) project succeeds the studies made by the FP7 Design Study EUROv [1 - 3], regarding future neutrino facilities. ESSvSB [4] proposes to study a Super Beam which uses the high power linac (2.0 GeV protons, 5 MW) of the ESS [5] at Lund in Sweden as proton driver and with a MEMPHYS type detector [6, 7] located in a deep mine at a distance between 300 km to 600 km, near the second neutrino oscillation maximum.

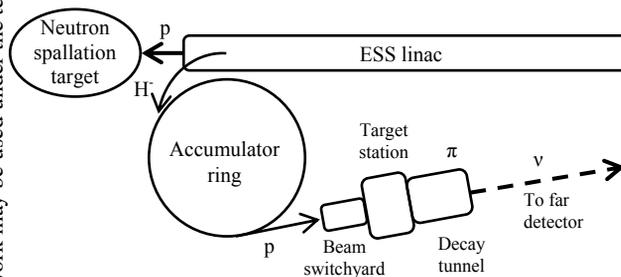


Figure 1: ESSvSB layout.

The aim is to use the ESS proton driver simultaneously for neutron and neutrino applications with no reduction in the spallation neutron production, thus decreasing considerably the cost of the proposed project as compared to constructing a dedicated proton driver (Fig.1).

In a second stage, the Neutrino Factory (NF) [8], considered as the ultimate neutrino facility, could benefit of this proton driver and technical developments. The 2.86 ms long pulses of the ESS linac would need to be reduced to a few  $\mu$ s long pulses allowing a limitation of the length of the very high current pulse in the hadronic collector (horn) producing severe heat dissipation problems. In order to do so,  $H^-$  ions have to be accelerated in the linac and injected in a proton accumulator ring to be designed for this application. Detailed studies will be made on the modifications of the ESS proton linac required to allow simultaneous acceleration of  $H^+$  and  $H^-$  ions at an average power of 5+5 MW.

An important part of the study is to evaluate through simulations the optimal distance of the far detector from the neutrino source. Once the result of this optimization has been made, the mine in Sweden that is at a distance closest to the optimum will be investigated in detail in order to find the best position in the mine to excavate the MEMPHYS underground halls. ESSvSB will profit from the studies already performed in the framework of the FP7 LAGUNA Design Study [9].

## THE ESS LINAC

ESS will be a major user facility providing slow neutrons for research laboratories and industry. A first proton beam for neutron production will be delivered at reduced energy and power by 2019. A proton beam of the full design power 5 MW and energy 2.0 GeV will be delivered by 2022 (Table 1). There will be 14 pulses of 62.5 mA current and 2.86 ms length per second. In order for the ESS to be used to generate a neutrino beam in parallel with the spallation neutrons, some modifications of the proton linac are necessary.

The proposed plan for simultaneous  $H^-$  acceleration is to have one 2.86 ms long 62.5 mA  $H^-$  pulse accelerated in the 71.4 ms long gap between the proton ( $H^+$ ) pulses, requiring the linac pulse frequency of 14 Hz to be raised to 28 Hz. The radiofrequency (RF) is 352.2 MHz in the first low energy spoke cavity section of the ESS linac and 704.4 MHz in the second high energy elliptical cavity section. This implies that the RF phase of the second section would have to be dynamically shifted back and forth between the  $H^+$  and  $H^-$  pulses. An  $H^-$  source will

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have to be added to the  $H^+$  source. The possibility to use  $H^-$  for both applications, neutrons and neutrinos, is also investigated.

Table 1: Main ESS facility parameters

Parameter	Value
Average beam power	5 MW
Proton kinetic energy	2.0 GeV
Average macro-pulse current	62.5 mA
Macro-pulse length	2.86 ms
Pulse repetition rate	14 Hz
Max. accelerating cavity surface field	45 MV/m
Max. linac length	352.5 m
Annual operating period	5000 h
Reliability	95%

A duplication of the very low energy part of the linac will be needed probably up to some point downstream of the Radio Frequency Quadrupole (RFQ). The whole acceleration process of the  $H^-$  beam will be studied using simulations.

To avoid beam spillage at the injection into the ring and during RF capture, one needs to introduce a gap in the train of bunches using a high speed chopper. Because of this chopping, the  $H^-$  beam pulse will have spectral components within a few 10 MHz of the nominal frequencies and the generated harmonics may excite Higher Order Modes (HOMs) in the accelerating cavities. These HOMs will be simulated in detail to determine an acceptable chopping scheme. A careful collimation and shielding design, based on simulations, will be made with the aim to minimize beam losses. The average power of the linac will have to be doubled from 5 MW to 10 MW, requiring a corresponding doubling of the average output power from the RF sources.

The effect of doubling the average linac power on the cooling of the cavities, of the power couplers and of the cryo-modules, will be studied. A prototype 352 MHz spoke cavity for the ESS linac will be tested at Uppsala University in Sweden already as from July 2014 in a cryostat at 14 Hz pulse frequency and at the full instantaneous power required for ESS proton acceleration, which is 350 kW.

## THE ACCUMULATOR RING

A first study of a 318 m circumference accumulator ring to compress the pulses has already been made in the EUROv Super Beam project. This study will be continued in ESSvSB. Each pulse from the ESS linac will contain  $1.1 \cdot 10^{15}$  protons, which for a normalized beam emittance (95%) of 100-mm-mrad in the ring by multi-turn injection (the emittance from the linac should be in the order of a few mm-mrad) will lead to the very large space-charge tune shift of about 0.75. A way to reduce the tune shift is to divide the ring up on 4 superposed rings located in the same tunnel, each ring receiving 1/4 of the bunches during the multi-turn injection. This will lead to a reduction of the tune shift to the level of around 0.2, which is acceptable for the 2.86 ms storage time.

The lattices and collimators of a single ring accumulator and of a four rings accumulator will be designed. These designs will be used for simulations of the accumulation process in which high order momentum compaction factor will be taken into account, in order to evaluate collective effects and to develop optimization and correction schemes.

Four separate targets are needed in order to mitigate the high power dissipation in the target material. Each of the four beams from the four accumulator rings will be led to one of the targets. Within EUROv, a beam distribution system downstream of a single accumulator ring to four target stations has already been studied [3]. For ESSvSB a similar system will be studied for the distribution of the beam from the linac to the four rings.

The  $H^-$  ions will be fully stripped at injection into the accumulator using a laser-stripping device. The extraction of the beam from the ring needs a group of kickers that should have a rise time of not more than 100 ns.

## THE TARGET STATION

The target station includes the target itself that is hit by the protons leading to the production of short-lived mesons, mainly pions, which decay producing muons and muon neutrinos. Following the EUROv studies, a packed bed of titanium spheres cooled with cold helium gas has become the baseline target design for a Super Beam based on a 2-5 GeV proton beam with a power of up to 1 MW per target. The packed bed concept has been studied using Computation Fluid Dynamics (CFD) software tools.

However, the flow regime is complex and it is necessary to carry out prototype measurements in order to test the concept and gain confidence in the design. An experimental program is planned using an induction heater power supply to generate heating of the individual spheres. A short but representative length of the target proposed will be produced for the tests. A well instrumented helium flow loop will be constructed to cool this target. The individual target spheres and container walls will be instrumented in order to measure both the effect of the heating and the cooling efficiency and make comparisons with the CFD model.

Other main components of the target station are the hadron collector called magnetic horn, which focuses the hadrons towards the far neutrino detector, and the decay tunnel, long enough to allow the mesons to decay, but not as long as to allow for a significant amount of the muons to decay. In order to mitigate the detrimental effects of the very high power of the proton beam hitting the target, EUROv [1, 2] has proposed a system with four targets and horns, sharing the full beam power between the four. This system will be adopted here.

## UNDERGROUND DETECTOR SITE

Two mines are currently under investigations to host the large underground Water Cherenkov detector: the Northern Garpenberg mine at 540 km NW of the ESS site

in Lund and the Zinkgruvan mine at 360 km at the northern tip of lake Vättern in Sweden.

Preliminary simulation results indicate that the performance for CP violation discovery with a 2.0 GeV proton energy beam is somewhat better with the base line 360 km of the Zinkgruvan mine than with the 540 km base line of the Garpenberg mine. A possible option would be to accelerate the beam in the linac from 2.0 GeV to 3 GeV (empty space is foreseen in the linac for future upgrades) for which energy the CP performance with these two baselines is about equivalent and somewhat better than with 2.0 GeV proton energy and the 360 km baseline. However, in view of the possibility that the proton energy will be 2.0 GeV, preliminary studies of the conditions will be also performed for detector installation and operation at the Zinkgruvan mine.

The selected mine will then be studied in further detail collecting geological and rock mechanics information at potential detector locations, situated at 1000 m depth (3000 m water equivalent) and at least 500 m from locations with active mining operations, by making core drillings, core logging, rock strength testing and rock stress measurements of the surrounding rock.

Once a suitable location for the neutrino detector underground halls has been determined, which should have a total volume of  $6 \cdot 10^5 \text{ m}^3$ , a design of the geometry and construction methods for the underground halls will be made based on the measured strength and stress parameters of the rock.

As detector for the appearing electron neutrinos, it is proposed to use a large water tank Cherenkov detector. Although the MEMPHYS detector has been extensively studied by LAGUNA, readjustments of the shape of the detector volumes will be made according to the rock quality at the chosen location. The effect of these readjustments on the detector efficiency will be evaluated and integrated in the whole physics performance evaluation of the project.

## PHYSICS PERFORMANCE

An important parameter to be determined is the optimal neutrino beam baseline, given the parameters of the achievable neutrino beam. The simulation software developed by the EUROv project has already been used to make first evaluations of the potential for leptonic CP violation and neutrino mass hierarchy discoveries. In particular, the fraction of the full CP violation phase range within which CP violation and neutrino mass hierarchy can be discovered, at different baselines, has been computed [4].

According to these first evaluations, for which 5% systematic error on the signal and 10% systematic error on the background were assumed, leptonic CP violation could be discovered at  $5 \sigma$  confidence level within at least 50% of the CP phase range for baselines in the range 300-550 km with an optimum of about 58% of the phase range at a baseline of about 420 km, already a very competitive physics performance [10]. According to the same first evaluations, the neutrino mass hierarchy can be

determined at more than  $3 \sigma$  confidence level for baselines in the range 300–500 km depending on the proton beam energy. In addition, inclusion of data from atmospheric neutrino oscillations in the mass hierarchy determination will certainly improve the physics reach of this project. For these first evaluations, the target, horn and decay tunnel parameters have been optimized for the ESS proton driver energy of 2.5 GeV taking into account future linac upgrades.

The study and optimization of the physics performance will be continued using the new input parameters resulting from the Super Beam component simulations and prototype tests and improvements of the physics simulation software.

## ACKNOWLEDGMENTS

We are indebted to the European Spallation Source AB, CERN and Uppsala University for the support we have received. We would also like to thank P. Coloma and E. Fernandez for all physics calculations.

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