ESSnuSB PROJECT TO PRODUCE INTENSE BEAMS OF NEUTRINOS AND MUONS

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Abstract

A new project for the production of a very intense neutrino beam has arisen to enable the discovery of a leptonic CP violation. This facility will use the world's most intense pulsed spallation neutron source, the European Spallation Source (ESS) under construction in Lund. Its linac is expected to be fully operational at 5 MW power by 2023, using 2 GeV protons. In addition to the neutrinos, the ESSnuSB proposed facility will produce a copious number of muons at the same time. These muons also could be used by a future Neutrino Factory to study a possible CP violation in the leptonic sector and neutrino cross-sections. They could be used as well by a muon collider or a low energy nuSTORM. The layout of such a facility, consisting in the upgrade of the linac, the use of an accumulator ring, a target/horn system and a megaton Water Cherenkov neutrino detector, is presented. The physics potential is also described.

ESSνSB PROJECT

The ESSνSB (standing for European Spallation Source Neutrino Super Beam) project proposes to study a Super Beam which uses the high power linac of the ESS facility [1] based at Lund in Sweden as a proton driver and a MEMPHYS type detector [2, 3] located in a deep mine at a distance of about 500 km, near the second neutrino oscillation maximum (Fig. 1).

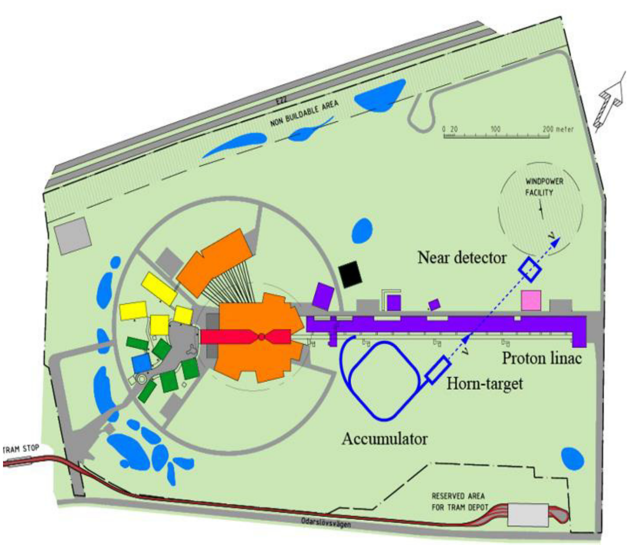

Figure 1: ESSνSB layout on top of the ESS facility.

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The ESS Linac

ESS will deliver a first proton beam for neutron production 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 2023. There will be 14 pulses of 62.5 mA current and 2.86 ms length per second (Table 1). 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. A preliminary study of these modifications that are required to allow simultaneous acceleration of H^+ (for neutron production) and H^- (for neutrinos) ions at an average power of 5 + 5 MW has been made [4].

Table 1µ Main ESS Facility Parameters [1]

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. acc. cavity surface field	45 MV/m
Max. linac length	352.5 m
Annual operating period	5000 h
Reliability	95%

The Accumulator Ring and Beam Switchyard

An accumulator ring to compress the pulses to few µs is mandatory to avoid overheating issues of the neutrino targets. A first estimation gives a ring having a circumference of 376 m [5] (Table 2). Each pulse from the ESS linac will contain 1.1×10^{15} protons, which for a normalized beam emittance of 200 π 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 space-charge tune shift of about 0.75.

Table 2: Accumulator Parameters [5]

Parameter	Value
Circumference	376 m
Number of dipoles	64
Number of quadrupoles	84
Bending radius	14.6 m
Injection region	12.5 m
Revolution time	1.32 µs

The H^- ions will be fully stripped during the injection into the accumulator using either stripping foils or a laser-stripping device [5, 6]. 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.

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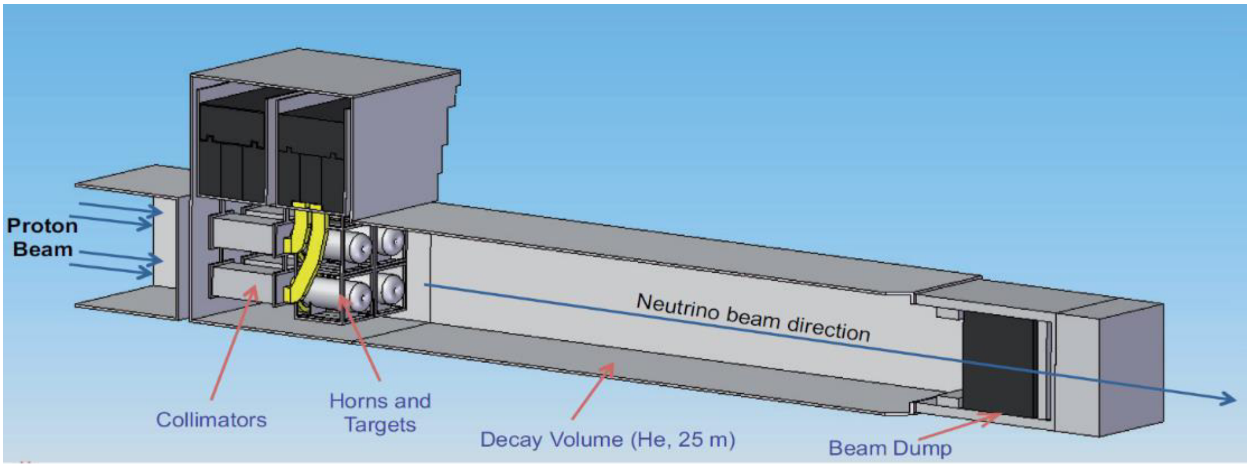

Figure 2: Schematic view of the target/horn station [7].

Four separate targets are needed in order to mitigate the high power dissipation in the target material. A beam switchyard system downstream the accumulator ring will distribute the protons onto the targets [8] (Figs. 2,3).

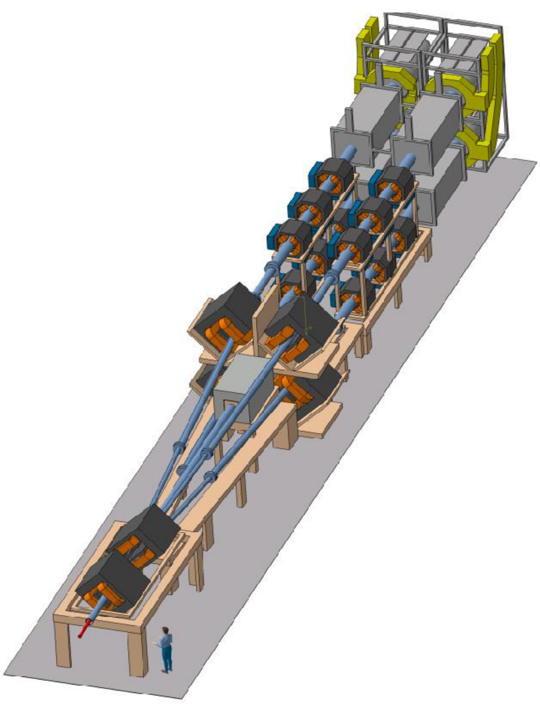

Figure 3: Beam switchyard.

The Horn/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 produce muons and muon neutrinos. A packed bed of titanium spheres cooled with pressurized 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 1.2 MW per target. The packed bed concept has been studied using Computation Fluid Dynamics (CFD) software tools [7].

Other main components of the target station are the hadron collectors called magnetic horns (Fig. 4), which focuses the hadrons towards 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, EUROν [7] has proposed a system with four targets and horns, sharing the full beam power between the four. This system will be adopted here.

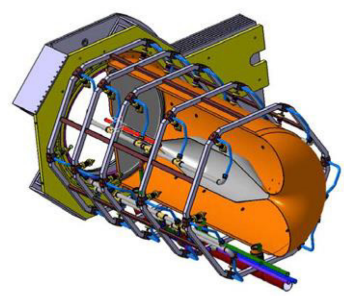

Figure 4: Horn layout (the target is inside).

Underground Detector Site

The Northern Garpenberg mine, located at 540 km NW of the ESS site in Lund in Sweden, is one of the candidate mines that could host the large underground Water Cherenkov detector. This mine is being studied in 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 (total volume of $6x10^5$ 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.

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PHYSICS POTENTIAL

According to first evaluations [9], 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 σ 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 σ 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.

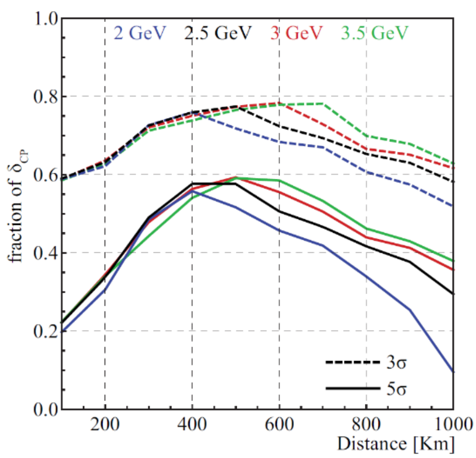

Figure 5: The fraction of the full CP range as function of the baseline. The lower (upper) curves are for CP violation discovery at 5 σ (3 σ) significance.

Figure 5 presents the CP fraction coverage versus the distance to the far detector for 3 σ and 5 σ confidence level. To estimate this performance several proton energies have been used on top of the default one of 2 GeV since it is possible to upgrade the linac to deliver higher energy protons.

MUON PRODUCTION

In addition to the neutrinos, the ESSnuSB proposed facility will produce a copious number of muons at the same time. 2.7×10^{23} protons are foreseen to hit the targets within one-year operation. Preliminary studies show that 3.5×10^{20} pions and 4.2×10^{22} muons, per m^2 and per year will be available at the level of the beam dump which is located 25 m after the horn-target system [11, 12]. Figure 6 presents the impacts of remaining pions and produced muons at the surface of the beam dump.

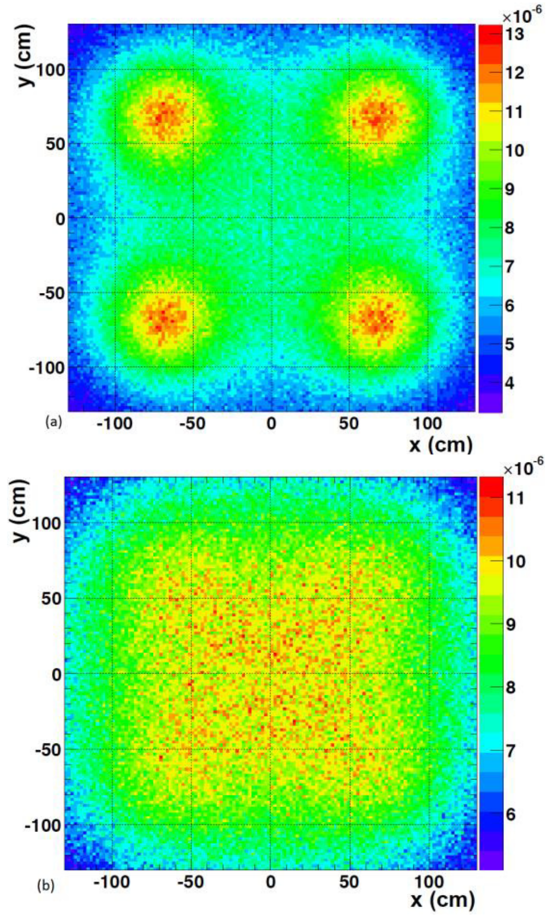

Figure 6: Pions (a) and muons (b) at the surface of the beam dump (normalized by proton).

The produced muons could be used by a low energy nuSTORM [13] facility to measure neutrino cross-sections at the energies where this neutrino facility will be operated. They could also be useful for 6D muon cooling experiments and in an ultimate stage they could be used to operate a Neutrino Facility or a muon collider.

The mean value of the momentum of pions and muons is 0.7 GeV and 0.46 GeV, respectively (Fig. 7). For these energies, the mean free path of pions is of the order of 40 m after which they will decay to give some more muons. The mean free path for the muons is 2.9 km which is enough to send them in a ring, as the one foreseen for nuSTORM, where they can decay in straight sections to produce muon and electron neutrinos to be used to measure cross-sections.

Table 3: Magnetic Rigidity for Protons, Pions and Muons

Particle	<Ek> (GeV)	Bσ (T.m)
Protons	2.0	9.28
Pions π^+, π^-	0.7	2.76
Muons μ^+, μ^-	0.46	1.85

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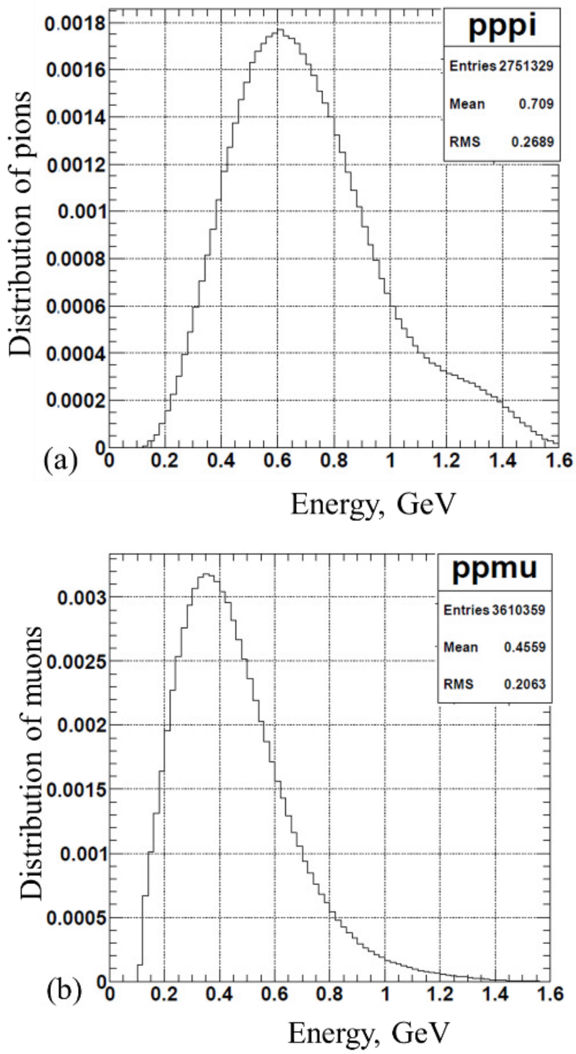

Figure 7: Momentum distribution: pions (a); muons (b).

While for nuSTORM muon beam an iron absorber is needed to lower the muon momentum to a mean value of 400 MeV in order to perform 6D muon cooling experiments (of which success could lead to the construction of a Neutrino Factory and of a muon collider), for ESSnuSB the muon momentum is directly around the required values. nuSTORM plans to collect in the region between 200 MeV/c and 500 MeV/c about 4.3×10^{17} muons per year while the ESSnuSB facility could provide more than 2.5×10^{20} muons per year for the same momentum range.

MUON EXTRACTION

As shown previously in Fig. 6, four spots induced by the four targets and horns are visible for the pion distribution while for the muons coming from the pion decays these spots are more diluted. The majority of these particles is concentrated over a surface of 2x2 m^2 which constitutes a difficulty for their extraction and injection in a beam pipe.

Several configurations are currently under studies to extract these particles. One of them consists in moving further back in the tunnel the beam dump and placing absorbers with the aim of absorbing the protons and some of the remaining pions. The muons would be then collimated, with some remaining pions, and deflected using bending magnets (Fig. 8).

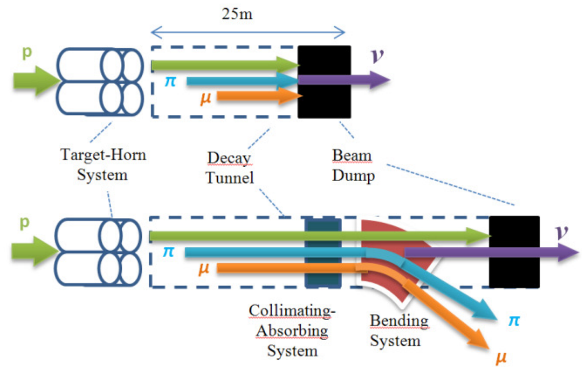

Figure 8: Principle of muon extraction.

From the particle kinetic energies, the magnetic rigidity is estimated to be 2.76 T.m and 1.85 T.m for the pions and the muons respectively (Table 3). As an example, the deflection of the muons of an angle of 175 mrad (10°) with respect to the proton beam axis would need an induced magnetic field of 0.25 T. In the meanwhile, the remaining pions would also be deflected by 117 mrad. The angle of divergence of the pions and muons, which mainly depends on their kinetic energy, is needed to properly design the absorbers. The characteristics of these secondary beams have to be carefully defined in order to estimate the impact on the bending system.

Moreover, such a system is supposed to be protected from any particle interactions to avoid radiation issues and also it has to be accessible for any maintenance operation in case of failure.

Estimations of the losses during the absorption process will also help in determining if the deflection of the particles produced by a single horn-target (instead of the 4) would be sufficient for the facilities which are located downstream. The focussing of these particles will be done out of the tunnel once the deflection process is achieved.

ACKNOWLEDGMENT

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