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DESIGN STATUS OF THE BEAM SWITCHYARD FOR ESSνSB

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On behalf of the ESSνSB project

Abstract

The ESSνSB project, recently granted by the EU H2020 programme for a 4-year design study, proposes to use the proton linac (2 GeV, 5 MW) of the European Spallation Source (ESS) currently in construction in Lund (Sweden) to deliver a neutrino super beam. One of the work packages of this design study concerns the primary proton beam-line completing the linac. It will mainly consist of an accumulator ring and of a switchyard to distribute the protons onto a 4-target station. This paper presents the objectives of this work package and the status of the design of the switchyard system.

THE ESSνSB PROJECT

ESSνSB (standing for European Spallation Source Neutrino Super Beam) has been granted for 4 years under the H2020 European framework and started in January 2018. Its aim is to study the feasibility and design a European Super Beam facility based on the ESS proton linac to measure, for the first time, the CP-violating phase in the leptonic sector. This study will also take care to preserve the possibility of adding new facilities to the proposed one as potential next generation upgrades guided by new physics results and scientific needs. These upgrades could be, for example, for projects on sterile neutrino searches, neutrino cross-section measurements and muon cooling tests for a future muon collider. In addition, in case this is needed, a Neutrino Factory could be envisaged using the large number of muons produced together with the muon neutrinos by the Super Beam facility. The main components of ESSνSB are:

Proton Driver (ESS linac)

The under construction ESS linac gives an excellent opportunity to provide H^- ion acceleration for the production of a uniquely high intensity neutrino beam interleaved simultaneously with proton acceleration for spallation neutron production. In the current design, the ESS linac will 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 (Table 1). The proposed plan for simultaneous H^- and proton acceleration is to increase (e.g., double) the repetition rate.

Accumulator Ring

It will be important to generate neutrino pulses that are as short as possible in order to minimise the length of the high-current pulse that needs to be sent to the hadronic collector (see below) and also limit the background from cosmic rays. The 2.86 ms long pulses from the ESS linac need to be compressed by about three orders of magnitude. This will be achieved using a ~400 m circumference accumulator ring. The lattice of the accumulator ring including collimators will be designed and used for simulations. The beam transfer line from the linac to the accumulator, the multi-turn injection, including the H^- stripping system, the extraction kicker and the beam switchyard that will split the beam up on to 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.

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Table 1: Beam Parameters for ESSνSB [1]

Parameter	Value
Particle	H^-
Proton kinetic energy (GeV)	2.0
Pulse intensity (mA)	62.5
Avg beam power (MW)	5
Beam rigidity (Tm)	11.02
Macro-pulse length (linac) (ms)	0.715
Pulse length (accu.) (μs)	1.5
Pulse repetition rate (Hz)	14

Target Station

The Target Station includes the proton target itself, the hadron collector, the decay tunnel and the beam dump. A challenging component of this project is the enormous target heat-load generated by the 5 MW proton beam. In order to reduce this heat-load there will be four targets, which will be hit in sequence by the compressed proton pulses, thereby reducing the beam power on each target to 1.25 MW. Following the EUROν studies [1,2], a packed bed of titanium spheres cooled with helium gas has become the baseline target design for a Super Beam based on a 2 GeV proton beam. The hadron collection will be performed by four hadron collectors (magnetic horns), one for each target. Each of these target/hadron-collector assemblies will receive proton pulses three times more frequently than in present projects, and by an average beam power of 1.25 MW, which is twice as high as in present neutrino projects.

Near and Far Detectors

A detector, located close to the neutrino production point, is needed to measure and monitor the neutrino beam flux but also, very importantly, to measure neutrino cross-sections in the energy range of interest and, thereby, to reduce significantly the systematic uncertainties related to the neutrino flux. The relatively low neutrino energy and high flux impose challenges on the design parameters of this detector that will be studied in detail. A far detector

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will be located within the range 350-550 km from the ESS site. A mine at Garpenberg (540 km) looks very promising in terms of geology, logistics and industrial/regional engagement to host this detector. A memorandum of understanding (MoU) has already been signed with the mine owners and preliminary civil engineering reports are favourable. The far detector itself will be of the type already studied in the LAGUNA Design Study – megaton scale Water Cherenkov detector, called MEMPHYS.

BEAM PULSE LENGTH REDUCTION

The accumulator and the BSY (beam switchyard) represent an entire work package of the project. The objectives of this WP are:

- Study of the accumulator operation scheme.
- Design of the ring, its transfer line and its extraction kicker.
- Study the stripping of H^-.
- Design of the ejection switchyard.

The high charge of the beam pulse injected in the accumulator makes it necessary to split the 2.86 ms linac pulse into shorter pulses making the linac and the accumulator work at a higher frequency.

Preliminary investigations were done on the design of the accumulator [3]. First calculations give a ring having a circumference of 376 m (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 [3]

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

Following this first result, a design of the accumulator lattice, including in particular the injection optics, has been made. This design will be used for simulations of the accumulation process in order to evaluate collective effects and to develop lattice optimization and correction schemes.

The location of the underground accumulator needs to be studied in detail, taking into account the space constraints on the ESS site. Its position will in turn constrain the design of the transfer line from the linac which has to fulfil several requirements regarding its curvature, to limit H^- beam loss, its optics and its branch point from the linac.

The H^- ions need to be fully stripped during the injection into the accumulator. A foil stripping solution has been calculated [3]; this solution can be used at an initial phase of the accumulator operation. This will be used for the present simulations. Laser stripping studies are on-going at BNL and would be the preferred solution. Similar lattice structure can be used for both options (foil or laser-striping) adapting the optics; this is the option we will develop. An empty space in the bunch train will be provided in the linac by chopping the beam regularly according to the circumference of the accumulator to enable multi–turn injection. The extraction of the beam from the ring needs a group of kickers which should have a rise time of not more than 100 ns. The multi–turn injection process, the stripping system and the extraction system (including kickers and septum magnet) will be developed using simulations.

BEAM ONTO TARGET STATION

Four separate targets are needed in order to mitigate the high-power dissipation in the target material. A beam distribution system downstream of the accumulator ring to four target stations is necessary. The feasibility of such system was preliminarily investigated within EUROν project and will be improved for ESSνSB [4].

The final design of the BSY will mainly depends on the parameters such as transverse emittances, beta functions, beam shape, beam size and momentum dispersion of the proton beam exiting the accumulator ring. Indeed, these parameters will allow the design of the optical elements (kickers, quadrupoles and dipoles) that will constitute the beam switchyard to distribute and focus the protons onto the targets according to the requirements. The technology, the dimensions of the magnets and the length of the switchyard will be defined.

Current Layout

Figure 1 presents the principle of operation of the BSY that will need to be updated for the ESSνSB project.

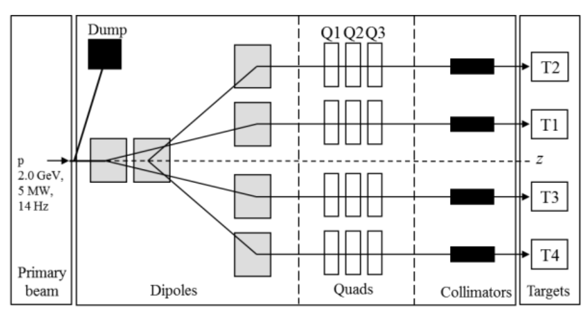

Figure 1: Principle of the BSY.

The beam is deflected diagonally onto the target axes (T1, T2, T3 and T4) using two bipolar magnetic dipoles. A total of 12 quadrupoles are necessary to focus the protons onto the target station. The maximum B-field needed by the 2 m long dipoles is calculated to be 0.65 T (25.7 kA turns per pole).

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The beam envelopes and the emittances are investigated using the code TraceWin [5]. The maximum size of the beam envelope is estimated to be 160 mm (y axis in the 2nd quadrupole), which represents 80% of the total aperture of the quadrupoles (Fig. 2).

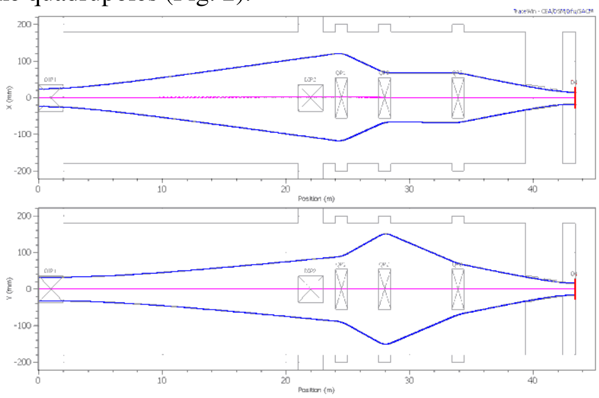

Figure 2: Beam envelopes (4σ) – T1 axis.

The quadrupoles are 1 m long (200 mm aperture). Their field gradients are presented in Table 2. The total length of the BSY is estimated to be 43.4 m.

Table 2: Field Gradients and Intensities

Quadrupole	Q1	Q2	Q3
Field gradient, T/m	1.9	-2.4	1.1
Intensity, NI per pole, kA	30.8	39.0	17.8

The plots of the beam output phase-space confirm that the proton beam meets the requirements once at the target with Xmax and Ymax equals to 14.92 mm and to 14.93 mm respectively (Fig. 3).

A beam dump, made of graphite-cast iron and water cooled, is foreseen before the pair of bipolar magnets to be able to stop a beam power of 71.4 kW (one pulse of protons).

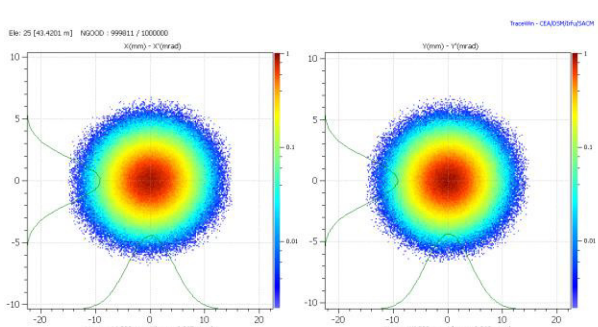

Figure 3: Beam output phase-space distributions in (*x, x'*) and (*y, y'*); T1-T3 beam lines.

Beam Parameter Definition

The normalised rms transverse emittances of the beam extracted from the ESS linac are foreseen to be 0.33 µm. Therefore, transverse emittance at the exit of the accumulator will be much larger than the one at the end of the ESS linac. This is due to charge exchange the during the injection process. Current studies suggest the emittance of the beam coming from the accumulator to be of several tenths of µm [3]. In the following, the normalised transverse emittance of the proton beam are assumed to be 225 µm (99.7%) and the rms momentum dispersion 0.1%. The required beam size at the target station is 4 mm rms.

Ongoing Investigations

Thorough investigations are currently being performed. These investigations concern the impact of any eventual fluctuations of one of the physical parameters involved in the transport of the proton beam along the BSY. These parameters are the magnetic fields of the optical elements, the size and the position of the beam and the energy. The design of the dipoles and quadrupoles composing the beam lines are also under investigation. The feasibility of the power supply units of these elements has to be evaluated and confirmed.

Additional beam instruments (monitors, diagnostics and steerers) is foreseen all along the beam lines and their dimensions have to be carefully estimated.

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