ACCUMULATOR-TO-TARGET BEAM TRANSFER LINE FOR ESSνSB+

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Abstract

The ESSnuSB project aims to generate an intense neutrino beam and the associated muon flux, using a 5 MW high-power proton driver, requiring precise and reliable transport of the accumulated beam to the target station. To achieve this, a dedicated transfer line, named R2T, guides the extracted protons from the accumulator toward the neutrino beam direction while meeting strict geometric constraints. The beam transfer line accommodates horizontal and vertical angular offsets of 16.8° and 1.14° using a compact sequence of horizontal and vertical dipoles, with quadrupoles ensuring controlled beam size and minimal losses. Simulations show that a lattice just over one hundred meters long successfully preserves beam quality and aligns the beam with the required neutrino direction. This guarantees stable, low-loss delivery of the beam to the downstream target system.

THE ESS NEUTRINO SUPER BEAM PROJECT

Understanding the origin of the matter-antimatter asymmetry in the Universe remains one of the most fundamental open questions in modern physics. A compelling explanation requires physics beyond the Standard Model, in particular the existence of Charge-Parity Violation (CPV) in the leptonic sector. The experimental discovery and precise measurement of leptonic CPV would have profound implications for particle physics and cosmology. However, such measurements are extremely challenging due to the weak interaction of neutrinos with matter, which necessitates the use of very intense neutrino beams and large-scale detectors.

The ESSνSB (European Spallation Source neutrino Super Beam) project has been proposed to address this challenge by exploiting the unique capabilities of the European Spallation Source (ESS) linear accelerator [1]. The ESS linac, currently under construction, will deliver a 5 MW proton beam at 2 GeV for neutron production [2]. ESSνSB proposes to upgrade this facility to simultaneously generate an intense neutrino beam by increasing the duty cycle from 4% to 8%, achieved through a doubling of the pulse repetition rate. The concept further relies on the acceleration of H^- ions and the use of an accumulator ring to compress the proton pulse length from 3 ms to 1.2 μs, making it compatible with the operation of a magnetic horn system.

To address the extreme thermal and mechanical stresses induced by such high power and short pulses on the neutrino production target, the beam is distributed over four sequential targets, each equipped with a focusing horn. The facility design also includes a near detector for precise characterization of the neutrino beam and a far Water Cherenkov detector located at a baseline optimized for oscillation studies.

The Conceptual Design Report of ESSνSB has demonstrated the feasibility of the proposed facility and its outstanding physics potential [1]. In particular, the experiment is designed to operate at the second oscillation maximum, where sensitivity to CP violation is significantly enhanced compared to the first maximum. This approach allows for a substantial reduction in the impact of systematic uncertainties, especially those related to neutrino–nucleus cross-sections, which currently represent a major limitation due to the scarcity of data in the relevant energy range (0.2-0.6 GeV).

Based on these results, the ESSνSB+ Design Study aims to further develop and consolidate the project in preparation for submission to the ESFRI roadmap. This extended program includes civil engineering and site studies, as well as the development of complementary facilities for precise cross-section measurements and sterile neutrino searches, and a monitored neutrino beam inspired by the ENUBET concept [3]. These additional infrastructures will play a crucial role in reducing systematic uncertainties and broadening the scientific reach of the project.

Beyond its primary scientific goals, ESSνSB represents a major opportunity to extend the use of a leading European research infrastructure into the domain of fundamental physics. The project is expected to drive technological innovation, stimulate industrial development, and strengthen Europe's position at the forefront of neutrino research.

MAIN COMPONENTS OF THE FACILITY

The ESSνSB facility is based on four main components: the proton driver, an accumulator ring, the neutrino target station, and the near and far detectors (Fig.1).

Proton Driver (ESS Linac): The ESS linac will accelerate protons to 2 GeV in 3 ms pulses at 62.5 mA and 14 Hz for neutron production. Its low duty cycle (4%) allows interleaved H^- pulses, which are used to generate a high-intensity neutrino beam.

Accumulator Ring: To efficiently operate the hadronic focusing system, it is necessary to deliver extremely short and intense proton pulses. The 3 ms pulses from the linac must therefore be compressed by approximately three orders of magnitude. This is achieved using an accumulator ring with a circumference of about 400 m, where the beam is accumulated and rapidly extracted, resulting in pulse lengths of the order of 1 μs.

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Target Station: The station includes the target, horn, decay tunnel, and beam dump. To manage the 5 MW beam power, the load is distributed over four target–horn systems operated sequentially (~1.25 MW per target).

Near and Far Detectors: A near detector monitors the neutrino flux, while a far detector (~538 kt), located at the second oscillation maximum, and ensures sufficient statistics. A Water Cherenkov design is retained for its proven performance at low energy.

The extended ESSνSB+ program includes, in addition to civil engineering and licensing studies, the following developments: **Reduced-power target station:** A single target–horn system will be used to feed both the Low Energy nuSTORM and the Low Energy Monitored Neutrino Beam (LEMNB) facilities with pions and muons. This requires the implementation of dedicated pion and muon extraction systems, as well as potential re-optimization of the horn geometry. **Low Energy nuSTORM racetrack ring:** A muon storage ring will be designed to produce well-characterized neutrino beams from muon decays, enabling precision cross-section measurements and searches for sterile neutrinos. **Low Energy Monitored Neutrino Beam (LEMNB):** A monitored neutrino beam using tagged neutrinos, based on either long linac pulses or compressed pulses. **Detectors:** Studies will assess the feasibility of using the ESSνSB near detector as a far detector for LEnuSTORM, potentially with minor modifications. A new detector will also be designed to serve as a near detector for both LEnuSTORM and LEMNB. In addition, the impact of gadolinium doping in the far Water Cherenkov detector will be investigated to enhance neutrino–antineutrino discrimination.

R2T TRANSFER LINE

Beam extraction from the Accumulator Ring

After longitudinal compression in the accumulator ring, the beam is fast-extracted and transported to the neutrino production targets via a dedicated transfer line. Given the high beam power and short pulse duration (~1.2 µs), a single-turn fast extraction scheme is required.

Conventional extraction schemes using slow orbit bumps and fast kickers are not directly applicable to the ESSνSB accumulator, which operates in a continuous fill-and-extract mode. Instead, the extraction system is optimized by placing the septum as close as possible to the closed orbit and by using a dedicated extraction straight section.

The adopted design is based on a simplified layout using sixteen fast kickers grouped around a central quadrupole doublet in the straight section [4]. These kickers deflect the beam in a single turn towards a Lambertson septum magnet, which provides the horizontal separation into the extraction line. The scheme is inspired by SNS, combining vertical deflection by kickers and horizontal bending by the septum.

Requirements

In the ESSνSB+ configuration, the beam is transported towards a single target. The transfer line must align the proton beam with the neutrino beam direction, corresponding to a vertical downward angle of 2.29°. At the septum exit, the beam already carries significant angular components (16.8° horizontal and ~1.14° vertical), requiring additional vertical bending and precise optics control. The beamline must also preserve beam quality, minimize losses, and remain as compact as possible (beam size less than 15 mm).

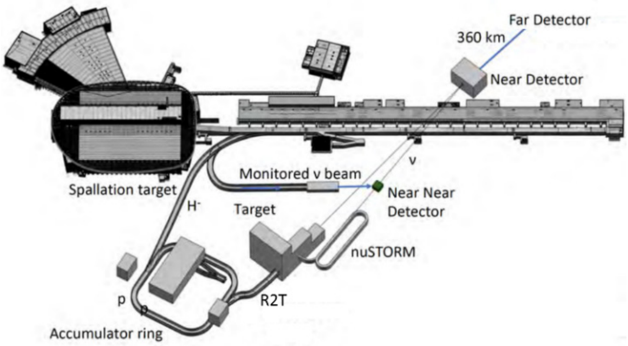

Figure 1: Layout of the ESSnuSB+ infrastructure on the ESS site in Lund, Sweden.

Design of the R2T beamline

The beamline optics is designed using particle distributions from the anti-correlated painting process, ensuring realistic transverse phase space and momentum spread. A key aspect of the design is the proper matching of the Twiss parameters (β, α) and dispersion at the septum exit to the periodic solution of the transfer line lattice. The extraction induces non-zero dispersion and angular offsets, which are progressively corrected along the line. Table 1 presents the main characteristics of the beam from the accumulator.

Table 1: Beam Parameters From Accumulator

Parameter	**Value**	**Unit**
Kinetic energy	2499.9	MeV
Relativistic momentum	3307.7	MeV/c
Emittances $\varepsilon_x/\varepsilon_y$ [rms]	27.1/25.9	π mm mrad
Emittances $\varepsilon_x/\varepsilon_y$ [99.95%]	244.0/233.8	π mm mrad
σ_x/σ_y [rms]	11.3/15.8	mm
$\sigma_{x'}/\sigma_{y'}$ [rms]	1.1/0.7	mrad
β_x/β_y	9.9/20.3	m
α_x/α_y	-0.0005/0.0032	

Simulations indicate that the most effective configuration is a lattice composed of eight horizontal and three vertical dipoles (each 2 m in length). This arrangement ensures a progressive bending of the beam while keeping magnetic field strengths within reasonable limits (approximately 690 mT horizontally and 960 mT vertically) and preventing excessive dispersion growth.

Fewer than 40 quadrupoles are distributed along the line in a targeted manner to control the evolution of the β-functions and to maintain the beam envelope within acceptable bounds. The optics are optimized to provide a smooth variation of βx and βy, avoiding strong focusing peaks and ensuring a large acceptance along the entire beamline. Figure 2 presents the layout of the R2T beamline relative to the neutrino direction. The total length of this line is 115 m.

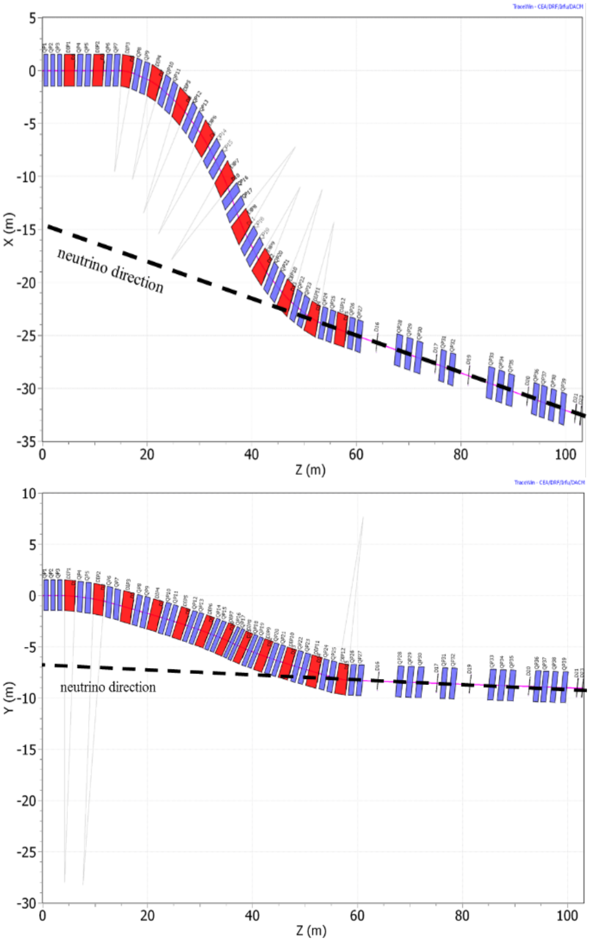

Figure 2: Horizontal (top) and vertical (bottom) synoptics of the R2T beamline versus the neutrino direction [5].

Dispersion generated by the horizontal bends is controlled through appropriate quadrupole settings, allowing partial suppression towards the end of the line and ensuring compatibility with the target requirements.

Investigations show that the transverse beam envelopes remain well contained within the available apertures along the full transfer line, with sufficient safety margins (Fig. 3). The combination of controlled β-functions, managed dispersion, and smooth optics transitions ensures efficient beam transport with minimal losses, meeting the stringent requirements imposed by the high beam power. The downstream end of the straight section has been specifically designed to accommodate the beam switchyard studied in the previous project [1]. The maximum beam size remains below the 15 mm requirement at the target (Fig.4).

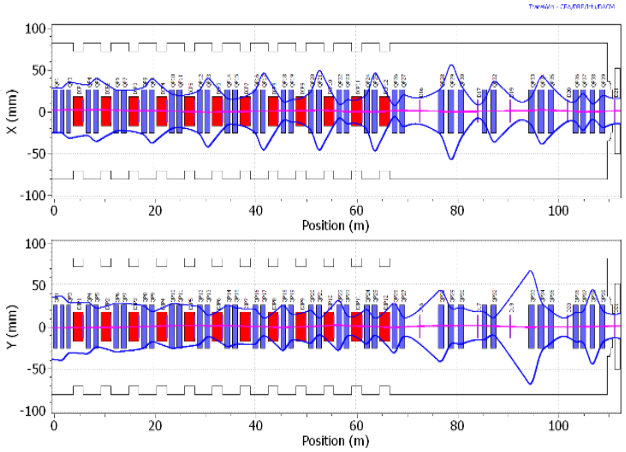

Figure 3: Transverse beam envelops along the R2T beamline at 4 σ (top: horizontal, bottom: vertical).

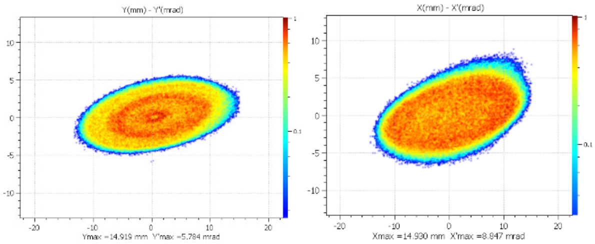

Figure 4: Transverse phase space (left: yy’, right: xx’) of the particles at the end of the R2T beamline.

CONCLUSION

The design of the Ring-to-Target (R2T) transfer line for ESSνSB+ demonstrates that efficient and robust beam transport can be achieved under stringent geometrical and high-power constraints. Starting from realistic beam distributions at the septum exit, the optics has been carefully matched to control the evolution of the β-functions and dispersion, ensuring a smooth envelope and minimizing sensitivity to momentum spread. The combination of distributed horizontal and vertical bending with optimized quadrupole settings allows precise alignment with the neutrino beam direction while maintaining large transverse acceptance. The resulting compact lattice (~115 m) provides stable, low-loss transport compatible with multi-megawatt beam operation. These results confirm the feasibility of the proposed design and establish a solid basis for further studies, including error analysis, collimation strategy, and integration with the target station.

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