ESSNUSB+: TARGET STATION STUDIES

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On behalf of the ESSνSB+ collaboration

Abstract

The ESSnuSB+ project aims to accurately measure the neutrino cross-sections for ESSnuSB leptonic CP violation measurements and to perform sterile neutrino searches and astroparticle physics. The implementation of the whole project depends on the time evolution of the European Spallation Source (ESS) beam power. Three phases are under consideration: 300 kW (Stage 1), 1.25 MW (Stage 2) and the full power at 5 MW (Stage 3).

This article will focus on the status of the 1.25 MW target station (phase 2). The full chain from particle production to energy deposition across major components of this target station has been estimated thanks to a Monte Carlo simulation. The design of all these components, which are exposed to high levels of radioactivity, is essential for validating the feasibility of the target station facility, assessing the lifetime of the components, and guiding the design of the cooling and shielding systems.

THE ESSNUSB+ TARGET STATION

The next generation of neutrino experiments, such DUNE [1] in USA or HK [2] in Japan, aims at addressing fundamental open questions in particle physics, such as the determination of the neutrino mass ordering and the search for CP violation in the leptonic sector. Accelerator-based facilities rely on high-intensity neutrino beams produced from the decay of secondary particles, primarily pions, generated by the interaction of a high-power proton beam impinging a solid target. In this context, the ESSnuSB collaboration [3] proposes to exploit the high-power proton linac of the European Spallation Source (ESS) to produce an intense neutrino superbeam.

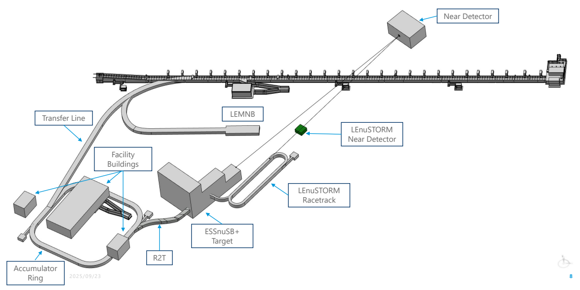

Figure 1: Facilities implementation in the ESSnuSB+ project.

A 2.5 GeV proton beam impinges on a target station, where secondary pions are produced, focused by a magnetic horn into a decay tunnel (Stage 3) or deviated by a magnetic dipole located downstream of the horn to feed a muon racetrack ring in the case of ESSnuSB+ (Stage 2) as shown in Fig 1. The target station constitutes a critical component of the facility, as it must withstand high power deposition and intense radiation fields while ensuring efficient secondary particle production and collection. The optimisation of this system involves a trade-off between maximising the useful π^+ (or π^-) flux and limiting energy deposition in sensitive components, such as the target, horn, and downstream elements. In this work, the simulations are performed to describe the full chain of interactions within the target station. The results provide quantitative estimates of power deposition, as well as updated predictions of pion production, supporting the design and optimisation of the ESSnuSB+ facility.

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SIMULATION SETUP

The simulations were performed using the FLUKA Monte Carlo code [4, 5] to model the interaction of a 2.5 GeV proton beam with the target station, as shown in Fig 2. The geometry implemented in the simulations includes the main components of the ESSnuSB+ target station, described below.

Target and Canister The granular target consists of a 78 cm long cylinder with 3 cm diameter filled with 3 mm titanium spheres. The cylinder is surrounded by a titanium canister equipped with slits on top and bottom to allow a pressurized helium gas circulation for an efficient transverse cooling. In the simulation, the uniform titanium cylinder with a density of $\rho = 2.57\,\text{g/cm}^3$ to take in account the sphere arrangement.

Magnetic Horn The target system is enclosed within a MiniBooNE like horn made of aluminium. The magnetic field is generated by a 350 kA pulse (100 microseconds half-sinusoid width) circulating in the conductor. Theses pulses are synchronized with the proton pulse frequency at 14 Hz. A specific power supply based on modular approach has been developed to work under these specific conditions.

Shielding - Collimator A shielding element, referred to as the collimator, is placed between $z = 300\,\text{cm}$ and $z = 450\,\text{cm}$. It is primarily made of iron and includes a tungsten ring to enhance radiation absorption (see Fig 3). The aperture of the tungsten insert is 30 cm, which imposes constraints on the horn focusing performance to ensure efficient transmission of useful pions selected by the physics objectives (700 MeV $\pm 10\%$).

Bending Dipole A bending dipole magnet is located between $z = 450\,\text{cm}$ and $z = 600\,\text{cm}$. This component is one of the most critical elements of the target station due to the

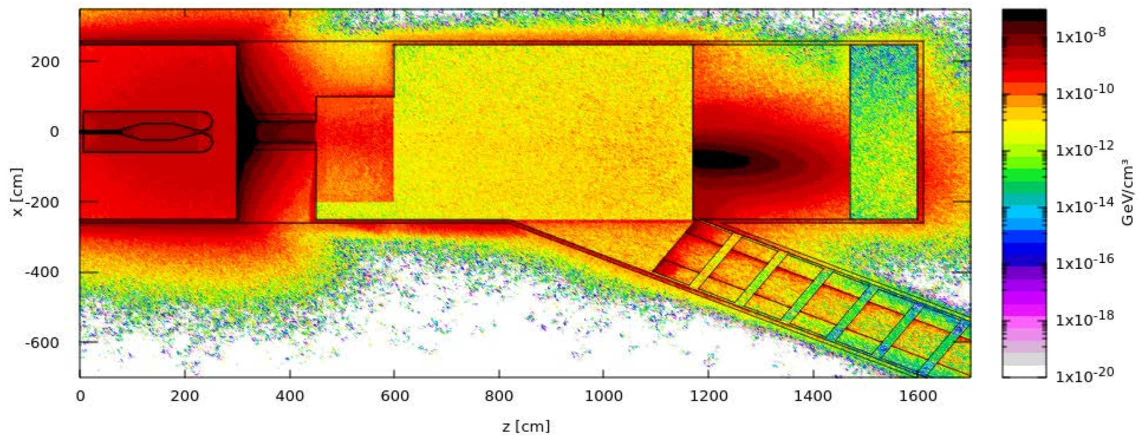

Figure 2: Schematic layout of the ESSnuSB+ target station. The colour map represents the energy deposition [GeV/cm^3] across the simulation, averaged over 5 simulation of 100k primary protons.

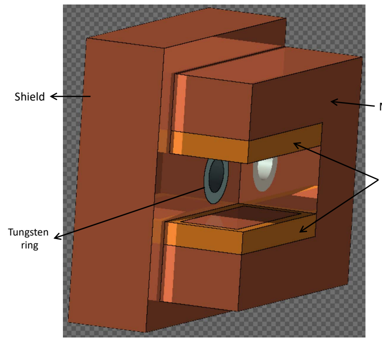

Figure 3: Illustration of the shield and C-shaped dipole.

high radiation and energy deposition levels. The dipole has a C-shaped geometry (see Fig 3) designed to reduce particle losses on the magnet structure. It consists of an iron yoke and copper coils. The coils have a width of 20 cm and a height of 40 cm, while the gap length is 100 cm. The magnetic field is defined only within the gap and is oriented along the vertical direction, with $B_y = 0.76$ T and $B_x = B_z = 0$.

Transfer Line and Quadrupoles The transfer line begins at $z = 800$ cm, where positively charged pions are deflected with an angle of 29.5°. In the current simulation setup, the transfer line includes seven quadrupole elements. No magnetic field is implemented at this stage, and this section is used as a first-order approximation to evaluate energy deposition in downstream components.

Walls and Decay Tunnel All the experimental is enclosed in a helium-filled environment to limit the production radioactive isotope. The decay tunnel consists of a rectangular section of dimensions 500 cm × 500 cm. Its total length is 1800 cm, extending from $z = -200$ cm to $z = 1600$ cm. At the interface with the surrounding environment, a, iron structural vessel of 10 cm thickness is implemented, followed by 5 m of Portland concrete to ensure adequate shielding.

Beam Dump The beam dump is located at $z = 1200$ cm and represents the last component of the simulated geometry. It is made of a graphite block and is designed to absorb the residual particle in particular the protons.

POWER DEPOSITION STUDIES

Figure 2 shows the energy deposition map simulation layout. Particular attention is given to regions exposed to high radiation levels, as these directly impact material degradation and component lifetime. In addition, Table 1 summarises the total power deposited in each component.

The target (124 kW) and the magnetic horn (34.4 kW) are subject to high radiation levels, requiring efficient cooling systems. The collimator effectively shields the downstream dipole, absorbing a large fraction of the radiation, with 283 kW deposited in the iron part and 146 kW in the tungsten part. Further studies will investigate alternative materials, including the addition of 10% water to the iron and tungsten components, and 5% tantalum to the tungsten ring. The copper coils of the dipole receive approximately 0.97 kW, which may lead to rapid material degradation. Mitigation strategies are currently under investigation, such as the addition of a tungsten plate to provide additional shielding. The beam dump absorbs the remaining proton beam and therefore experiences a high level of power deposition (246 kW). The power deposition in the quadrupoles is not reported here, as this study provides a first-order estimation (see Fig 2) and does not fully account for their exact positioning. However, this preliminary results indicate that the first quadrupole may experience significant energy deposition ($>10^{10}$ GeV/cm^3), and will require particular attention in future studies.

PION PRODUCTION

Aside from managing radiation and energy deposition within the layout, a key objective is to maximise the useful π^+ flux. Figure 4 shows the distribution of 700 MeV $\pm 10\%$ π^+ at the entrance of the transfer line (T2R). The boundaries of the T2R are indicated by black lines. Each dot represents the position of a π^+, and its colour corresponds to the angle θ at which the particle is deflected by the dipole. The mean value of θ is $-30°$, slightly above the expected value of $-29.5°$ for the T2R.

Table 1: Power deposited in the main components of the target station. The deposited power corresponds to the mean value obtained from 1000 independent simulations of 10k primary protons each. The standard error is computed as $\sigma/\sqrt{N}$, where σ is the standard deviation across simulations and $N = 1000$ is the number of simulations.

Component	Deposited Power [kW]	Standard Error [W]
Target	124	19.8
Horn	34.4	10.8
Fe Shielding	283	87.2
W Shielding	146	85.0
Fe Dipole	3.28	5.59
Cu Dipole	0.97	2.4
Beam Dump	246	12.5

It should be noted that the dipole magnetic field used in this simulation is a first approximation of the real field and will be refined and optimised in future studies. Furthermore, a significant fraction of pions is lost along the transport: in our simulation, 1M primary protons produce 29 343 π^+ at the target, whereas only 4 315 reach the entrance of the transfer line, corresponding to a loss of approximately 85%. Future optimisation of the horn design is expected to reduce these losses.

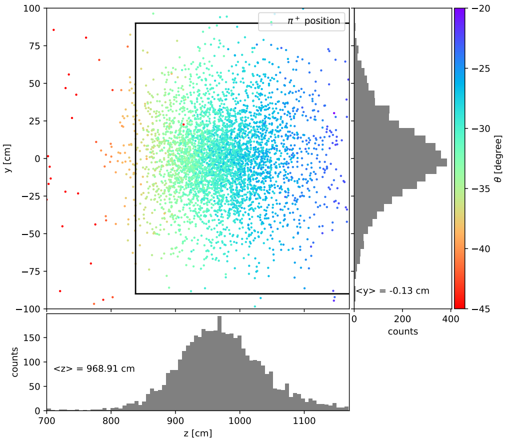

Figure 4: Distribution of π^+ at the transfer line entrance ($x = -250$ cm). The black lines indicate the transfer line boundaries. The right border of the main panel corresponds to the beam dump position ($z = 1170$ cm). The colour scale represents the particle angle, with a mean angle of $\theta = -30°$. Bottom and right plot are the distribution of pions in the z and y axis, respectively.

CONCLUSION

Detailed FLUKA simulations of the ESSnuSB+ target station have been performed, covering particle production and energy deposition across the main components. The results provide quantitative estimates of deposited power and energy, supporting the validation of the target station design and informing engineering decisions related to cooling, shielding, and material selection. In particular, the simulations highlight critical regions such as the target and horn, the dipole coils, and the first quadrupole, which may experience significant energy deposition. Updated predictions of pion production at the target and at the entrance of the transfer line have also been presented, showing substantial losses along the transport (approximately 85%). These findings constitute an important step toward optimisation of the neutrino beam and will guide future improvements, including horn design adjustments and dipole field refinement. Future work will focus on refining the geometry, improving the modelling of particle transport, investigating mitigation strategies for high-dose components, and optimising the magnetic elements to maximise the useful π^+ flux, thereby enhancing the overall performance of the ESSnuSB+ facility.

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