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Abstract

This milestone report presents an updated evaluation of the ESSνSB+ target station baseline design, covering the hadronic collector, the Large Aperture Dipole Magnet (LADM) and power deposition studies. The horn geometry was already optimised via a genetic-algorithm-based deep-learning approach to maximise pion yield at the dipole level. To protect the LADM coils, whose wires are equipped with PEEK material for electrical insulation, a 40 cm tungsten shield was introduced. FLUKA simulations shows that this shielding allows to keep the cumulative dose below the 10 MGy PEEK limit over the duration of the experiment. Finite element simulations confirm that the shielding does not significantly distort the magnetic field, which remains uniform within 2% in the collimator region. In conclusion, the modifications brought in the simulation increase the lifetime of the target station and allow to run the experiment over 10 years.

List of abbreviations The following table presents by alphabetical order, the acronyms used in this milestone:

Abbreviation	Description
ESS	European Spallation Source
ESSnuSB	European Spallation Source Neutrino Super-Beam
LEnuSTORM	Low Energy neutrinos from STOred Muons
BD	Beam Dump
LADM	Large-Aperture Dipole Magnet
T2R	Target to Ring
WP	Work Package
LBL	Long-baseline neutrino beam

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1 Introduction

The production of the high intensity neutrino superbeam based on the ESSνSB+ concept depends on many elements which select the pions in a specific energy range determined by the physics to be injected in the LEnuSTORM ring. One of the main challenge relies on the optimization of the whole elements of the chain in particular the hadronic collector, the dipole and the Target To Ring transfer line elements (T2R) to get the maximum intensity. The first iteration has been achieved in the previous studies [1, 2]. Another iteration has been performed taking in account the full chain including the design Target To Ring transfer line elements [3]. In the following, the status of these elements will be reviewed.

2 Update on the Target station Facility

The hadronic collector has been first optimized regarding the pion intensity at different position of the large aperture dipole magnet (LADM) as shown in Figure 1. The optimisation procedure was based on a deep learning technic using a Genetic Algorithm to shape the inner conductor of the horn. The horn is positioned before the collimator (CLMT) as shown in Fig 1 (Left).

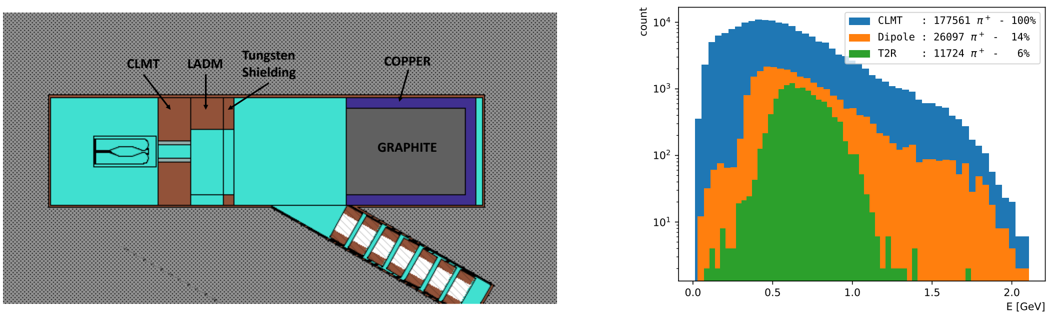

Figure 1: Transverse View of Target Station Facility (Left) Pion distribution at several transverse position (Right).

The pion distribution downstream of the LADM shows a significant flux reduction due to the low energy proton energy and the technical limitations of the horn focussing power Fig 1 (Right). The pions are deviated by the Large Aperture Dipole Magnetic whose field is produced by two coils surrounding the iron poles near the aperture. These two coils, made of copper wires surrounded by PEEK material for electrical insulation will be submitted to high radiation levels and requires shielding to improve their lifetime.

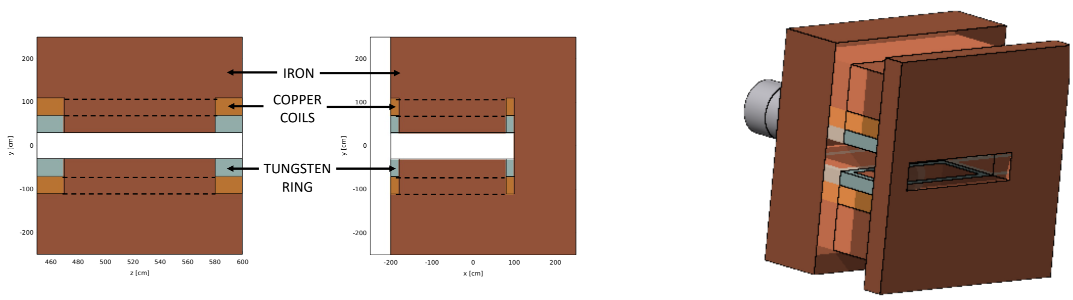

Figure 2: 2D view of the Large Aperture Magnet Dipole (Left) Large Aperture Dipole Magnet 3D view (Right).

The design of the target station facility has been updated in consequence with additional shielding to protect sensitive parts of the facility against the high level of radiations, in particular some elements of the Large Aperture Dipole Magnet. Additional passive shields have been added to protect the coils producing the magnetic field in the LADM aperture as shown in Fig 2 (Right).

3 Large Aperture Dipole Magnet

In the initial design of the target station facility, the coils producing the magnetic field of the Large Aperture Dipole Magnet were located near the aperture. The large amount of radiations at this level impacts the lifetime of the electrical cable carrying the high intensity DC current to produce the magnetic field for deviating the pions into the Target To Ring lines. It has a significant impact on the lifetime of the some material, especially the PEEK material whose the acceptable dose to keep stable the electrical properties stable is below 10 MGy [4].

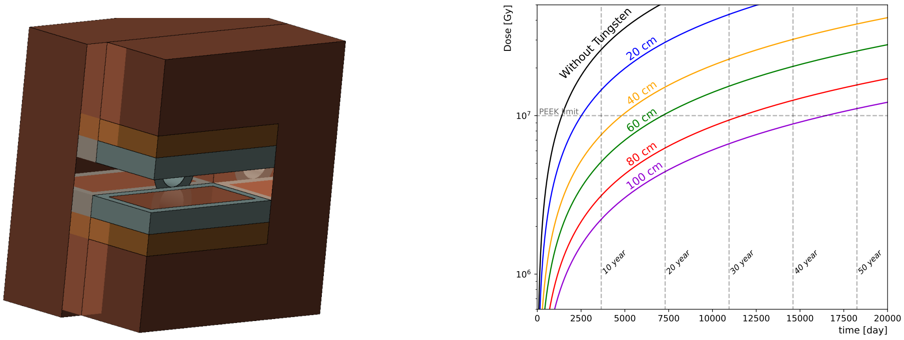

Figure 3: Geometry of the shielding (Left) Evolution of the Dose curve wrt the thickness of the tungsten shielding (Right).

Several thicknesses of tungsten shielding have been simulated under FLUKA environment [5, 6] and the integrated Dose evolution with time has been estimated as shown in Fig 3 (Right). The thickness has been fixed to 40 cm to keep stable the electrical properties over 10 years corresponding to the duration of the experiment.

The impact of the displacment of the copper coils under the magnetic field has been checked through a finite element simulation under COMSOL environement [7].

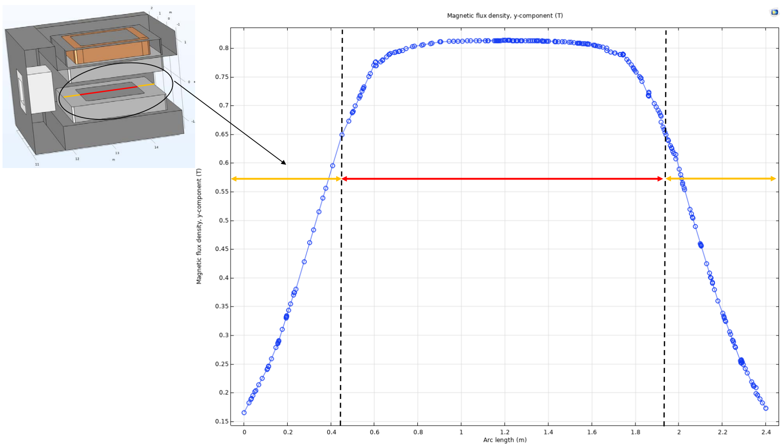

Figure 4: Geometry of the LADM simulated in COMSOL (Left) Magnetic field intensity in the aperture (Right).

The simulated geometry contains a 40 cm belt made of tungsten as shown in Fig 4. The field intensity profile shows a strong edge effects in the total aperture region represented in red in Fig. 4 (Right). However, in the region corresponding to the collimator end along the path of pions, the magnetic field remains uniform within 2% level.

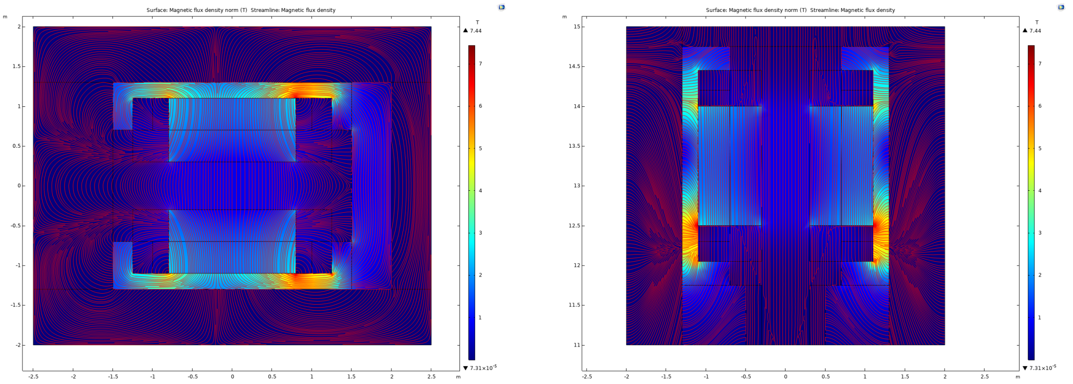

Figure 5: Magnetic field lines at the large aperture dipole

The magnetic field line geometry shown in Fig 5 confirms a good uniformity and the tungsten shielding has no significant impact compared to the previous situation. A non uniformity appears in the iron yoke due to the non symmetric geometry and the thickness of the dipole in the edge which could imply a distortion of the magnetic field map around the location. Out of the aperture, this should not affect the deviation of pions.

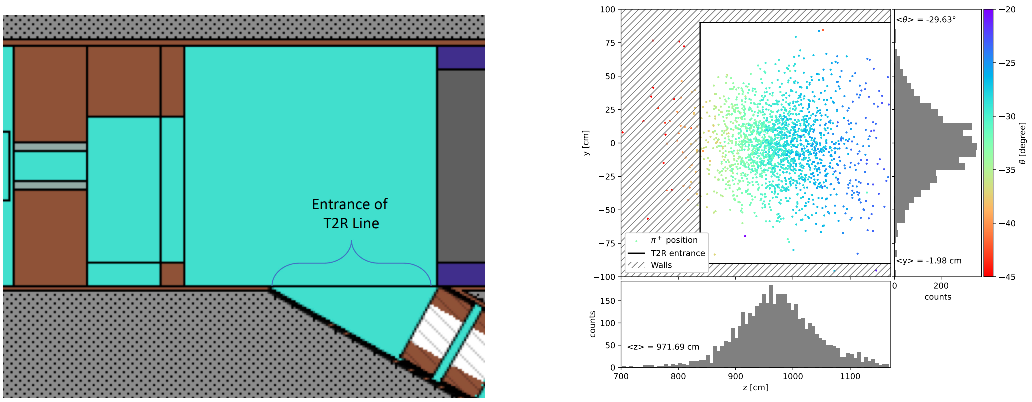

Figure 6: Enlarged view indicating the entrance of the T2R line (Left) Distribution of π^+ at the transfer line entrance ($x = -250$ cm). The black lines indicate the transfer line boundaries. The right border of the main panel corresponds to the beam dump position ($z = 1170$ cm). The colour scale represents the particle angle, with a mean angle of $\theta = -29.63°$. Bottom and right plot are the distribution of pions in the z and y axis, respectively (Right).

Beyond the control of radiation and power deposition within the beamline layout, a primary goal is to maximise the useful π^+ flux. Fig 6 (Right) illustrates the spatial distribution of 700 MeV $\pm 10\%$ π^+ at the entrance of the transfer line (T2R). The boundaries of the T2R acceptance are shown by black lines. Each point corresponds to a π^+, with the colour scale representing the deflection angle θ induced by the dipole magnet. The mean value of θ is found to be $-30°$, slightly above the nominal value of $-29.5°$ assumed for the T2R.

It is important to note that the dipole magnetic field implemented in the FLUKA simulation is considered as constant in the aperture region. The simulation shows that 15% of the pions are successfully transported to the Target To Ring line entrance.

4 Power Deposition in the Target Station Facility

Figure 7 presents the simulated power deposition map layout. Particular attention is devoted to regions subjected to high radiation levels, as these critically influence material degradation and component lifetime. In addition, Table 1 summarises the total power deposited in each component.

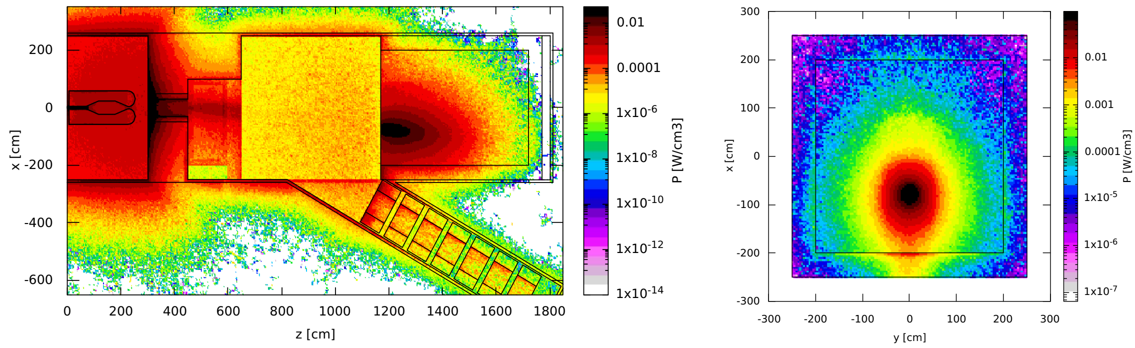

Figure 7: Power Desposition in Target Station facility (Left) Power deposition at beam dump level (Right).

The target (124 kW) and the magnetic horn (34.4 kW) are exposed to substantial radiation levels, thereby requiring efficient cooling systems. The collimator provides effective shielding for the downstream dipole by absorbing a significant fraction of the radiation, with 283 kW deposited in the iron section and 146 kW in the tungsten section. Further investigations will consider alternative material configurations, including the incorporation of 10% water into the iron and tungsten components, as well as 5% tantalum in the tungsten ring. The copper coils of the dipole receive approximately 0.97 kW, which may lead to accelerated material degradation. Mitigation strategies are currently being studied, including the possible addition of a tungsten plate to enhance shielding. The beam dump absorbs the remaining proton beam and therefore experiences a significant power deposition of 246 kW.

Table 1: Power deposited in the main components of the target station. The deposited power corresponds to the mean value obtained from 50 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 $N = 50$ is the number of simulations.

Component	**Deposited Power [kW]**	**Standard Error [W]**
Target	124	89
Horn	34.4	56
Fe Shielding	283	329
W Shielding	146	411
Fe Dipole	9.63	73
Cu Dipole	0.31	2.27
W Dipole	4.82	46
DS Shielding	3.87	42
Cu Beam Dump	7.14	54
Beam Dump	232	559

The power deposition in the quadrupoles is not reported here, as this study provides only a first-order estimate and does not fully account for their precise positioning. Nevertheless, these preliminary results indicate that the first quadrupole may experience substantial energy deposition (above 10^{10} GeV/cm^3), warranting further dedicated studies.

A beam dump concept has been already developed in the previous phase of the project, but to estimate the power deposition a simple block of graphite and a layer of copper have been considered in this simulation. The additional layer is made of a copper alloys CuCr1Zr. This alloys offers an excellent combination of electrical and thermal conductivity, along with a high mechanical strength after age hardening and should be efficient to evacuate the power deposited in the graphite block.

The simulation showed that this simplified beam dump absorbs 232 kW representing 18% of the power delivered by the proton beam. The presence of the LADM magnetic field shifts the position of the power deposition distribution from the centre to the right side of the beam dump as shown in Fig 7 (Right).

5 Summary

The modification of the target station facility shows no significant impact in the magnetic field compared to the previous geometry without shielding. However, the pions propagation has been simulated considering a perfect uniform field in the LADM aperture region, and a small variation below 2% of the field should have no significant impact and should be certified by including a more realistic magnetic field map including the fringe field. In conclusion, the modifications brought in the simulation increase the lifetime of the target station and should allow to run the experiment over 10 years.

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