

DESIGN OF PION TRANSPORT FROM THE ESSnuSB+ TARGET TO THE LEnuSTORM RING*

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Abstract

Measurements of neutrino oscillations in low-energy regimes will require precise knowledge of neutrino-nucleus interaction cross sections for low-energy neutrinos. The ESSnuSB+ project aims to fill the gap in the interaction cross section data by creating a well-quantified neutrino beam from the circulation of stored muons in a low-energy racetrack decay ring, LEnuSTORM. To produce the circulating muon beam, a pion beam will be generated via the impingement of a 1.25 MW proton pulse on a target. The pions must then be focused, transported, and injected to the production straight of the decay ring wherein the pions will decay to muons. This contribution discusses the transport of the pions from the megawatt-class target station to their injection in the ring, and considerations for maximizing the muon yield – including momentum selection, maximization of acceptance, and designing a line with minimal path length to increase pion survival whilst accommodating optics matching and layout constraints.

INTRODUCTION

ESSnuSB [1] is a proposed long-baseline neutrino oscillation experiment making use of the 5 MW proton pulses at 2 GeV provided by the European Spallation Source (ESS) linac. Pulses from the linac are to be redirected to an accumulator ring before being sent onto a target assembly; the resulting secondary particles are focussed in the forwards direction by using an array of four magnetic horns; pions in the secondary particle shower will then decay to muons, producing a uniquely intense pulse of neutrinos for the neutrino oscillation measurements.

To support these physics studies, and as an intermediate stage to the construction of the full ESSnuSB experiment, the ESSnuSB+ project has been proposed [2]. This project will take only one in four pulses from the linac for an average beam power of 1.25 MW, directing these onto a single target/horn assembly. Forward-focussed pions will then be transported via a short beamline to a racetrack layout decay ring based on the nuSTORM concept [3]. This low-energy decay ring, termed LEnuSTORM, uses the stochastic injection principle [4] to inject this pion pulse, which passes along one of the ring's two straights (the so-called production straight), wherein the majority of the pion beam decays to muons. Muons at the desired momentum of 600 MeV/c then circulate for a number of turns; the decay of muons in the production straight produces a focussed beam of muon and electron neutrinos. This beam is then used to make precision

measurements of neutrino-matter interaction cross-sections in the low-energy regime.

To facilitate the production of this precise neutrino beam, it is first necessary to transport the pions from the target station environment to the decay ring. This transfer line must satisfy a number of key requirements: firstly, it must be as short as possible to minimise premature pion decay; it must match the Courant-Snyder parameters (beta functions, alpha functions, and dispersion) of the pion distribution downstream of the horn to those demanded by the periodic Courant-Snyder parameters of the production straight; it must maximise its transverse and momentum acceptance to maximise pion yield; and finally, it must meet the geometric constraints established by the project's design.

LAYOUT

As shown in the schematic depicted in Fig. 1, the axis of the target station beam (and downstream decay tunnel) is directed towards the long baseline near detector, which is then shared with the neutrino beam produced by the LEnuSTORM production straight. The injection point of the LEnuSTORM ring must then be separated by sufficient distance from the target station to pass through the radiation shielding of the megawatt-class target station environment, as well as ensuring that the production straight does not intersect with the decay tunnel or its shielding. The requirement of a shared detector for the decay tunnel axis together with the separation requirement for the LEnuSTORM sets the constraints for the total bending angle required for the transfer line. The minimum angle α between the production straight and decay tunnel axes is given as $\tan \alpha = \frac{w}{s-T}$, in which w is the half-width of the decay tunnel and associated shielding, assumed to be 8 m, T is the length of the decay tunnel, and s is the position of the near detector with respect to the target station. Then, by computing the angle of the pion beam at injection with respect to the production straight, the total bending angle of the transfer line is determined.

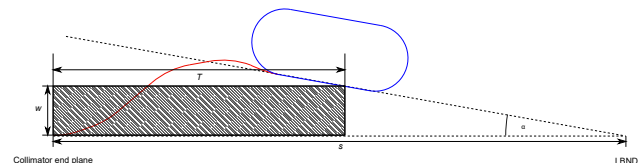


Figure 1: Geometry diagram showing the decay tunnel and shielding (shaded area), pion transfer line (red), and LEnuSTORM ring (blue). The elements are not depicted to scale.

The transfer line is based on a two-arc concept. The bending angle of the initial dipole is limited due to the low maximum field of the large-aperture target station dipole (LADM).

* EU Grant Agreement No 101094628

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By installing a second dipole with the same bending angle downstream (outside of the target station environment), the horizontal deflection of the beam can be increased to more rapidly traverse the required lateral distance. Then a quadrupole triplet is installed in the intermediate space between the dipoles to ensure a 180 degree phase advance in the horizontal plane, meaning that the first-order dispersion is closed back to zero at the end of the second dipole. A similar concept is then used at the opposite end of the transfer line to bend in the reverse direction, though this contains four intermediate quadrupoles - this was determined to be optimal to match to the non-zero dispersion at the injection point whilst preserving the acceptance of the beam.

The dimensions of these arcs are set by constraints on the fields allowable in each magnet, assuming 1.0 T in the LADM dipole and its counterpart, and 1.5 T in the second arc based on conventional limits for normal-conducting magnets, and the spacing requirements between elements. After finalising the design of these arcs, they are joined with a dispersion-suppressed straight that contains an array of quadrupoles to match the optics between the two.

INITIAL PARAMETERS AND TARGET STATION ARC

The target and horn are simulated using FLUKA [5, 6] to obtain an initial pion distribution on the upstream plane of the collimator. The particle distribution is then transformed into the co-moving Frenet-Serret coordinate of the beamline, assuming a reference momentum of 1050 MeV/c. A modified Xsuite [7] simulation was used to propagate the distribution through the collimator and later to simulate particle dynamics throughout the arc.

Figure 2 shows the output pion distribution of the horn, within a $\pm 10\%$ momentum cut around the reference momentum, overlaid with the ellipses corresponding to different

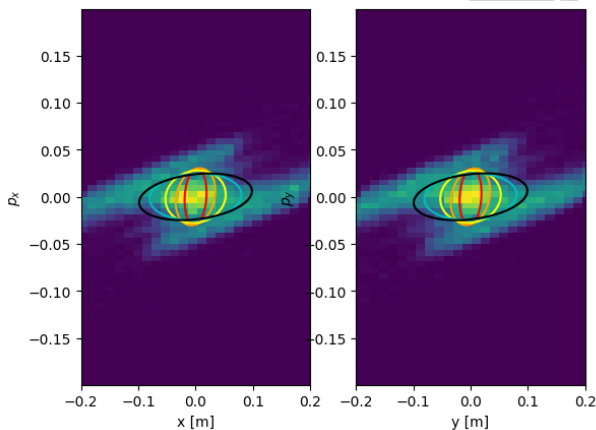


Figure 2: Initial phase space of the pion beam within the assumed $\pm 10\%$ momentum acceptance. The coloured ellipses represent the Courant-Snyder ellipses corresponding to fractions of the beam with the lowest radial distance from the axis as follows: red, 10%; orange, 25%; yellow, 50%; cyan, 90%; black, 100%.

fractions of the distribution. This shows that the distribution is highly non-uniform, but contains a dense beam core, with the innermost 50% of the distribution having similar parameters. For the initial optimisation based on linear optics, the parameters of this 50% distribution are assumed as the baseline.

The design of the first arc of the transfer line is constrained by the limited fields of the LADM dipole. The LADM is modelled in XSuite as a Bend element with an edge angle corresponding to the overall bending angle of the element (i.e. a rectangular element with an entrance plane perpendicular to the beam axis). The k_0 value (inverse of the radius of curvature) is set by assuming a dipole field of 0.79 T and computing the magnetic rigidity of the beam. For the initial design study, the second dipole of the arc is considered as a mirror-symmetric copy (about the midpoint of the arc), but manufacture costs could be optimised by reduction of the aperture of this second dipole owing to its positioning outside of the high-radiation target environment.

To control the phase advance in the horizontal plane, whilst minimising overall beam size and maximising acceptance in both planes, a triplet configuration of quadrupoles is positioned between the two dipoles. These magnets are placed as tightly as possible with respect to each other, and as close to the dipoles as geometric and shielding constraints permit. The study of shielding between the dipole and first quadrupole and effects of shielding on the design of this arc will be the subject of further simulations in FLUKA. The quadrupole coefficients for the arc k_{1F} and k_{1D} are set such that dispersion and its first derivative at the end of the dipole are equal to zero.

The distribution is propagated through this arc and used to define beam size limits of downstream elements (under the assumption that the simultaneous horizontal dispersion and beta-function maxima in the central quadrupole of the arc will be an unavoidable bottleneck on the overall acceptance of the line).

END PARAMETERS AND INJECTION-MATCHING ARC

The transfer line must transform the Courant-Snyder parameters of the output distribution from the horn to match those at the input of the stochastic injection section. The latter are computed by evaluating the periodic optics of the production straight and then propagating them in reverse through the stochastic injection section (illustrated in Fig. 3). The optics of the LEnuSTORM ring are discussed in further detail in another contribution [8].

The overall bending angle of the two dipoles in the second arc is given by the sum of the angle of the pion beam at the injection point and the total angle of the first arc, which was determined based on field constraints. For these dipoles we assume a more conservative aperture will allow a higher dipole field, which we assume to be 1.5 T based on limits for normal-conducting magnets. As this line is not a closed-dispersion arc (as it matches from the defined optics of the

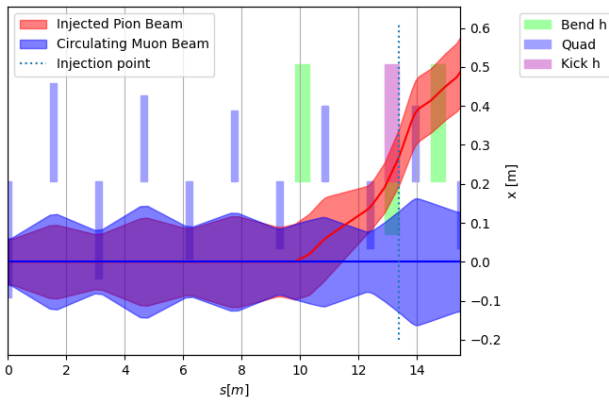


Figure 3: Beam envelopes for the pion and muon beams propagating in reverse direction from the production straight into the injection arc. Initial parameters of both beams are determined from the periodic optics of the lattice, with the emittance of the pion beam at the nominal value used elsewhere in this document, and the emittance of the muon beam taken to be 3 mm. The momentum spread in each case is assumed to be $\pm 10\%$. The central muon momentum is the reference momentum of 600 MeV/c selected for the LEnuSTORM ring and the central pion momentum is 1050 MeV/c. The downstream plane of the septum magnet (dashed vertical line) is the point at which the transfer line connects to the ring. The pion optics to the right of this in the figure are not considered relevant as pions do not traverse this section of the ring.

stochastic injection straight to a zero-dispersion section), it need not preserve optical symmetry and we find an optimised configuration for four quadrupoles. The strength and spacing of the quadrupoles is set based on matching the dispersion conditions at the arc's start and end, whilst minimising transverse beam size. As long as the horizontal beam size in the second arc is kept below the maximum horizontal beam size achieved in the first arc (which is as low as achievable), the arc will not impose any additional limitations on the horizontal acceptance. The vertical beam size is maintained below the 400 mm diameter assumed as the quadrupole aperture.

OVERALL LINE OPTICS AND PERFORMANCE

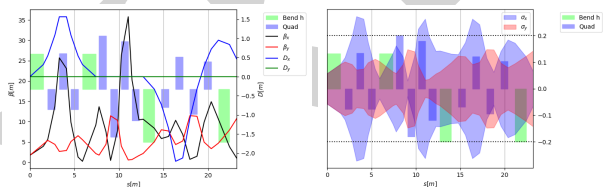


Figure 4: Linear optics of the full transfer line from the collimator end plane to the injection septum of the LEnuSTORM ring (left). Projection of the design beam onto the transverse axes. The assumed magnet apertures are shown with dashed horizontal lines (right).

Figure 4 (left) shows the final optics of the full transfer line, with linear optics matched between the 50% beam of the initial distribution and the periodic pion optics of the production straight by the inclusion of a straight between the two arcs of the transfer line. The envelope of the beam in each dimension is then displayed in Fig. 4 (right), assuming the 50% emittance value from the previous section, and a $\pm 10\%$ momentum spread.

With the assumed magnet aperture of ± 20 cm in each plane, the full beam is accepted in the vertical plane. It can be seen that the assumed design beam exceeds the aperture in the horizontal plane at the midpoint of the first arc - this is an unavoidable consequence of the constraints on magnet spacing in the first arc. This is the maximum in the transverse beam size, and all subsequent transverse beam size peaks are maintained below this value.

Tracking of the pion distribution was performed using Xsuite. The transverse phase space distributions at the end of the line (at the injection septum of the LEnuSTORM ring) are shown in Fig. 5.

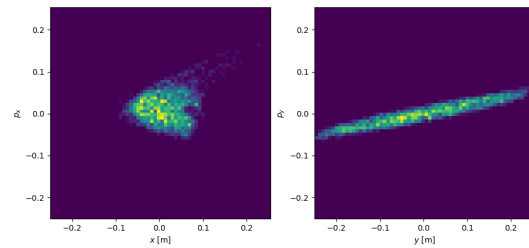


Figure 5: Horizontal (left) and vertical (right) phase space of the pion beam at the injection point.

In the Xsuite tracking simulation, the fraction of pions in the input distribution transmitted through the collimator is 15.1% whilst the fraction of the pions transmitted through the entire collimator-transfer line assembly is 0.113%. The efficiency of the line can be expressed as the ratio of the pions at the downstream plane of the collimator, within the design momentum range of $\pm 10\%$, to the pion count at the injection point of the LEnuSTORM ring. This gives a value of 10.8%. Overall, this corresponds to a rate of 1.881×10^{-4} injected pions per proton on target.

CONCLUSION

A high-acceptance pion transfer line has been designed for the ESSnuSB+ project. The performance of the line was evaluated using a modified Xsuite simulation showing that it exceeds the required pion transfer rate per proton on target. A final tuning of line parameters should be made with an end-to-end tracking simulation once ring parameters are finalised and realistic magnet field maps are available. This may yield further improvements to the overall pion yield at the end of the rate, beyond the targets set for the project.

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