LEnuSTORM: A LOW-ENERGY MUON STORAGE RING FOR NEUTRINO CROSS-SECTION MEASUREMENTS

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Abstract

The LEnuSTORM (Low-Energy neutrinos from STORed Muons) is a proposed facility that enhances the performance of the ESSnuSB (European Spallation Source Neutrino Super Beam) project by measuring neutrino cross sections in the energy range 200–600 MeV, where data is largely missing. The facility utilizes a 1.25 MW proton beam from the European Spallation Source linac, which is compressed in an accumulator into 1.2 µs pulses and directed at a granular titanium target embedded in a horn. Pions collected by the horn are transferred and injected into a racetrack-shaped storage ring, where they decay and emit muons that will be stored in the ring for a few tens of turns. The neutrinos emitted in the muon decay in one of the straight sections will travel to a water Cherenkov detector, where the interactions are monitored.

At LEnuSTORM, the beam is large and very divergent, and thus difficult to contain. The ring design presented in this paper uses iron-dominated magnets to reduce complexity, and a compact FODO lattice to maximise neutrino production by allowing a large transverse acceptance. However, the design pushes fringe-field effects beyond the linear regime and requires a paraxial expansion with higher-order terms, introducing resonances and reduced dynamic aperture. We present here a design that aims at balancing the transverse and momentum acceptance with the dynamic aperture, to maximise neutrino production.

INTRODUCTION

The neutrino beam for the ESSnuSB (European Spallation Source Neutrino Super Beam) long baseline experiment to measure the leptonic charge-parity violation will be produced using the ESS proton linear accelerator. The ESS 5 W, 2.5 GeV, 2.86 ms proton beam will be sent to an accumulator ring and compressed into four sub-pulses, each of 1.2 µs duration before hitting a target [1].

As an extended project of ESSnuSB, the main goal of the LEnuSTORM (Low-Energy neutrinos from STORed Muons) facility is to study precisely the neutrino interaction cross-section for electron and muon neutrinos and their antiparticles. In LEnuSTORM, one of the 1.2 µs compressed proton pulses from the accumulator was extracted to hit a target to produce pions. They are then focused with a magnetic horn and transported to a muon storage ring through a pion transfer line. The transfer line includes a magnetic chicane to separate the pions from the other charged particles emerging from the target, including remaining protons, and will also serve as a momentum selection stage. The pions are injected into the storage ring at the end of one of the arc sections. The pions will decay into muons while traveling in the straight section. Muons within the acceptance will be stored in the ring for a few tens of turns until they eventually decay. Muons outside the acceptance will be dumped or lost, together with any remaining pions. At 30 m from the end of the first straight section, labeled the production straight, a detector named LEMMOND is placed to detect neutrinos produced in the muon decay.

To fulfill the physics goals of the ESSnuSB project, the muon momentum should exceed 400 MeV/c to produce a neutrino energy spectrum covering 200–400 MeV. We have chosen 600 MeV/c muons as the reference circulating particle and 1000 MeV/c pions for the injection. When these pions decay, they will produce 600 MeV/c muons at angles small enough to fall within the ring acceptance.

LATTICE DESIGN

Due to the short lifetime of pions and muons, the geometry of the racetrack ring and the particle momenta influence the neutrino flux. A production straight section of approximately 80 m is sufficient to allow the majority of the pions to decay before they reach the arc. Furthermore, the arc length should be no more than half of the length of the straight section, to enhance the amount of usable muon decays, those occurring within the straight section.

In this design, we aim at favoring a so-called stochastic injection method, which relies on a distinct separation in pion and muon momentum, and the merging of the beams in a dispersive region [2]. The arc must thus offer sufficient dispersion for the physical separation of the beams before the merge.

Since the muons to be stored in the ring have an unusually large transverse emittance and a large momentum spread, our primary goal is to maximise both the transverse and the momentum acceptance. For simplicity, this study only considers normal-conducting magnets, with the magnetic field strength limited to below 2 T. We aim at an aperture radius of 20 cm to reduce cost. These parameters and aspects constrain the storage ring design.

Previous studies of higher-energy nuSTORM facilities have demonstrated the feasibility of a racetrack ring composed of focusing-defocusing (FODO) cells [3]. Other designs use a fixed-field alternating gradient lattice only [4] or in combination with FODO cells [5]. In this design, we explore the use of FODO cells exclusively.

To maximize the number of stored muons, the transverse acceptance of the FODO-cell should be maximized, which implies that the cell length is minimized. We employ a fairly

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short quadrupole length of 0.25 m. The length of each dipole has to be long enough to reduce non-linear kinematic effects and fringe field effects, while short enough to keep the peak dispersion in the dipole down. We set the dipole length to 0.7 m to balance these aspects. With 0.2 m spacing between each dipole and quadrupole, we reach an arc FODO-cell length of 2.7 m. The same cell structure and quadrupole lengths are used in the straight-FODO cell and the matching cell. Note that we have a reversed polarity with respect to the standard, i.e., each cell starts with a defocusing quadrupole in the horizontal plane, since it turns out to facilitate injection.

Straight Section

The straight section consists of a long segment with periodic FODO cells, which is sandwiched between two matching cells. The matching cells adapt the incoming periodic Twiss functions from the arc to the outgoing periodic Twiss functions in the straight-FODO segment, and vice versa.

The quadrupole strengths in the FODO cell are determined by optimising the phase advance per cell. Initially, both the horizontal and the vertical phase advance, μ_x and μ_y respectively, are set to 77° to minimize the β functions. Once we have the ring lattice, the quadrupole strengths are used to fine-tune the overall ring tunes. As a result, the final values of μ_x and μ_y may deviate a few degrees from 77°. The final quadrupoles strengths are optimized in Xsuite [6] to 3.69 m^{-2} and 3.79 m^{-2}, which is well below the maximum value of 7.5 m^{-2} for a 2 T field at the pole tip 20 cm from the center. The cell layout and the corresponding optimised beta functions are shown in Fig. 1.

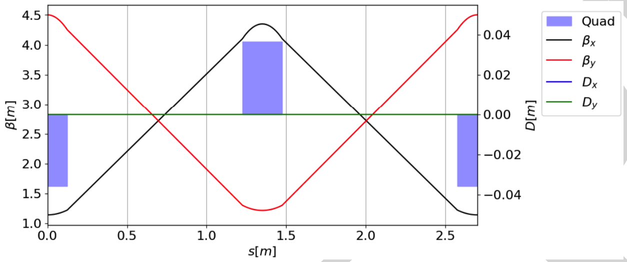

Figure 1: The beta and dispersion functions of the FODO cell in the straight section.

The number of FODO cells in the straight section is chosen so that the total length of the straight section is just above 80 m, in this case 24 cells. Due to the periodicity, the length can be easily adjusted up or down in units of the FODO cell length.

Arc Section

For the arc section, we have chosen a ”supercell” which consists of two FODO cells with two identical sector dipoles in the exterior drift spaces, and with bends missing in the two inner drift spaces. The missing bend creates extra space for injecting the pions onto the muon trajectory in the ring.

By combining multiple supercells and exploiting the periodic behaviour of the optical functions, it is possible to select a phase advance per cell in the horizontal plane, i.e. the bending plane, that cancels the dispersion at the end of the arc. The condition for dispersion closure is given by $\mu_x = 2\pi n/N_{\mathrm{cell}}$, where n is any positive integer and N_{cell} is the number of cells in the arc. The value n indicates the number of dispersion peaks in an arc section. In this design, we choose $n = 2$ to facilitate pion injection because the two peaks will be located at the two ends of the arc to create enough beam separation for the injection. Alternative dispersion suppression methods, such as achromat and half-bend schemes, were also considered but deemed unsuitable. The former was also rejected in a previous study [3]; the latter would result in a longer arc.

Provided that the dipole field remains within the limit <2 T, N_{cell} should be chosen to reduce the total arc length and the beta functions, for given magnet and drift lengths. As a compromise, we select $N_{\mathrm{cell}} = 5$, which gives a horizontal phase advance of $\mu_x = 4\pi/5 = 144°$ per supercell, or 72° per FODO cell. The vertical phase advance is again set to $\mu_y = 154°$ per supercell, or 77° per FODO cell, to provide the smallest possible vertical beam size.

With these phase advance values, we obtain quadrupole strengths of −3.8 m^{-2} and 3.4 m^{-2}. The corresponding dipole strength is $k_0 = 0.45$ m^{-1}, which is well below the $k_{0,\mathrm{max}} = 1.5$ m^{-1} limit as well. Figure 2 shows a representation of the lattice (top) and the periodic beta functions and the dispersion in the five supercells connected to the 27 m long full arc. The dispersion reaches a maximum value of just below 1.5 m and is closed at the end of the arc.

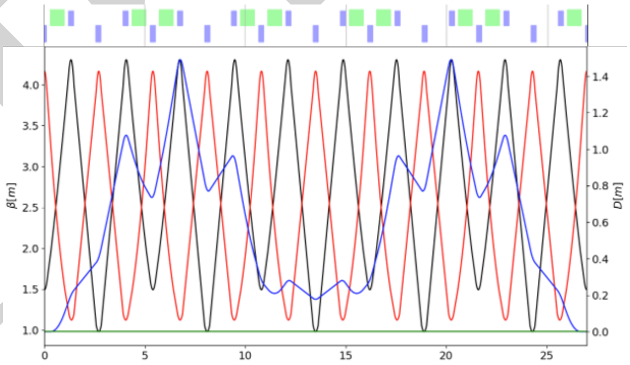

Figure 2: Beta and dispersion functions of the arc. Green blocks are dipoles. Refer to Fig. 1 for other graph labels.

Matching Cell

Each matching section consists of two half-quadrupoles, five quadrupoles and drift spaces. The half-quadrupole at the beginning and end of the cell retain the fixed strengths used in the arc-supercell and the straight-FODO cell, respectively. Only the five quadrupole strengths in between are adjusted to match the Twiss functions between the arc supercells and the straight FODO cells while keeping the drift spaces unchanged. This layout has been chosen among several tried varieties because it provides a smooth transition from arc to straight section.

Since there are four matching conditions, β_x, β_y, α_x, and α_y, but five degrees of freedom, the optimization is under-constrained and not unique. When matching from the straight-FODO cell to the arc section, the first two quadruples are initiated at the same strengths as the straight FODO cell, while the last two quadruples start with the strengths from the arc cell. The middle quadrupole is assigned the average of the values from the straight-FODO cell and the arc. This initialization typically results in the smoothest beta function transitions, as illustrated in Fig. 3.

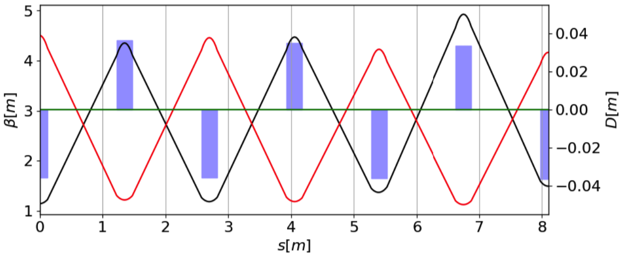

Figure 3: The Twiss functions of the matching cell. The quadrupole strengths of the middle five quadrupoles, from left to right, are 3.76 $\mathrm{m^{-2}}$, −3.71 $\mathrm{m^{-2}}$, 3.60 $\mathrm{m^{-2}}$, −3.75 $\mathrm{m^{-2}}$ and 3.45 $\mathrm{m^{-2}}$.

For simplicity, we have chosen a ring with a two-fold symmetry, which is, for racetrack geometries, the highest available. To this end, the mirror image of the matching section described above is used to match the Twiss functions from the arc section to the straight-FODO cells. That means that the full straight section is composed of, in sequence, the mirrored matching section, 24 straight-FODO cells, and the original matching section.

The Whole Ring

By combining two 27 m arcs and two 81 m straight sections, we reach a full ring circumference of 216 m, and a straight-to-circumference ratio of 0.375. Since muons decay uniformly throughout the ring, the ratio directly influences the maximum neutrino flux in the detector.

The current working point of the ring is (16.19, 16.12), and the natural chromaticity is (−17.81, −18.12). The tight focusing gives a high-acceptance lattice, but also high chromaticity. If we ignore the effect of momentum spread and dispersion, and non-linear effects, we reach a transverse acceptance of 8.9 mmrad.

The high chromaticity and the large beam momentum spread could potentially drive particles into resonance and result in beam losses. It could be reduced by including sextupoles in the design. However, sextupoles are non-linear objects, likely to reduce the dynamic aperture and, through this, the final neutrino flux. An alternative strategy to reduce chromaticity is to relax the focusing in the straight-FODO cells, for example, by extending the cell length while maintaining the phase advance. This action will either severely reduce the acceptance or demand an increase of the already large aperture.

Momentum Acceptance

To further assess the performance of the ring, multi-particle tracking simulations were performed using Xsuite with non-linear models. A beam distribution was generated using a water-bag distribution in phase space with 99 % beam emittance of 8.9 mmrad, optically matched to the ring. The momentum acceptance of the ring is evaluated by first assigning a random uniform relative momentum deviation, δ, in the range from -0.1 to 0.1 to the water-bag distribution. The beam is then tracked in the ring for 40 turns, at which point 90 % of the muons will have decayed (although decay is not activated in the simulation). The surviving particles are registered after the tracking, and the momentum distributions before and after the tracking are shown in Fig. 4. We notice that there is partial momentum acceptance all the way to $\delta = \pm 0.1$ when there is no chromaticity correction.

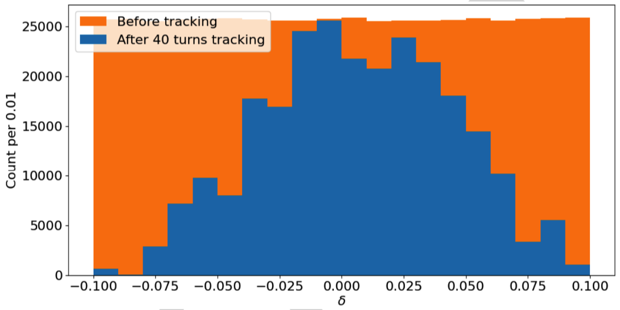

Figure 4: The momentum distribution of particles before (orange) and after (gray) tracking for 40 turns in Xsuite. In the transverse dimensions, the initial 500k macroparticles follow the water-bag distribution. About 255k macroparticles (51 %) survive the 40-turn tracking.

CONCLUSION

An optical design for a muon storage ring has been produced for the ESS-based LEnuSTORM facility. It aims at maximising both the transverse acceptance and the momentum acceptance. The ring employs a complete FODO lattice design and features a high linear transverse acceptance of about 9 mmrad. The dispersion suppression scheme allows a shorter arc. The supercell layout maintains a high transverse acceptance while favouring pion injection. The short-term particle tracking result with an error-free lattice shows no significant particle loss from resonances even under high chromaticities.

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