ESS neutrino Super Beam plus

Co-funded by the European Union

Project Number:
101094628

Project Acronym:
ESSnuSBplus

Call Identifier:
HORIZON-INFRA-2022-DEV-01

Project Full Title:
Study of the use of the ESS facility to accurately measure the neutrino cross-sections for ESSnuSB leptonic CP violation measurements and to perform sterile neutrino searches and astroparticle physics

Start date of project: 2023-01-01
Duration: 4 years
Milestone 4.1 title: Evaluation of the LEnuSTORM requirements and parameter range (WP4+)
Due delivery date: 2024-06-30
Actual delivery date: 2024-06-27
Organization name of lead contractor for this milestone: Uppsala University (UU)

Project co-funded by the European Commission within Horizon Europe Framework Programme		
Dissemination level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	
EU-RES	Classified information: RESTREINT UE (Commission Decision 2005/444/EC)	
EU-CON	Classified information: CONFIDENTIEL UE (Commission Decision 2005/444/EC)	
EU-SEC	Classified information: SECRET UE (Commission Decision 2005/444/EC)	

Milestone number	M4.1
Milestone name	Evaluation of the LEnuSTORM requirements and parameter range
Type of document	Report
Work Package	WP4: LEnuSTORM
Lead Contractor	UU, Sweden
Lead Coordinators	UU Sweden, ESS Sweden, CERN Geneva

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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
nuSTORM	neutrinos from STored Muons
LEnuSTORM	Low Energy neutrinos from STored Muons
LEMMOND	LEnuSTORM / MOnitored beam Near Detector

Contents

1 Introduction

The neutrino beam for the ESSnuSB long baseline experiment will be produced using the ESS proton linear accelerator. The ESS 5 W, 2.5 GeV, 3 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 Low Energy neutrinos from STored Muons (LEnuSTORM) is to precisely study neutrino interactions cross-section for electron and muon neutrinos and their antiparticles. In LEnuSTORM, one of the 1.2 µs compressed protons pulse from the accumulator were extracted to hit a target to produce pions. They are then focused with a magnetic horn and transported to the muon storage ring, through a pion transfer line. The transfer line includes a magnetic chicane to safely separate the pions from the other charged particles, including remaining protons, emerging from the target, and will also serve as a momentum selection stage. The pions are injected into the storage ring at the beginning of one of the straight sections. The pions will decay into muons while travelling in the straight section. Any pions that have not decayed by the end of the straight section will be dumped. Conversely, muons will keep circulating in the ring for a few tens of turns. At tens of meters away from the end of the production straight section, a detector called LEMMOND is used for detecting the neutrinos decayed from the muons.

This report discusses LEnuSTORM's requirements and parameter range. Key information will be bolded. Many parameters are intertwined with each other, and there is no single way to explain them in an easily understandable manner for everyone. Here, we choose to start from the purpose of the experiment and the physics of the particles.

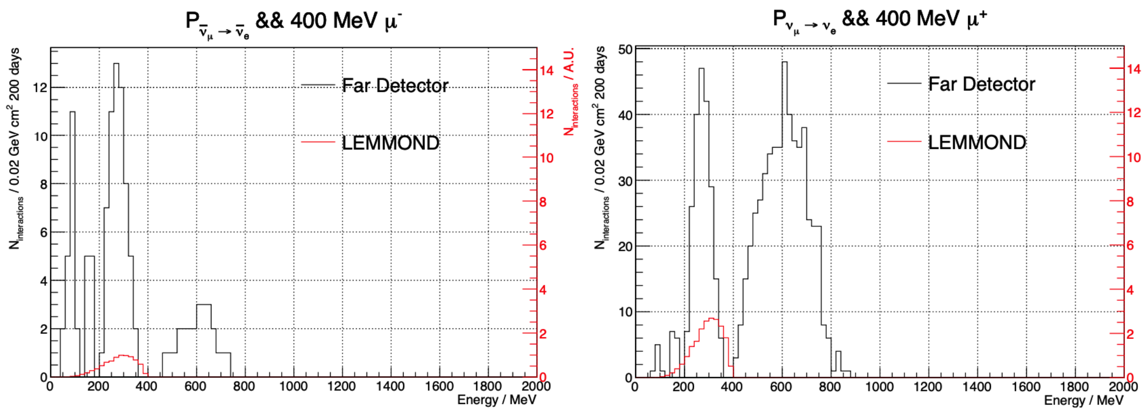
2 Neutrino energy

In order to reduce the systematic error in the ESSnuSB long baseline experiment, we aim at using the LEnuSTORM to measure precisely the neutrino interaction cross-sections in the energy range of interest to ESSnuSB, that is around a few hundred MeV. To maximize the benefit of the LEnuSTORM, the neutrino energy spectrum detected in LEMMOND should overlap with that in the far detector of ESSnuSB. That is, the resulting neutrino energy distribution should overlap with the expected distribution in the far detector, which has the second oscillation peak at about 300 MeV. We have performed a preliminary simulation to identify which muon energy results in the best overlap. In the simulation, monochromatic muon beams are aimed at LEMMOND[1] which has 5 m radius and is placed 50 m away horizontally from the source. When they decay, the muons emit neutrinos. We have estimated the spectrum of those neutrinos that interact with the detector. Muons of 100 MeV/c to 800 MeV/c momentum were simulated. The best match seems to be with neutrinos from a 400 MeV/c muon beam, shown in Figure 1. As a result, **we plan to store muons of 400 MeV/c**.

3 Neutrino and muon beam divergence

The angular distribution of the neutrinos will affect the LEnuSTORM ring design and neutrino detection. Neutrinos emitted from muon decay have a wide range of emission angles. The angular distribution

[1]For details about the detector, please see: MS3: Identification of requirements for LEnuSTORM / monitored beam near detector, in DocDB.



(a) Muons

(b) Anti-muons

Figure 1: First estimated neutrino spectrum in LEMMOND of LEnuSTORM and in the far detector of ESSnuSB. The rightmost peak is the first oscillation maximum whereas we strive to obtain an overlap with the second oscillation maximum which is centered at just below 300 MeV

probability density can be described by the headlight equation, which is valid for (nearly) massless daughter particles [2]:

$$\rho(\theta) = \frac{1}{2} \sin\theta \frac{1 - \beta_r^2}{(1 - \beta_r \cos\theta)^2}, \tag{3.1}$$

where θ is the emission angle between the parent and the daughter particle in the lab frame and $\beta_r = \frac{v}{c}$, with v being the speed of the parent particle in the lab frame, which only travels in the forward direction. With $P_\mu = 400\,\mathrm{MeV/c}$ and $m_\mu = 105.66\,\mathrm{MeV/c^2}$, the relativistic γ_r and β_r factors are 3.96 and 0.966, respectively. The most probable emission angle, i.e. where the probability is at its maximum, is then 0.15 rad. However, the experimental setup of LEMMOND only accepts neutrinos emitted at an emission angle below 0.06 rad with respect to the muon beam axis.

In reality the muons will not all be aimed directly at the LEMMOND. Simulations have been done to investigate how the muon beam direction affects the number of neutrinos reaching LEMMOND. We used a mono-chromatic 400 MeV/c muon pencil beam of 10^6 muons launched towards LEMMOND with the same setup as mentioned in section 2. Eight simulations have been done for eight different angles, from 0 to 0.07 rad, w.r.t. the forward direction. Figure 2 shows the result of the number of neutrinos as a function of the angle, with the y-axis normalised to 1 for the 0 angle case. There are 80% of neutrinos detected at the muon angle of 0.03 rad. At 0.04 rad, only 50% of neutrinos are able to reach the detector. The number of neutrinos drops significantly after this value. It is, therefore, of little use to accept muons of such a high divergence since their contribution to the neutrino flux is very small. **To this end we aim at accepting muons up to 0.04 rad.**

4 Pion momentum

Now that we have settled on the fact that we want to store muons at 400 MeV/c at a divergence up to 0.04 rad we can examine which pion momentum can produce such muons.

Through simulations, we have studied the angular and momentum distribution of muons from pions by allowing monochromatic pions from 400 MeV/c to 700 MeV/c to decay at a long but finite distance. To determine which pion momentum to use, we then look to Figure 3 which shows the muon distribution

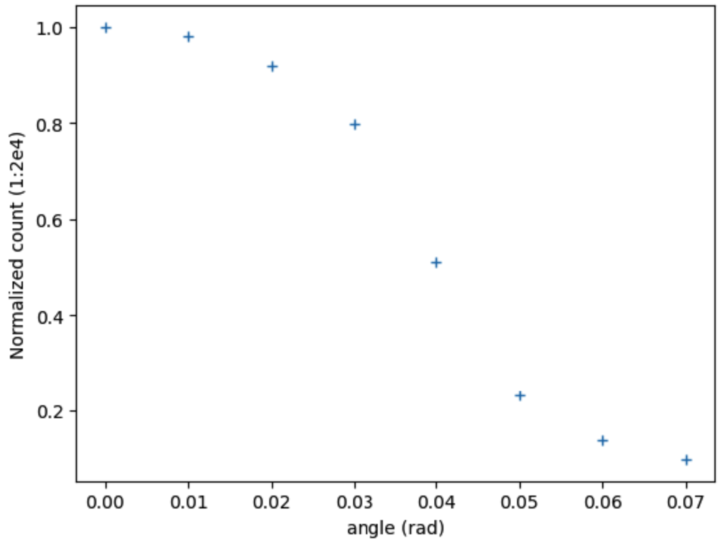


Figure 2: Number of neutrinos reaching LEMMOND as a function of the angle of direction of the muon pencil beam.

from pion decay in momentum and emission angle, which is defined as the angle deviating from the pion beam forward axis. Pions of all four momenta can produce 400 MeV/c muons. However, only 400 and 700 MeV/c pions emit 400 MeV/c muons at an angle below 0.04 rad, which is the cut-off angle we mentioned in the previous section. **We suggest to choose 700 MeV/c pions rather than 400 MeV/c**, for the following reasons:

1. When created at the target, on average the 700 MeV/c pions have a smaller divergence than the 400 MeV/c pions. In other words, if we select pions within an angular acceptance of < 40 mrad, we can collect more pions in the higher momentum case. We here assume that the pion and muon beamlines will have a momentum acceptance of $\pm 10\%$, similarly to the previous nuSTORM designs described in Ref. [3].

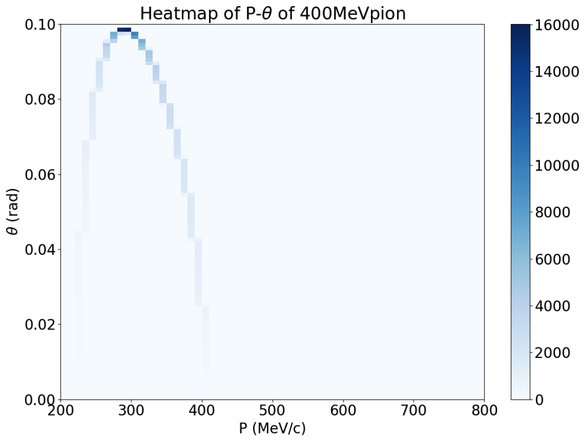
2. The momentum separation between the pion and the muon would be significant, which could be a benefit for an efficient pion injection and extraction using the stochastic injection method, which relies on the momentum difference between pions and muons [4].

3. We want most of the pions to decay in the first straight section of the storage ring. Since the higher momentum implies a longer lifetime, by using the higher momentum pions the requirement on the maximum length of the pion transfer is somewhat relaxed.

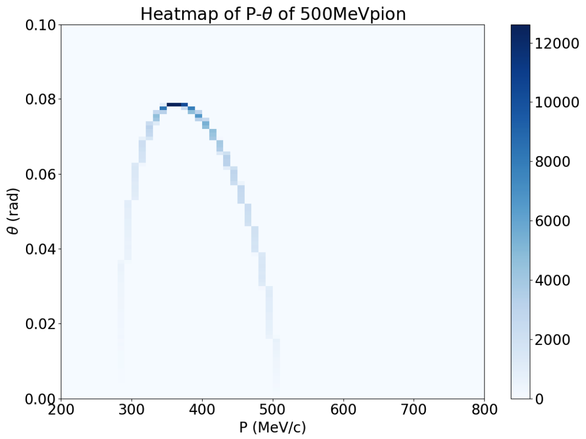
To sum up, if we choose 700 MeV pion beam, we can most likely propagate more pions into the production straight section and collect more muons per pion and, through this, improve the performance of the LEnuSTORM facility. Now that we have selected the most suitable pion momentum, we will use it to define the dimensions of the pion and muon beamlines.

5 Beamline dimensions

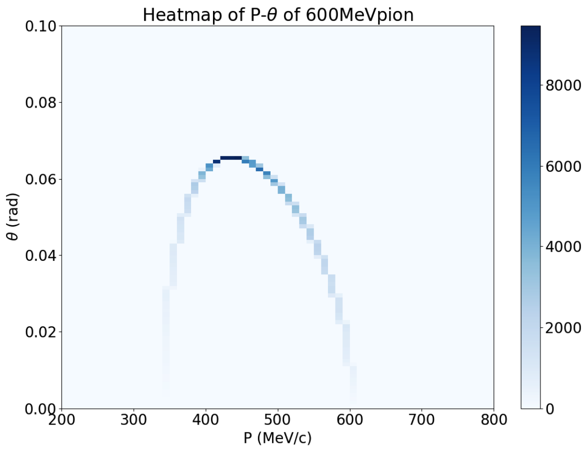
The pions travel from the source through a transfer line and are then injected into the production straight section of the muon storage ring. The number of pions that remain after the transfer line is described



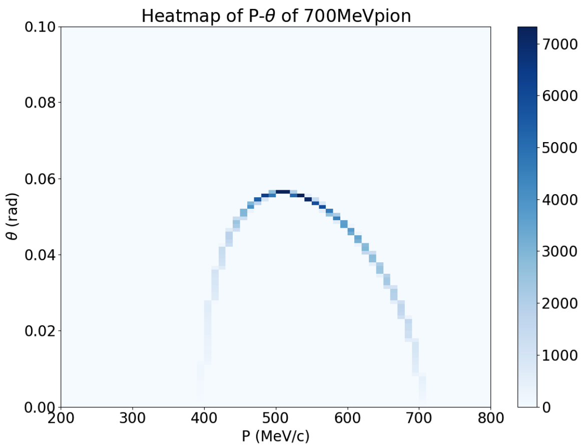
(a) 400 MeV/c.



(b) 500 MeV/c.



(c) 600 MeV/c



(d) 700 MeV/c

Figure 3: Momentum and angular 2D distribution of muons emitted in a pion decay for four different pion momenta.

by an exponential decay, which means that the transfer line is better short than long. The decay length, τ_π, of a 700 MeV/c pion is 39 m. **We are aiming to design a transfer line that is less than 20 m long,** in order to have a more than 60% chance that the transferred pion decays after the transfer line.

Ideally we want all the remaining pions to decay inside the production straight section of the ring. The following equation gives the ratio R_π of pions that decay inside the straight section compared to the initial number of pions at the source:

$$R_\pi = e^{-\frac{L_t}{\tau_\pi}}(1 - e^{-\frac{L_s}{\tau_\pi}}),. \tag{5.1}$$

Here, L_t is the length of the transfer line and L_s is the length of the straight section. The first exponential describes the decay in the transfer line. The second part of the equation shows that the ratio R_π of "useful" pions flattens out as L_s increases. Figure 4 shows the plot of R_π as a function of L_s with a fixed transfer line length of $L_t = 20$ m. For the purpose of neutrino production, L_s should be as long as possible. However, the longer the straight section, the higher the cost. To balance performance and cost, **we select L_s = 100 m as the maximum length, and $L_s = 75$ m as a more probable length.**

Since neutrinos are produced everywhere in the ring, the number of neutrinos that can reach the LEMMOND detector is maximized by maximizing the ratio of the length of the straight section to the

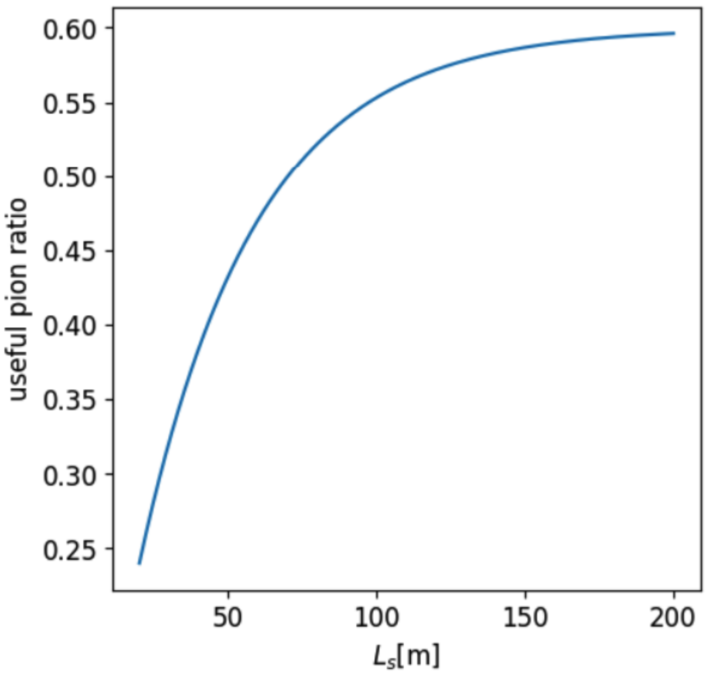


Figure 4: Pion decay ratio in the straight section as a function of L_s with $L_t = 20\,\mathrm{m}$.

ring circumference. In a racetrack ring design, this ratio is given by

$$R_\nu = \frac{L_s}{2L_s + 2L_a} = \frac{1}{2(1 + L_a/L_s)} \tag{5.2}$$

where L_a is the length of one arc, and L_s is the length of one straight section. Figure 5 shows the ratio as a function of L_s/L_a. The equation implies that the arc should be as short as possible, which, in turn, means a high field strength in the arc magnets and a densely packed magnet lattice, which can increase the cost and complexity of the ring. However, in the figure, we observe that the ratio flattens out at around $L_s/L_a > 3$. Previous studies have used $L_s/L_a \sim 1.7$ [5, 3]. We believe that $L_s/La \leq 3$ is a cost-efficient value that does not compromise the performance. With the previously set maximum length of the straight section of 100 m, **we aim for a maximum arc length,** $L_a = L_s/3 \approx 33\,\mathbf{m}$, but most likely, we will achieve a lower value.

Each arc will bend the 400 MeV/c muons at an angle of 180° using dipole magnets. As described above, it should be as short as possible, which implies high magnetic field strengths and a densely packed magnet lattice. We have chosen to aim for an arc design that uses conventional, separate-function, normal-conducting magnets. The maximum operational limit of a normal-conducting magnet is 2 T because of the saturation of the magnetization. In order to have a safety margin in the design, **we target a maximum field of** $B \leq$**1.5 T.** The bending radius, ρ can be calculated through the expression for magnetic rigidity:

$$\begin{aligned} p\,[\mathrm{GeV/c}] = 0.3B\rho\,[\mathrm{T{\cdot}m}] \quad \Longleftrightarrow \\ \rho\,[\mathrm{m}] = \frac{p\,[\mathrm{GeV/c}]}{0.3B\,[\mathrm{T}]} \end{aligned} \tag{5.3}$$

where p is the momentum. With $B \leq 1.5\,\mathrm{T}$ and $p = 0.4\,\mathrm{GeV/c}$, we obtain

$$\rho \geq \frac{0.4\,\mathrm{GeV/c}}{0.3 \cdot 1.5\,\mathrm{T}} = 0.89\,\mathrm{m}. \tag{5.4}$$

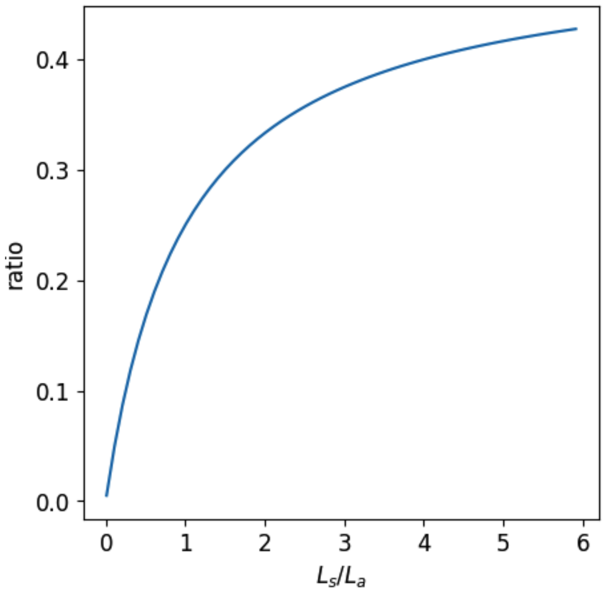


Figure 5: The ratio between the length of the straight section L_s and the ring circumference as a function of L_s/L_a with L_a being the arc length.

From the minimum bending radius and the total bending angle $\theta = \pi$ rad we can calculate the minimum effective length S of the total bend through $S = \theta\rho \geq \pi \cdot 0.89\,\text{m}{=}2.8\,\text{m}$. This, however, is not the same as the minimum total length of the arc since we will also need quadrupoles for focusing and higher-order magnets for chromatic corrections, etc. in the arc. In addition, we want to minimize the maximum dispersion in order to reduce the maximum beam size in the arc. This may require separating the dipole magnets into several smaller units which requires additional space. If needed, we will consider using combined-function magnets at a later stage, as a measure to make the arc more compact.

Although a large aperture, simply speaking, means a higher muon flux in the ring it also impacts the technical complexity and cost of reaching the high magnetic field strength that is desired. Previous studies have considered very large apertures, up to 60 cm diameter, in their storage ring designs [3]. It is likely that our design will require similar apertures in order to deliver sufficient neutrino intensity. **Therefore, as a starting point in this study we consider a full aperture of ⌀= 60 cm.** However, the possibility of using a smaller aperture, down to ⌀= 20 cm, will also be investigated to lower the overall cost.

The acceptance of a storage ring refers to the maximum phase space area that a particle beam can occupy. It consists of a geometric acceptance, imposed by the physical aperture, and a dynamic acceptance, which is due to nonlinearities in the magnetic fields and other effects. The existing nuSTORM designs at higher energy report acceptances of 1 mmrad [3] and 2 mmrad [5]. An even larger transverse acceptance may be needed in this project for accepting the large divergence muons and pions which is a result of the lower energy. We aim for 5 mmrad but the acceptance value in our ring is still under study.

6 Twiss parameters

In the beamline design, we can control the magnet configuration in terms of magnet type, position and strength, which is mathematically represented by the so-called optical the beta function that varies from point to point along the beamline. In each position, we can calculate the beam size and the beam divergence from the beta function if we know the beam footprint in phase space, or *emittance* ϵ, i.e. in position x and direction x' with respect to the ideal particle trajectory. Emittance is defined as a finite area in the position-direction space and is a conserved quantity throughout the beamline and an intrinsic property of the beam. Note that emittance itself is a two-dimensional quantity with a unit of m·rad.

Since the magnet configuration is different at different longitudinal positions s, the beta value, beam size and divergence are different too. In locations with no dispersion and where there is no correlation between beam size and divergence we can easily calculate the beam size and divergence through

$$\sigma_{x'} = \sqrt{\frac{\epsilon}{\beta}}, \tag{6.1}$$

$$\sigma_x = \sqrt{\epsilon\beta}. \tag{6.2}$$

If we now assume that the maximum divergence we can accept is $\sigma_{x',\mathrm{max}}$, which will occur at position s_d at the center of a defocusing quadrupole magnet where the beam size is small, we can calculate the minimum value of beta β_{min} in the beamline:

$$\beta_{min}(s_d) = \frac{\epsilon}{\sigma^2_{x',max}}. \tag{6.3}$$

Similarly, if we assume that the maximum beam size we can tolerate is $\sigma_{x,\mathrm{max}}$, we can calculate what value the beta function can maximally take, β_{max}, through

$$\beta_{max}(s_f) = \frac{\sigma^2_{x,max}}{\epsilon}. \tag{6.4}$$

where s_f is the longitudinal position of the maximum value in the beamline, at the center of a focusing quadrupole.

Table 1 shows a summary of the minimum value of the beta function that would be required for a given beam emittance and the maximum divergence of $\sigma_{x,\mathrm{max}} = 0.04$ rad. Here, we have used similar values for the beam emittance as were stated for the transverse acceptance. For example, if $\epsilon = 1$ mmrad and $\sigma'_x = 0.04$ rad, then $\beta_{min} = 0.63$ m. Note that these are the respective beta values we must reach if we want the beam line to accept muons with a divergence 0.04 rad.

Table 1: The minimum value β_{min}, calculated using equation 6.3 given the maximum divergence and emittance values listed below.

ϵ [mmrad]	$\sigma_{x',max}$ [rad]	β_{min} [m]
0.1	0.04	0.063
1.0	0.04	0.63
2.0	0.04	1.25
3.0	0.04	1.87
4.0	0.04	2.50
5.0	0.04	3.13

If we similarly assume that the maximum beam size $\sigma_{x,\mathrm{max}}$ we can accept is equal to the physical aperture r, we can calculate the maximum value of beta, β_{max} using equation 6.4. These values are listed in Table 2 where we again have used emittance values similar to those mentioned in the discussion on the transverse acceptance. As an example, we see that if $\epsilon = 1$ mmrad and $\sigma_{x,\max} = 0.1$ m $(= r)$, then $\beta_{\max} = 10$ m.

Table 2: The maximum value β_{max}, calculated using equation 6.4 given the maximum beam size (equal to the aperture radius) and the emittance values listed below.

ϵ [mmrad]	$\sigma_{x,\max}$ [m]	β_{max} [m]
0.1	0.1	100
1.0	0.1	10
2.0	0.1	5.0
3.0	0.1	3.3
4.0	0.1	2.5
5.0	0.1	2.0
0.1	0.2	400
1.0	0.2	40
2.0	0.2	20
3.0	0.2	13
4.0	0.2	10
5.0	0.2	8.0
0.1	0.3	900
1.0	0.3	90
2.0	0.3	45
3.0	0.3	30
4.0	0.3	23
5.0	0.3	18

From Tables 1 and 2 we immediately observe that certain combination of parameters will be difficult or impossible to reach. We will use the content of the tables as guidance when we design the muon storage ring. Later on we will perform simulations to assess its performance and extract the actual value of the transverse acceptance, etc.

7 Summary

We have evaluated the LEnuSTORM requirements and parameters in order to identify the most important boundary conditions for the nuSTORM design. The first estimated neutrino spectrum in LEMMOND of LEnuSTORM and the far detector of ESSnuSB from 400 MeV/c muons shows the best overlapping with the second oscillation maximum. From this, we have decided to design the muon storage ring for 400 MeV/c muons.

Although the angular acceptance of LEMMOND is 0.06 rad we have concluded the neutrino collection efficiency is below 50% for muon angles larger than 0.04 rad, which is why that is the maximum muon beam divergence we plan for the ring to accept.

To generate 400 MeV/c muons at a divergence smaller than 0.04 rad we plan to collect pions at 700 MeV/c from the target. These will be transferred to the storage ring in a $\lesssim 20$ m long transfer line in order to allow for a maximum of 40% of the pions to decay already before the ring. A 75-100 m straight section is a cost-efficient choice that allows most of the remaining pions to decay in the productions straight section. The straight section will be up to three times longer than the arc, which means a maximum arc length of 33 m.

We target a maximum magnet field of 1.5 T, and a maximum aperture of 60 cm. We aim for a transverse acceptance between 1 and 5 mmrad.

Lastly, the parameters mentioned above have been used for setting limits for the optical ring design, by identifying how the beam divergence, the physical aperture and the desired acceptance affects the beam optical parameters. These values will give a starting point to the design of the pion and muon beamlines.

Needless to say, the detailed design of the storage ring and its performance assessment is still ongoing and some of the parameters discussed in this report may change as the work progresses.

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