ON THE SUITABILITY OF A SOLENOID HORN FOR THE ESS NEUTRINO SUPERBEAM

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Abstract

The European Spallation Source (ESS), now under construction in Lund, Sweden, offers unique opportunities for experimental physics, not only in neutron science but potentially in particle physics. The ESS neutrino superbeam project plans to use a 5 MW proton beam from the ESS linac to generate a high intensity neutrino superbeam, with the final goal of detecting leptonic CP-violation in an underground megaton Cherenkov water detector. The neutrino production requires a second target station and a complex focusing system for the pions emerging from the target. The normal-conducting magnetic horns that are normally used for these applications cannot accept the 2.86 ms long proton pulses of the ESS linac, which means that pulse shortening in an accumulator ring would be required. That, in turn, requires H- operation in the linac to accommodate the high intensity. As an attractive alternative, we investigate the possibility of using superconducting solenoids for the pion focusing. This solenoid horn system needs to also separate positive and negative pion charge as completely as possible, in order to generate separately neutrino and anti-neutrino beams. We present here progress in the study of such a solenoid horn.

INTRODUCTION

The European Spallation Source (ESS) will provide neutrons to a variety of experiments in the applied sciences, starting 2019. The spallation neutrons are generated by a 5 MW proton beam impinging at 2 GeV on a rotating tungsten target. This world-unique intensity attracts projects beyond the neutron sciences, one of which is the ESS neutrino superbeam study, ESSnuSB [1]. The ESSnuSB plans to use a 5 MW beam from the ESS linac to produce an intense neutrino beam in a separate target station, as shown with the sketch in Fig. 1. These neutrinos will be directed towards an underground detector several hundreds of kilometers from the ESS site, where the number of electron and muon neutrinos will be counted. Placed at the second neutrino oscillation maximum, the megaton water Cherenkov detector is expected to help settle the existence of CP violation in the leptonic sector, by recording and comparing the amounts of neutrinos and anti-neutrinos.

The nuclear reactions that occur as the proton beam hits the target generate a shower of hadrons, mostly pions. These pions are to be collected and focused so that they travel in the direction of the far detector before they decay into muons and muon neutrinos. The established way of hadron collection is with a magnetic horn [2], which consists of a toroidal magnet structure where the pions need to traverse a thin metallic conductor layer in order to reach the magnetic field region. The structure is powered by 350 kA [3], which leads to heavy ohmic heat dissipation in the conductor layer. As a result, the horn cannot accept the 2.86 ms proton pulse directly from the ESS linac, but an accumulator ring for pulse compression down to a few microseconds, is required [4]. For efficient injection into the ring the linac must support acceleration of H^- as well as the protons for neutron production, which has additional implications for the linac optics, and for the minimum curvature of transfer lines, etc. In addition, it requires an H^- source. In total, the horn requirements lead to an increase of the project complexity and cost and there are strong motivations for an alternative hadron collection scheme using superconducting magnets.

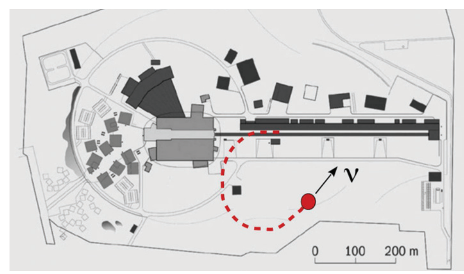

Figure 1: A sketch of the ESSnuSB layout at the ESS site.

BACKGROUND

An attractive alternative to the van der Meer horn is a superconducting solenoid. Earlier studies conducted for neutrino factories and muon colliders, as well as for neutrino superbeams, have shown that a solenoid horn could perform as well or better for certain neutrino energy ranges [5]. Here, we look specifically at the ESSnuSB case with a moderate proton beam energy of 2 GeV.

The pion distribution expected from the target was computed by N. Vassilopoulos for a van der Meer horn [3] and is shown in Fig. 2. We see a wide distribution both in total momentum and in emission angle θ with respect to the forward axis. The 2D distribution has its peak at around 500 MeV and 0.6 rad, which, with the strong tails, means that powerful collection directly at the target is necessary.

Figure 3 shows the decay scheme of the pions, whose life time in the rest frame is 26 ns. Since the detector cannot distinguish neutrinos from anti-neutrinos the pions of the wrong sign must be removed close to the source, before they have time to decay and contaminate the beam. Secondly, the length of the decay tunnel must be optimized so that the number of muons that have time to decay is mini-

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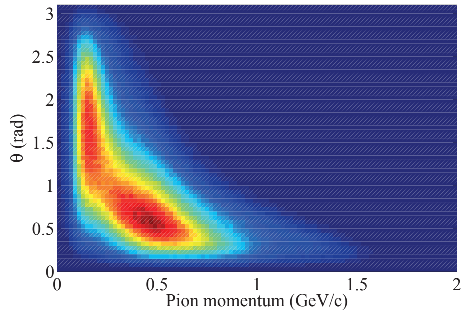


Figure 2: The pion distribution in total momentum and exit angle θ with respect to the forward axis.

mized. Since the pion decay gives an additional spread in angle to the emitted neutrino, it is only required to focus to an accuracy such that the final divergence is dominated by the pion decay kinematics. The functionality of the pion collector can thus be summarized as follows: collect as many π^+ (π^-) as possible such that the first generation neutrino flux at the detector is maximized, while simultaneously removing the π^- (π^+) as completely as possible.

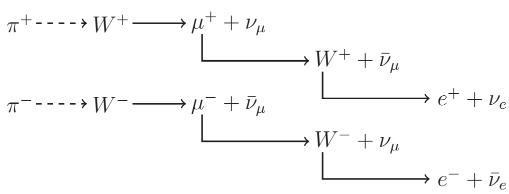


Figure 3: The decay chains of π^+ and π^-.

THE SOLENOID COLLECTOR

With the basic requirements given above as a basis for our study, we start with examining the focusing capabilities of solenoids. Although the pion distribution that we are dealing with is far from a paraxial beam, we use the paraxial ray envelope equation from Reiser [6]. This equation describes the evolution of the beam envelope $r(z)$ through an axi-symmetrical system, assuming an initial beam envelope of r_0 at the starting point. The paraxial ray approximation means that we consider a beam where the particles are close together in space, direction and momentum. We consider the longitudinal field on axis, including the fringe field.

Point-to-parallel Focusing

Since the detector is located several hundred kilometers from the target we can consider the nature of the focusing as point-to-parallel. In reality, we need only to reduce the beam divergence to the point where the angular spread from the pion decay is dominant.

In Fig. 4(a) we observe that it is possible, with a single solenoid, to focus a moderately divergent beam from a point before the magnet, where the residual magnetic field is small (a fraction 10^{-4} of the maximum field on axis), to a beam with almost no divergence at the exit of the solenoid. However, if we place the target inside the solenoid, we fail to achieve such focusing. The reason is described by Busch's theorem: the canonical momentum in the azimuthal direction p_θ is a constant of motion in the axisymmetrical system. And since $p_\theta \propto B_z r^2$, it implies that the envelope r grows if the field on axis B_z decreases.

A solution to this fundamental limitation is to let the envelope grow slowly by adding a weak magnetic field behind the first stronger solenoid. This combination of a short but strong solenoid followed by a long but weak solenoid, sometimes called the quarter-wave transformer [7], transforms a small but highly divergent beam into a large, quasi-parallel beam. An example is shown in Fig. 4(b). Note, however, that these results hold only for a beam with a narrow energy distribution. To increase the energy acceptance we turn to the so-called adiabatic device [7]. Instead of two solenoids, we use a continuously decreasing magnetic field accompanied with an increase of the bore radius, so that the highly divergent beam is allowed to slowly expand while losing transverse momentum. An example of such focusing is shown in Fig. 4(c). Figures 4(a)-4(c) all show the same beam parameters: relativistic Lorentz factor $\gamma = 4$, initial radius $r_0 = 10$ mm, and initial divergence $r'_0 = 100$ mrad.

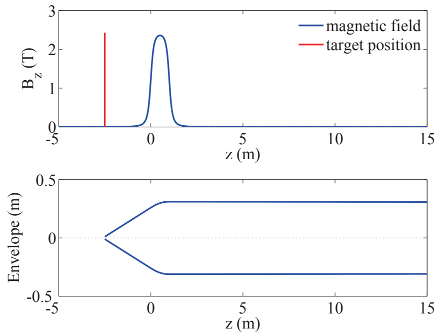
Now that we have seen that, given certain beam parameters, we can reach the focusing strength that we need, we attack the next challenge: the charge selection scheme.

Charge Separation

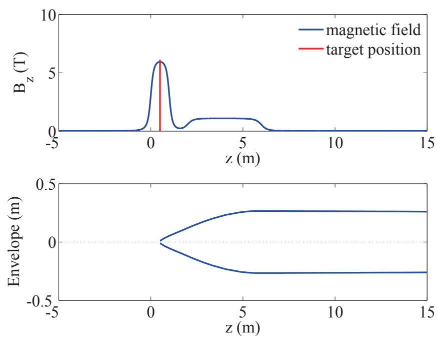
In order to separate the charges in the transverse plane we need to add a dipole field. Looking at the distribution in exit angle in the horizontal plane directly at the source we observe that a mere separation here is inconceivable due to the long tails extending to $\pm\pi/2$. With a requirement of a contamination below 1% we would have to separate the two charges by angles $\pm\pi/4$, respectively, or else we need to first collect the divergent particles with a solenoid and only after add the dipole field.

In order to continuously keep the pions focused we assume a solenoid field superimposed with the dipole field. This is equivalent to tilting the solenoid so that the resultant field vector is on the axis. For this calculation we employ transfer matrices, which means that we assume paraxial rays as well as hard-edge models for the magnet, for which the field is zero outside and constant inside the magnet.

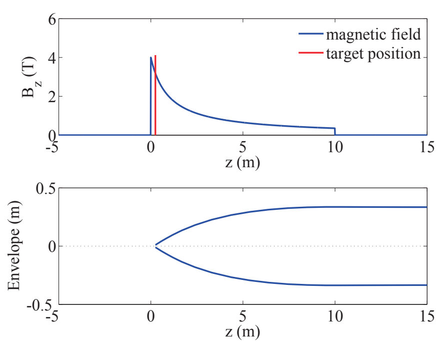
A first simple set-up, shown with a block diagram in Fig. 5, was tested in MatLab. Each function represent one or several magnets, e.g. a single solenoid, as for the initial collection stage, or a combined solenoid and dipole for the charge separation. An absorption stage in the middle would be used to stop the π^- while the π^+ can pass. The third stage is used for bringing the selected pions to the forward axis, and to reduce the envelope growth due to dispersion. Finally, the last step would consist of a collection of solenoids optimised to reduce the pion divergence below the angle corresponding to the pion decay kinematics. Figure 6 shows an example of the transverse distribution of π^+ and π^-, at the absorption position. Here, we have used a Gaussian particle distributions in the angular divergence, with rms width



(a) a single solenoid



(b) the quarter-wave transformer



(c) the adiabatic device

Figure 4: Beam envelope evolution for the case where a) the target is placed outside a single solenoid; b) the target is put inside a strong solenoid followed by a weaker one, and c) the target is put inside an adiabatic device with a continuously decreasing field

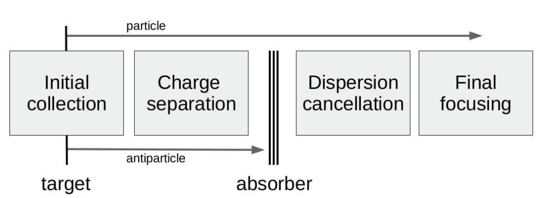


Figure 5: A scheme of the envisioned configuration of the solenoid system.

around 1 degree. The initial beam size is around 1 cm and the energy spread is 10% around 600 MeV. In this simple

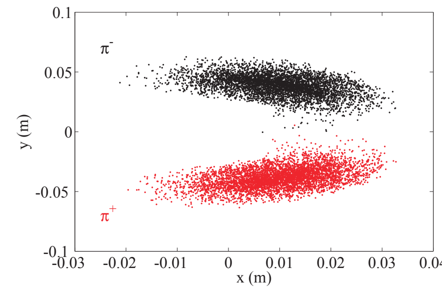


Figure 6: An example of the separation of charges in the middle of the set-up.

configuration it is thus possible to select one charge and remove the other.

CONCLUSION

The ESSnuSB aims at using the ESS linac to produce an intense neutrino superbeam for a long baseline oscillation experiment that could reveal CP violation in leptons. To reduce the cost and complexity of the project on the accelerator side, we have performed preliminary investigations of the possibility of using a superconducting solenoid to collect pions emerging from a target. The solenoid system should reduce the angular divergence down to the order of the spread caused by the pion decay. Furthermore, the two pion charges need to be separated close to the source, as completely as possible. Previous studies suggest that the focusing capabilities are enough. We observe that in order to find a solution to the charge separation problem, further studies, which go beyond the paraxial beam optics used here and take the full angular and momentum distribution into account, are needed.

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