NEUTRINOS FROM A PION BEAM LINE: nuPIL *

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Abstract

The Fermilab Deep Underground Neutrino Experiment (DUNE) was proposed to determine the neutrino mass hierarchy and demonstrate leptonic CP violation. The current design of the facility that produces the neutrino beam (LBNF) uses magnetic horns to collect pions and a decay pipe to allow them to decay. In this paper, a design of a possible alternative for the conventional neutrino beam in LBNF is presented. In this design, an FFAG magnet beam line is used to collect the pions from the downstream face of a horn, bend them by ~5.8 degrees and then transport them in either a LBNF-like decay pipe, or a straight FODO beam line where they decay to produce neutrinos. Using neutrinos from this PIon beam Line (nuPIL) provides flavor-pure neutrino beams that can be well understood by implementing standard beam measurement technology. The neutrino flux and the resulting δ_{CP} sensitivity from the current version of nuPIL design are also presented in the paper.

INTRODUCTION

The Deep Underground Neutrino Experiment (DUNE) aims at studying long-baseline neutrino oscillation by utilizing a wide-band neutrino beam from Fermilab. In the current design, DUNE will be supported by the Fermilab Long-Baseline Neutrino Facility (LBNF), which is required to provide a 1.2 MW proton beam power, upgradable to multi-megawatt power, and detectors for various physics searches. DUNE is required to have sensitivity to CP violation of better than 3σ over more than 75% of the CP-violating phase δ_{CP} [1].

However, there are many challenges in producing a neutrino beam following the LBNF design. These include the uncertainty in secondary particle production rate and dynamics, target and horn stability, and primary proton beam targeting stability. Many of these challenges can be handled by using a magnetic beam line to transport only the secondary pions of interest to a neutrino production straight.

The neutrinos from a PIon beam Line (nuPIL) concept, as a substitution for a conventional horn and decay pipe neutrino facility, works to provide a flavor-pure neutrino beam with precisely measurable flux. The nuPIL concept can avoid the difficulties caused by dissipating large amounts of radiation underground by using a bend to collect and transport only those particles within a desired momentum range. Uninteracted protons and high-energy secondaries are sent to an absorber located at grade.

Two types of beamlines were investigated and considered for nuPIL, a pure FODO lattice [2] and then an FFAG + FODO (hybrid) lattice. A pure FFAG lattice design is under way, but could have many challenges, such as the neutrino flux is unavoidably reduced when produced in an FFAG straight because of the “scallop angle" of the cell structure. In this paper, the present version of a hybrid lattice for nuPIL is presented. The optics design, tracking result, neutrino flux from the beamline, and the corresponding sensitivity to CP violation are presented.

OPTICS DESIGN OF THE FFAG STEERING BEND SECTION

In the current LBNF design, the neutrino beam is directed toward the Far Detector (FD) at the Sanford Underground Research Facility (SURF) by steering the primary high energy proton beam upwards on a hill, and then steering downwards at a 5.8° pitch angle with respect to the surface so that the neutrino beam points towards SURF. The target is bombarded by the proton beam, thus produce secondary pions that decay in a pipe. These pion decays produce a neutrino beam that points to the FD.

In order to prevent unwanted power from going deep underground, it is natural to bend the secondary pions to form the required 5.8° pitch angle after they are generated. The dipole field in the FFAG cells provides this pitch angle and allows one to keep either π^+ or π^- while pions with the opposite sign can be either absorbed, or potentially used by a short-baseline neutrino program, such as nuSTORM [3, 4]. The use of scaling FFAG magnets [5, 6] could increase the momentum acceptance of the pion beamline, therefore expand the neutrino energy spectrum, which is useful for the δ_δ studies [7]. Meanwhile, the Twiss β function in the steering bend section should be kept as small as possible to ensure good transmission. FFAG lattices have a large transverse acceptance, and thus are ideal for the pion beam after the collection horn, which has a large RMS emittance. The steering bend section is composed of a dispersion creator section to bring up the dispersion from 0 at the end face of the horn, followed by a dispersion suppressor to slightly reduce the dispersion for matching to a FODO straight. The optics of the FFAG section in shown in Figure 1.

HORN OPTIMIZATION BASED ON THE FFAG ACCEPTANCE

nuPIL uses a single horn with a 4 interaction lengths carbon target to produce and collect secondary pions. The

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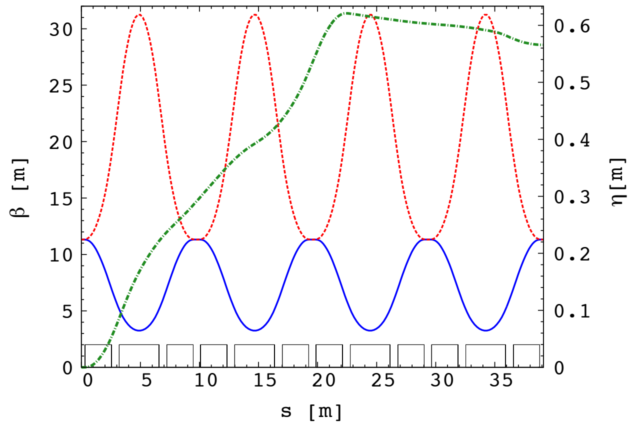

Figure 1: The optics of the FFAG steering bend section, which is followed by a FODO straight section to accommodate pions while they decay to neutrinos for the DUNE Far Detector.

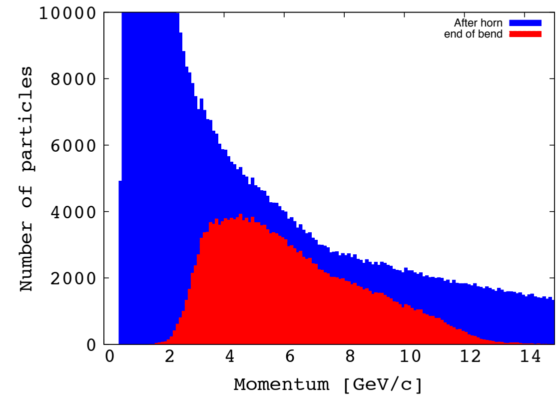

Figure 2: The momentum histograms of the pions after the optimized horn and at the end of the steering bend section.

pion production was simulated using MARS15 [8] and then pion transportation in the magnetic field of the horn was simulated separately using G4beamline [9]. The size and shape of the FFAG transverse phase space acceptance change with beam momenta for the lattice designed at 5 GeV/c. The momentum-wide transverse acceptance of the beamline has been defined by tracking. Correspondingly, an objective function was defined to maximize the number of particles in the acceptance at each momentum.

The Genetic Algorithm (GA) that was used in this optimization has been tested for several cases [10]. The package has been developed to a mature stage and many optimizations were done using NERSC machines. With the inherited nuSTORM horn as a seed in the optimization, the GA was able to converge on an optimal solution within 30 generations, increasing the objective value by 80%, compared to the initial seed. The momentum distributions of the pions after the optimized horn and those at the end of the steering bend section are shown in Figure 2.

THE FODO DECAY STRAIGHT SECTION

Two schemes for the FODO decay straight have been studied, one with a 3-quad matching section and the other with 6-quad matching, both being followed by triplet cells. Because the beam has a wide momentum spread, it is desirable to not only match the linear optics at the central momentum 5 GeV/c, but to find a balance between all momenta and minimize the chromatic effect. Also, the angular divergence of the beam must be minimized in the straight in order to produce enough neutrinos that can be accepted by the FD. The most representative figure of merit, which also served as the objective of the decay straight optimization, is the integrated ν_μ flux at the FD.

A software package was developed to adopt this requirement, which uses G4Beamline to record the direction of motion of particles before they decay, and an analytical formula to calculate the flux at a certain distance from the decay point [11]. 17 free parameters were used in this optimization, including all the drift lengths between magnets, 6 independent quadrupole gradients for the matching quads, and 2 gradients for the triplet cell structure. The same GA package as described in the previous section was used to do this optimization, which in the end yielded an 18% increase compared to the seed, which was designed based on the linear optics at 5 GeV/c.

NEUTRINO FLUX FROM NUPIL

The neutrino flux at the FD from the combined optimized target and horn, FFAG steering bend section and an optimized 6-quad matching FODO straight is shown in Figure 3. The current optimized neutrino beam with 3-horn focusing from LBNF is included as a comparison. nuPIL is capable of generating a wide-band beam that is comparable to the LBNF optimized beam, but, due to the finite beamline acceptance, the integrated flux over all neutrino energies is smaller. On the other hand, due to the sign-selection from bending the beam, the neutrino background from the opposite-sign decays is considerably lower. With all the effects combined, the corresponding comparison of the δ_{CP} sensitivity is shown in Figure 4.

CONCLUSION

A pion beamline design as an option for LBNF was described. The neutrinos from a PIon beam Line (nuPIL) was shown to possess many advantages. Many lattices were simulated, and an FFAG steering bend section with a fairly large momentum acceptance was obtained. Based on the FFAG acceptance, the single horn that is used to collect the secondary pions was optimized. The FODO straight section uses 6 matching quads and triplet cells to accommodate pions while they decay to neutrinos. The δ_{CP} sensitivity from the nuPIL beam is comparable to the current LBNF optimized beam. At the 3σ level, the performance of nuPIL

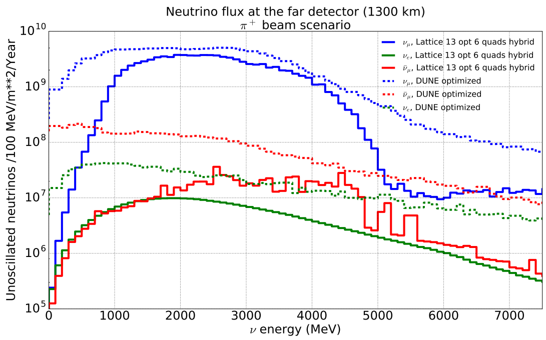

Figure 3: The neutrino flux at the Far Detector (FD), 1300 km away from the end of the FODO decay straight, compared with the optimized three-horn collection scheme.

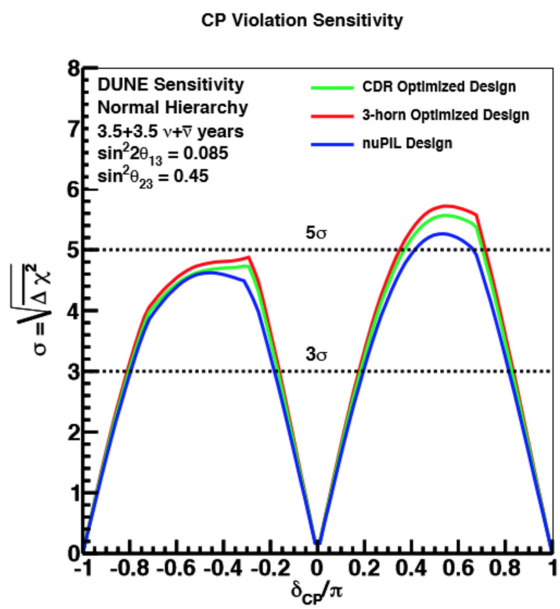

Figure 4: The δ_{CP} sensitivity from the neutrino beam generated in the current nuPIL hybrid lattice and from the current optimized 3-horn LBNF neutrino beam.

and current optimized LBNF is almost identical. Detailed studies on errors, energy deposition and realistic horn simulations are on the way.

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