A FODO BEAM LINE DESIGN FOR nuPIL*

A. Liu†, A. Bross, Fermi National Accelerator Laboratory, Batavia, USA
J-B. Lagrange[1], Imperial College, London, UK
[1]also at Fermi National Accelerator Laboratory, Batavia, USA

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, a FODO 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 a straight beam line where they decay to produce neutrinos. The idea of using neutrinos from the 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 FODO nuPIL are also presented in the paper.

INTRODUCTION

The Deep Underground Neutrino Experiment (DUNE) aims at studying long-baseline neutrino oscillation by utilizing a multi-megawatt wide-band neutrino beam from Fermilab. In the current design, DUNE will be supported by a Long-Baseline Neutrino Facility (LBNF), which is required to provide a 1.2 MW beam power upgradable to multi-megawatt power, and detectors for various physics searches. LBNF 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 regarding producing a neutrino beam following the design of LBNF. These include 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.

There are primarily two types of beamlines being considered for nuPIL, a FODO lattice or an FFAG lattice. In this paper, a FODO lattice for nuPIL is presented. The optics design, tracking result, neutrino flux from the beamline, and the corresponding sensitivity to CP violation are discussed.

OPTICS DESIGN AND TRACKING

In the current LBNF design, the neutrino beam is directed to point to 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 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 [1].

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. This can be achieved by using bending dipoles in the pion beamline, which also allows one to keep π^+ or π^- while pions with the opposite sign can be absorbed. A double bend achromat is designed to fulfill this task, and to minimize the beam size in the continuing decay straight formed by FODO cells.

Based on the pion beamline design for nuSTORM [2], with commercially available dipole and quadrupole magnets the pion beamline can accept beam up to 2 mm·rad in transverse emittance. The Twiss functions and dispersion function are controlled based on this information. The starting Twiss parameters were obtained by fitting the phase space of the pions after the nuSTORM baseline target + horn [3].

At the end of the steering bend section, the linear dispersion is corrected to 0. There are two scenarios to be considered:

- Scenario 1: Using a matching section, allow the beta functions to grow in order to yield a smaller beam angular divergence. Then continue the beamline with a LBNF-like decay pipe (~200 meters long with 2-meter radius), which could be constructed with much less concrete shielding because of the greatly reduced beam loss on the pipe wall after the bend.
- Scenario 2: With a large beta function like in scenario 1 after the matching, continue the beamline with standard periodic FODO cells. The length of all cells is approximately the same as that of the pipe.

The neutrino flux from the two scenarios will be compared in this paper. Scenario 1 may yield a higher neutrino flux

---

* Work supported by Fermilab, Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

† aoliu@fnal.gov

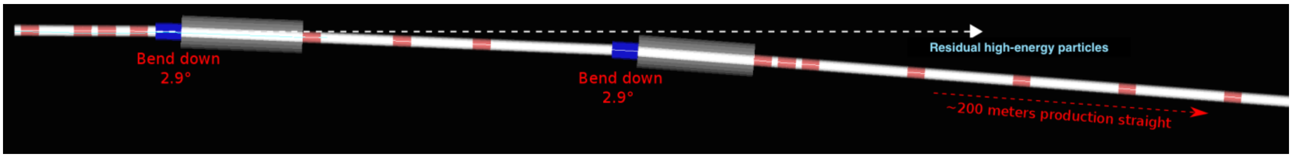

Figure 1: The schematic drawing of the beamline. The blue modules are the bending dipoles, red ones are the quads, and white ones are the drift tubes.

at the detectors, while scenario 2 allows for measurement instrumentations in the beamline, which will help to predict the flux more precisely.

The schematic drawing of the FODO and the optics of the pion beamline are shown in Figure 1 and Figure 2. The optics corresponds to the reference momentum $P_0 = 7$ GeV/c, which was chosen to give a wider momentum acceptance, and to center the neutrino flux at the FD at the first oscillation peak.

The performance of the pion beamline was checked in G4Beamline (G4BL) [4], where pions (π^+ and π^-) after the focusing horn were tracked while their decay products were also simulated and tracked. In G4BL, every particle will be recorded when its tracking is stopped, regardless of the reason (e.g. collimation, decay, end of tracking, etc.). Therefore, using an analysis program, the neutrino flux at the FD can then be calculated by the parent particles when they decay, using two-body and three-body decay formulae [5].

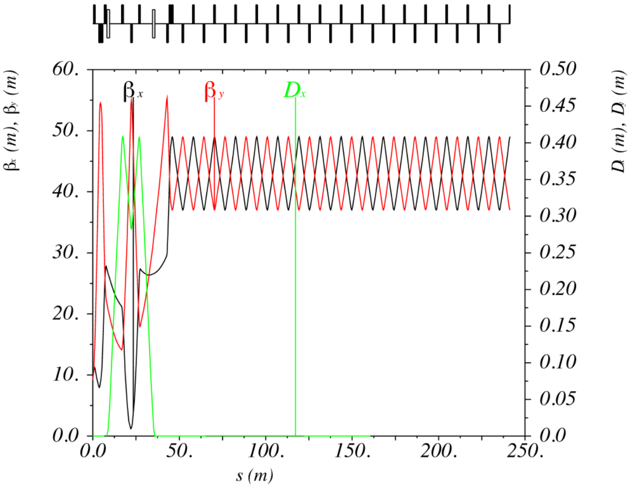

Figure 2: The optics of the 7 GeV/c reference pion in the beamline.

Due to the double bend structure, the wrong sign pions (π^- when producing ν_μ and vice versa) after the horn can be greatly from reaching the straight section. Therefore, neutrino flux with the opposite flavor is very small at both the near and far detector positions. The fluxes are compared with DUNE's FD fluxes and are shown in Figure 3 (neutrino beam configuration) and Figure 4 (antineutrino beam configuration) for both scenario 1 and 2.

Due to the sign selection by the dipoles and quads, the wrong-sign decays are greatly reduced, based on the antineutrino flux in Figure 3. Moreover, in a conventional neutrino experiment such as DUNE, the ν_μ background in a $\bar{\nu}_\mu$ beam is more problematic.

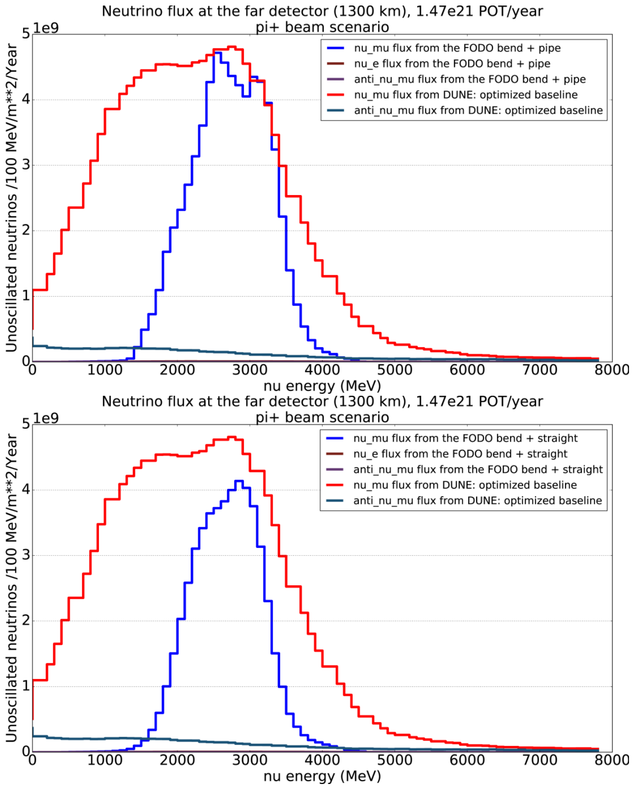

Figure 3: The FD flux from nuPIL (scenario 1: above; scenario 2: below), compared with DUNE's optimized flux. The horn and beamline were set up to produce ν_μ in this configuration.

There are a number of advantages of the FODO nuPIL over a conventional neutrino beam. First, with most beam loss contained in the target chase up to the end of the steering bend section (second dipole in Figure 1, the beam power loss on the decay pipe (in scenario 1) or on the vacuum chambers/magnets (in scenario 2) is reduced, by more than an order of magnitude, compared with LBNF's. Secondly, according to studies done on nuSTORM [6], established accelerator instrumentations can determine the beam properties in the straight FODO section to ~ 1%. By modeling the two-body decay the flux at the detectors can thus also be determined to similar precision.

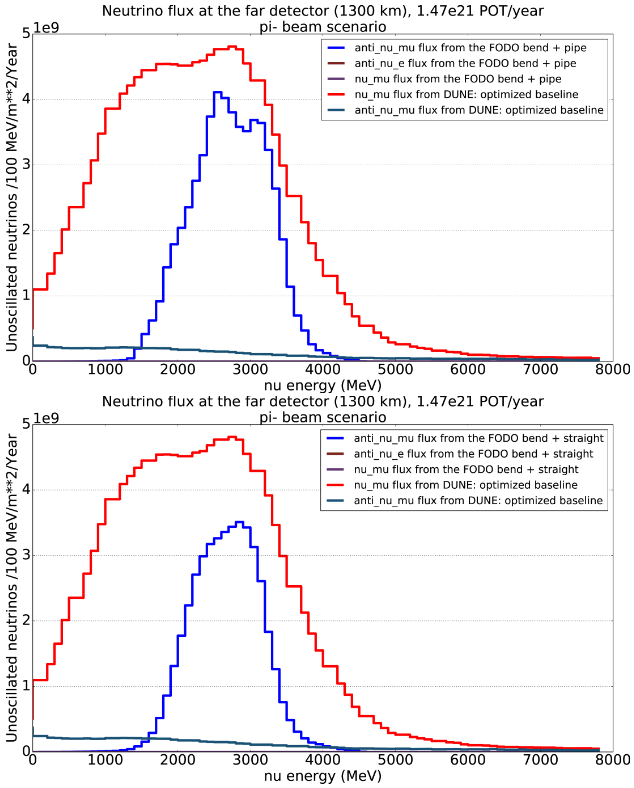

Figure 4: The FD flux from nuPIL (scenario 1: above; scenario 2: below), compared with DUNE's optimized flux. The horn and beamline were set up to produce $\bar{\nu}_\mu$ in this configuration.

OTHER BEAMLINE DESIGNS

While the FODO design utilizes only the most basic accelerator elements, it has been known that the FODO lattice can not provide a wide enough momentum acceptance large enough to be ideal. Therefore, FFAG nuPIL lattices were also investigated and these have shown improved performance regarding the width of the neutrino momentum spectrum [7]. The detailed comparison between the physics capabilities from these two types of designs is ongoing.

CONCLUSION

Any conclusions should be in a separate section directly preceding An FODO beamline design as an option for LBNF was described. The neutrinos from a PIon beam Line (nuPIL) was shown to possess many advantages. With the preliminary beamline design and no optimizations, the δ_{CP} sensitivity reach from nuPIL is already promisingly good. Optimizations on the horn and beamline are underway in order to improve the physics reach of nuPIL. The results will be compared with the alternative FFAG lattices.

ACKNOWLEDGMENT

The authors thank Dr. Jaroslaw Pasternek, Dr. Pilar Escribano, and Dr. David Neuffer for their support and discussions on nuPIL. The authors especially thank Dr. Pilar Escribano for her help in the neutrino physics analyses. This research used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

REFERENCES

[1] R. Acciarri *et al.* [DUNE Collaboration], "Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 1: The LBNF and DUNE Projects" arXiv:1601.05471 [physics.ins-det].

[2] A. Liu, D. Neuffer and A. Bross, "Design and simulation of the nuSTORM pion beamline", in *Nuclear Instruments and Methods in Physics Research Section A*, 2015, 801, pp. 44 - 50

[3] A. Liu, A. Bross and D. Neuffer, "Optimization of the magnetic horn for the nuSTORM non-conventional neutrino beam using the genetic algorithm", in *Nuclear Instruments and Methods in Physics Research Section A*, 2015, 794, pp. 200 - 205

[4] T. Robert and muons Inc. "G4Beamline: a particle tracking simulation program based on Geant4", `http://www.muonsinternal.com/muons3/G4beamline`

[5] M. Donega, "Study of neutrino oscillations with a low energy conventional neutrino superbeam", Ph.D. thesis, INSPIRE-1324303, unpublished.

[6] D. Adey *et al.* [nuSTORM Collaboration], "nuSTORM - Neutrinos from STORed Muons: Proposal to the Fermilab PAC," arXiv:1308.6822 [physics.acc-ph].

[7] J-B. Lagrange *et al.* "FFAG Beam Line for nuPIL (neutrinos from a PIon beam Line)" presented at the 7th Int. Particle Accelerator Conf. (IPAC'16), Busan, Korea, May 2016, paper THPMB054, this conference.