FFAG BEAM LINE FOR NUPIL – NEUTRINOS FROM PION BEAM LINE

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Abstract

The program of The Long Baseline Neutrino Facility (LBNF) aims to deliver a neutrino beam for the Deep Underground Neutrino Experiment (DUNE). The current baseline for LBNF is a conventional magnetic horn and decay pipe system. Neutrinos from a PIon beam Line (nuPIL) is a new concept being optimized for LBNF. It consists of a pion beam line after the horn to clean the beam of high energy protons and pions and wrong-sign pions before transporting the resulting beam into a decay beam line, where instrumentation could be implemented. This paper focuses on the FFAG solution for this pion beam line. The resulting neutrino flux is also presented.

INTRODUCTION

LBNF-DUNE is a project based at Fermilab to study neutrino oscillations precisely and in particular to search for the CP violation in the leptonic sector of the Standard Model [1]. The current baseline regarding the neutrino production considers the conventional approach, where a high energy proton beam hits a target, producing pions that are collected by a system of horns and that decay in a decay pipe. The LBNF decay pipe points toward detectors placed at the Sanford Underground Research Facility (SURF) in South Dakota, about 1300 km away, so the tunnel is tilted with a vertical angle of 5.8 deg. The target is aligned with the tunnel to maximise the flux and an embankment needs to be built to transport the primary proton beam up and then down so that it hits the target (which is set at 5.8 degree) head-on. The resulting pions are focused by three horns and are injected into the 4 m-diameter and 204 m-long pipe. The pipe is also filled with helium to minimize pion interactions in transit. In this configuration, the flux is indeed maximised, however radiation safety requires that the surrounding earth needs to be shielding by about 6 m of concrete surrounding the pipe, which makes a total excavation of a 16 m-diameter tunnel over 204 m. Furthermore, since all forward going particles would enter the decay tunnel, kaon decays, wrong-sign pion decays and muon decays will also produce neutrinos that can reach the detector, creating a background signal.

Another proposed solution described in this paper is the use of a pion beam line. The primary proton beam would hit the target on the surface, then a horn would collect the resulting pions. They would be transported in a 5.8 deg beam line bend and then either injected into the beam line or directly into the decay pipe. In this approach, the pions would go through a charge selection process in the bend, providing a cleaner neutrino beam at the detector. Furthermore, The engineering complexity is also lessened, since the remaining high energy protons would go straight in the bending part and thus remain on the surface which allows them to be collimated away, simplifying the radiation safety in the decay tunnel. In addition, the target is not tilted, so the embankment is not needed either. Instrumentation can also be installed, giving the possibility to have access to an actual measurement of the flux. Finally, the wrong sign pions could be collected in the bending part for cross-section measurements and sterile neutrinos search (i.e. nuSTORM [2]).

The decay channel can either be a decay pipe, like in the baseline scenario, or a beam line. In the case of a decay beam line, instrumentation can be installed in different points, giving a more accurate measurement of the flux. The tunnel could then be a conventional beam line tunnel, reducing the cost of the excavation and shielding. The beam line can be composed of large bore quadrupole or of straight scaling FFAGs [3] if the dispersion is zero or non-zero at the beginning of the decay beam line, respectively.

The design of a pion beam line to transport as many pions as possible between 3.5 GeV/c and 10.5 GeV/c has been done with large aperture separate function magnets (dipoles and quadrupoles) [4] to accommodate the pion distribution coming out of the horn that had been optimized for nuSTORM [5]. Although the resulting neutrino flux is promising, the transport of such a large momentum spread beam seems difficult with separated function magnets, especially in the bending section. The use of scaling Fixed Field Alternating Gradient (FFAG) magnets [3, 7] could increase the momentum acceptance. This paper will present the preliminary results of the FFAG design for the nuPIL concept.

FFAG BEND AND DECAY PIPE

A bending beam line composed of scaling FFAG magnets with a 5.8 deg. bend has been designed and its performance evaluated using Runge Kutta code. The layout of the FFAG bend is presented in Fig. 1. It is composed of a dispersion creator section to adjust the dispersion (null after the horn) to a suitable value and an optics matching section to minimize the divergence of the beam at the entrance of the decay pipe, while closing the required bending angle.

Dispersion Creator

The dispersion creator principle in scaling FFAGs was recently developed [6]. The dispersion creator in the nuPIL case involves a very large momentum spread, and several dispersion creators in cascade would be necessary to create a proper dispersion for all momenta. To keep the bending

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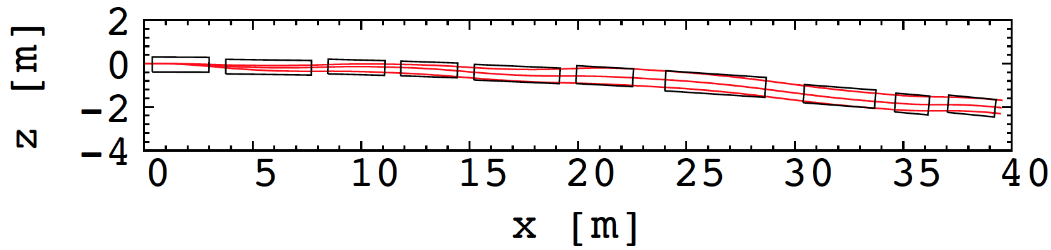

Figure 1: Beam line composed of scaling FFAG magnets with trajectories of 3 GeV/c, 5 GeV/c and 10 GeV/c in red. The horn is located at the $x = 0$ position, and the decay pipe starts at the end of the bend, at the $x = 39$ m position.

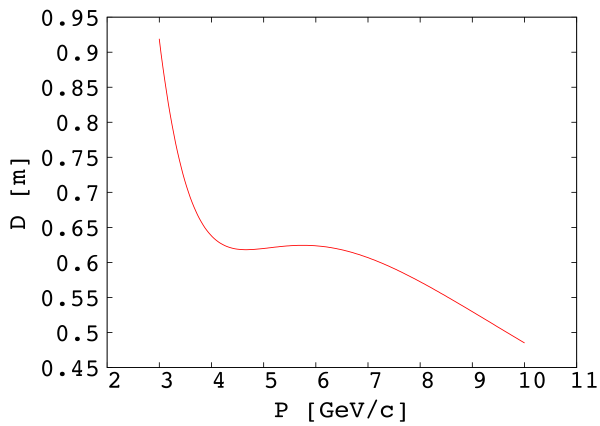

Figure 2: Dispersion value as a function of momentum at the exit of the dispersion creator.

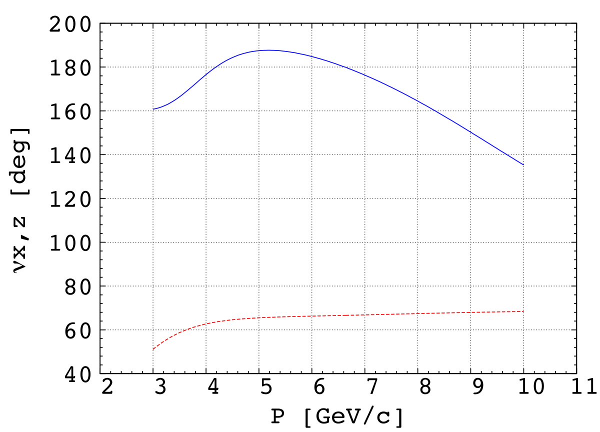

Figure 3: Phase advances in the bending plane (solid blue) and in the non-bending plane (dotted red) as a function of momentum at the exit of the dispersion creator.

beam line short, a single dispersion creator is used in the nuPIL design, with a phase advance higher than 180 deg. in the bending plane to accommodate a larger momentum spread. The dispersion and phase advances have been computed by tracking and the results are presented in Fig. 2 and 3.

Table 1: Lattice Parameters of the nuPIL FFAG Bend

Dispersion creator	FDF triplet ×2
radius (5 GeV/c)	386.3
k-value	1240
periodic dispersion [m]	0.31
final dispersion [m]	0.62
opening angle [deg]	1.7 ×2
final excursion (3-10 GeV/c) [m]	0.75
length [m]	23
phase advance (H/V) [deg]	(65, 187)
max magnetic field [T]	1.5
Bending cell 1	**FD doublet**
radius (5 GeV/c)	541.2
k-value	867.8
opening angle [deg]	1.2
periodic dispersion [m]	0.62
length [m]	11
Final beta [m] (5 GeV/c) (H/V)	(8.4, 48.1)
max magnetic field [T]	0.6
Bending cell 2	**DF doublet**
radius (5 GeV/c)	255.0
k-value	408.4
opening angle [deg]	1.2
periodic dispersion [m]	0.62
length [m]	5
Final beta [m] (5 GeV/c) (H/V)	(26.6, 24.1)
max magnetic field [T]	1.5

Optics Matching Section

The matching section is designed to give the wanted overall bending angle to the beam line and to adjust the optics to a suitable value at the entrance of the decay pipe. The divergence needs to be minimised, so the Courant-Snyder parameter $\gamma = \frac{1+\alpha^2}{\beta}$ needs to be minimised in both planes. The α parameter should then be null, and the beta value as large as possible.

Lattice Parameters and Performances

The parameters of the lattice are summarised in Tab. 1. The dispersion function and beta functions have been computed around 5 GeV/c in tracking and can be seen in Fig. 4. The magnetic field for the maximum momentum is presented

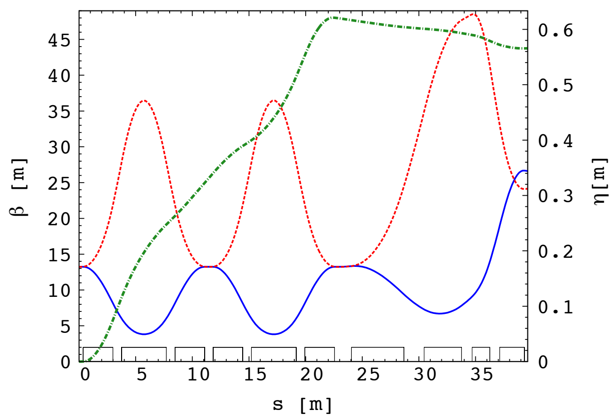

Figure 4: Beta functions in the bending plane (solid blue), in the non-bending plane (dotted red) and dispersion function (dot-dashed green) in the FFAG bend at 5 GeV/c.

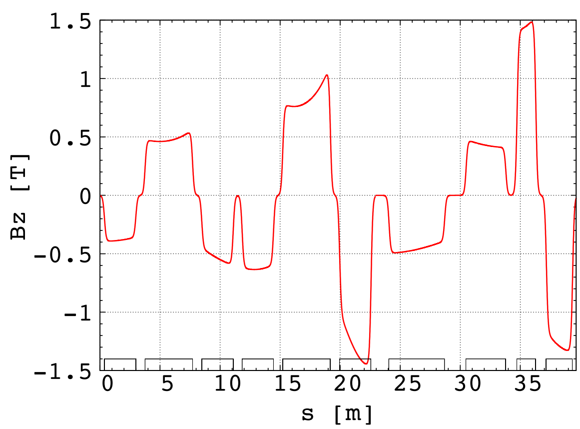

Figure 5: Magnetic field for 10 GeV/c pion reference trajectory in the FFAG bend.

in Fig. 5, and shows that the magnets are within the normal conducting range.

The pion distribution coming out of the nuSTORM horn has been tracked in the FFAG bend, and the surviving particles have been computed to estimate the resulting neutrino flux at the far detector and is presented in Fig. 6. The momentum distribution of the pions at different points in the beam line is presented in Fig. 7.

CONCLUSION AND FUTURE PLANS

The nuPIL concept aims to deliver a clean neutrino flux for the DUNE experiment. This configuration designed for LBNF gives several possibilities of upgrades, with a cost-effective implementation of nuSTORM and an experiment for demonstration of a 6D muon cooling ring. Preliminary results with respect to the produced neutrino flux promise a high physics reach. A more detailed study is needed and a design with a straight decay beam line is under development.

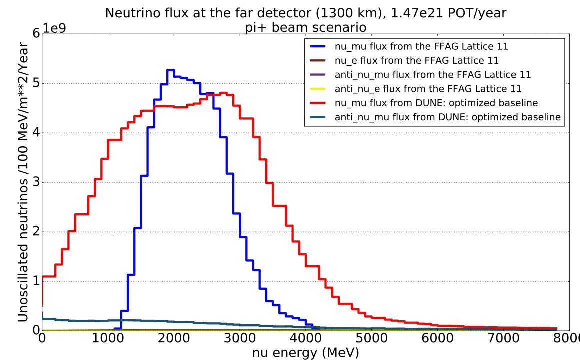

Figure 6: Neutrino flux in the nuPIL-FFAG case with a decay pipe and for the LBNF-DUNE 80 GeV-optimised configuration.

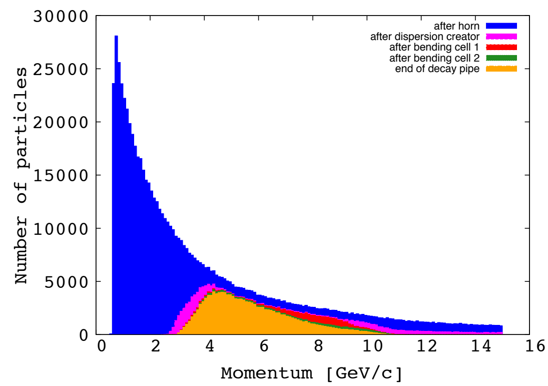

Figure 7: Momentum distribution of the pions from the nuSTORM horn at different points in the FFAG bend for nuPIL.

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