Neutrinos from PIon Beam Line, nuPIL*

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Abstract

LBNF-DUNE (Long Baseline Neutrino Facilities - Deep Underground Neutrino Experiment) is a project based at Fermilab to study neutrino oscillations. The current baseline regarding the neutrino production considers the conventional approach: a high energy proton beam hits a target, producing pions that are collected by a horn and that decay in a decay pipe. An alternative solution, called nuPIL (neutrinos from a Pion beam Line) consists of using a beam line to guide the pions to clean the beam and to put instrumentation to monitor it. This paper presents the concept and the first preliminary results.

INTRODUCTION

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. To maximise the flux, the target is also tilted and a hill needs to be built to transport the primary proton beam so it hits the target with the correct angle. The resulting pions are focused by two 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 high power beam should be shielded by a $\tilde{6}$ m of concrete surrounding the pipe, which makes a total excavation of a 16 m-diameter tunnel over 204 m. Furthermore, since all forwarding particles would enter the decay tunnel, kaon decays and wrong-sign pion decays will also produce neutrinos that can reach the detector, creating a background signal.

Another solution would be the use of a pion beam line, as presented in Fig. 1. 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 injected into a decay beam line. This approach has several advantages:

- the pions would go through a charge selection process in the bend, providing a clean neutrino beam,
- most of the kaons would decay in the bend, getting rid of this background at the detector,

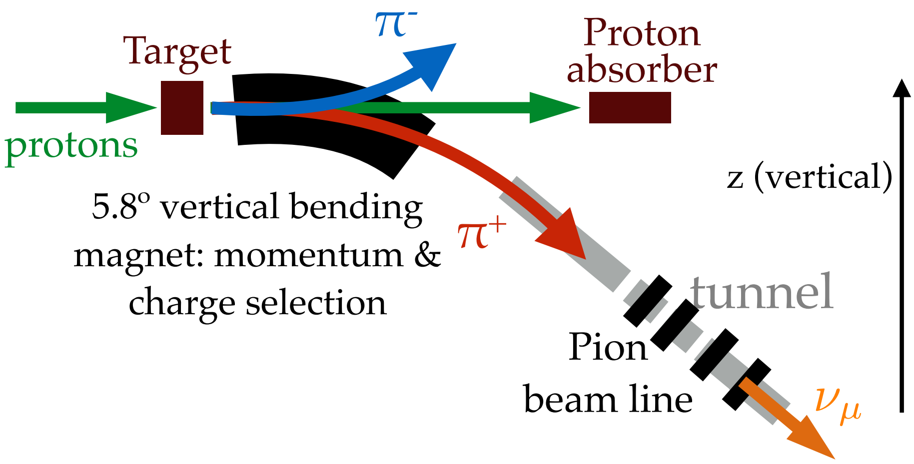

FIG. 1: Scheme of the nuPIL concept.

- instrumentation can be installed in the decay beam line, giving the possibility to have access to an actual measurement of the flux,
- since the target is not tilted, the hill is not needed,
- the remaining high energy protons would go straight in the bending part and thus remain on the surface, simplifying the radiation safety in the decay tunnel,
- the wrong sign pions could be collected in the bending part for cross-section measurements and sterile neutrinos search (i.e. nuSTORM [1]).

This approach had been investigated previously in the nuSTORM project [2, 3], but the resulting neutrino flux was too small to become an interesting possibility. However, increasing the length of the decay line to 204 m (like in the baseline scenario) and getting rid of both the chicane and the possibility to have a circulating muon beam, the number of pions can be greatly increase. Furthermore, the use of scaling Fixed Field Alternating Gradient (FFAG) magnets could also increase the momentum acceptance. This paper will present the preliminary results of the nuPIL concept.

FODO SOLUTION

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) to accommodate the pion distribution coming out of the horn that had been

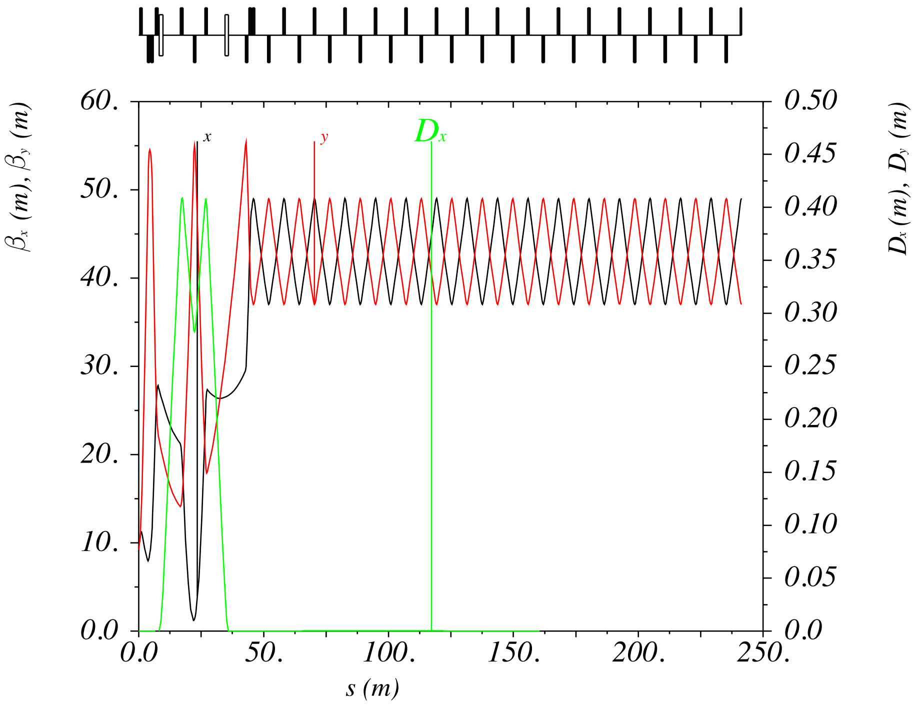

FIG. 2: linear parameters of the FoDo solution.

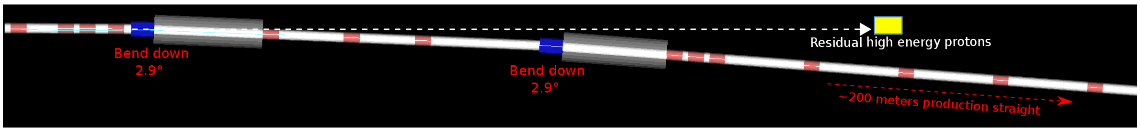

FIG. 3: FODO solution tracked in G4BL.

optimized for nuSTORM [4] into a small divergence beam in the decay line. The beta and dispersion function of the whole beam line is presented in Fig. 2. The bending section is around 40 m-long, and the straight section is around 200 m long. Tracking has been done in G4beamline with decay. The geometry can be seen in Fig. 3 and the resulting flux in blue in Fig. 4. No wrong-sign pions (π^-) has survived the bending part, so the resulting flux is very clean. The flux has been greatly increased compare to the nuSTORM flux (in red in Fig. 4). The horn was optimized for 5 GeV/c pions ±10%, and a proper optimization of the horn for 7 GeV/c pions ±50% could increase the flux.

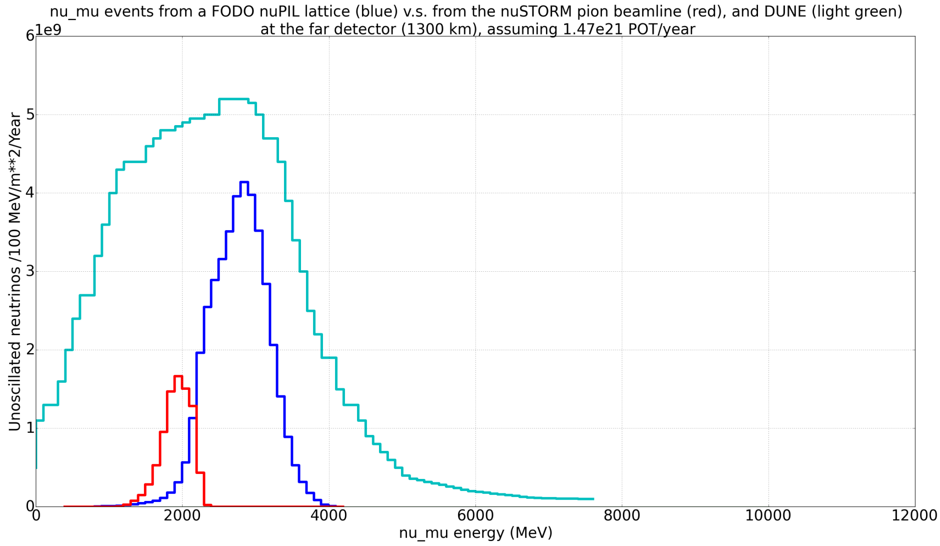

FIG. 4: Neutrino flux in the FODO solution.

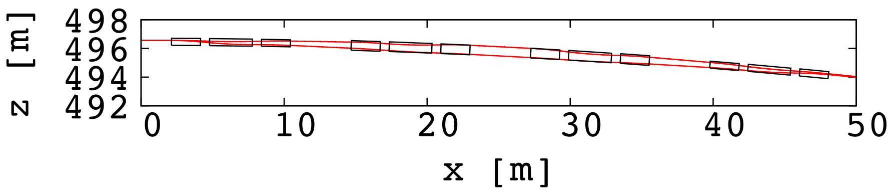

FIG. 5: FFAG double achromat bending beam line with trajectories of 3.5 GeV/c and 10.5 GeV/c in red.

FFAG BEAM LINE

The transport of such a large momentum spread beam seems difficult with separated function magnets, especially in the bending section. The use of achromatic FFAG magnets is being investigated to significantly increase the momentum acceptance of the line. A double achromat FFAG beam line with a 5.8 deg. bend has been designed and tracked using Runge Kutta code. The aim of this bend is to inject the surviving beam into large aperture quadrupole magnets forming the decay line. The FFAG bend is presented in Fig. 5. The dispersion function has been computed centered around 7 GeV/c in tracking and can be seen in Fig. 6. The magnetic field for the maximum momentum is presented in Fig. 7, and shows that the magnets are within the normal conducting range.

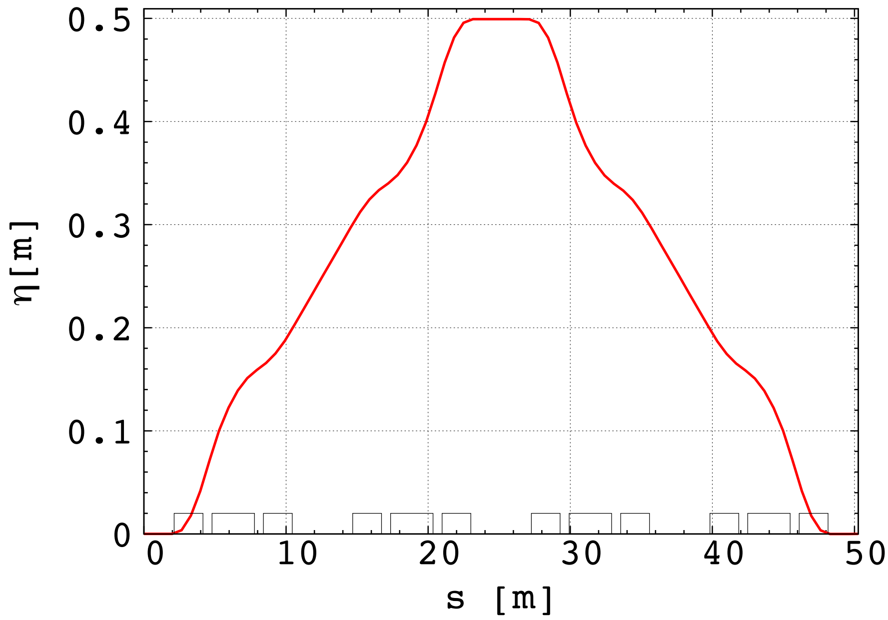

FIG. 6: dispersion function in the FFAG double achromat bend at 7 GeV/c.

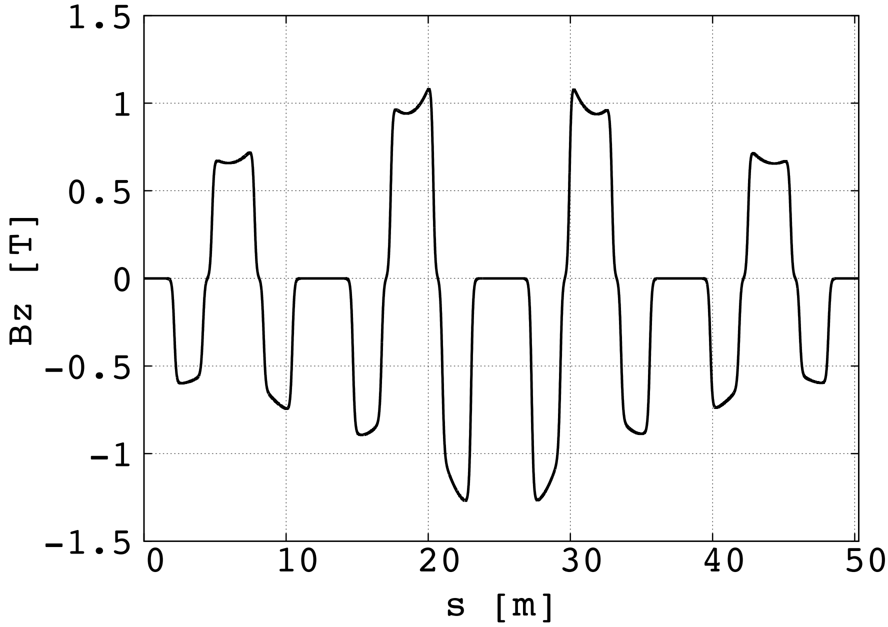

FIG. 7: Magnetic field for 10.5 GeV/c in the FFAG double achromat bend.

The survival of a large momentum range has been investigating by tracking 10000 particles within a water bag distribution. The unnormalized emittances are 2000 mm.mrad in both transverse planes, and the momentum is uniformly distributed around 7 GeV/c $\pm 50\%$. The survival rate at the end of the bend is 80%, with losses mainly seen at the extrema momenta

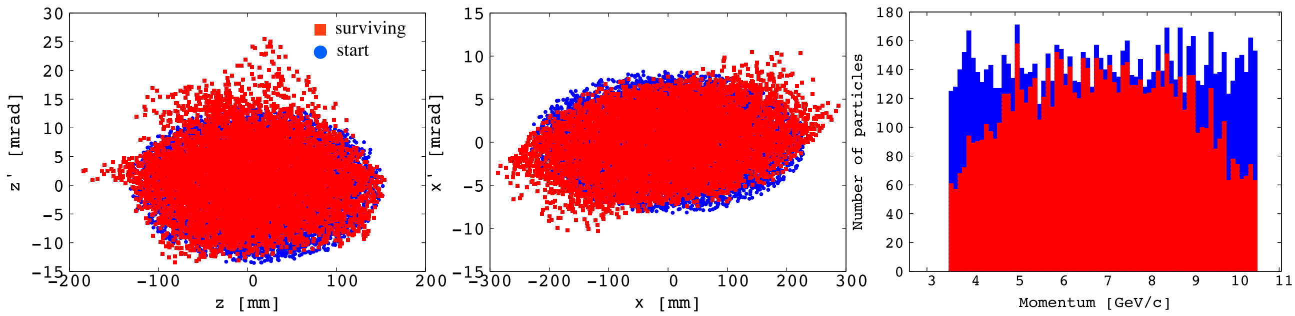

FIG. 8: Start (in blue) and surviving (red) pions π^+ after the FFAG double achromat bend in the bending phase space plane (left), in the non-bending phase space plane (center), and the momentum distribution (right).

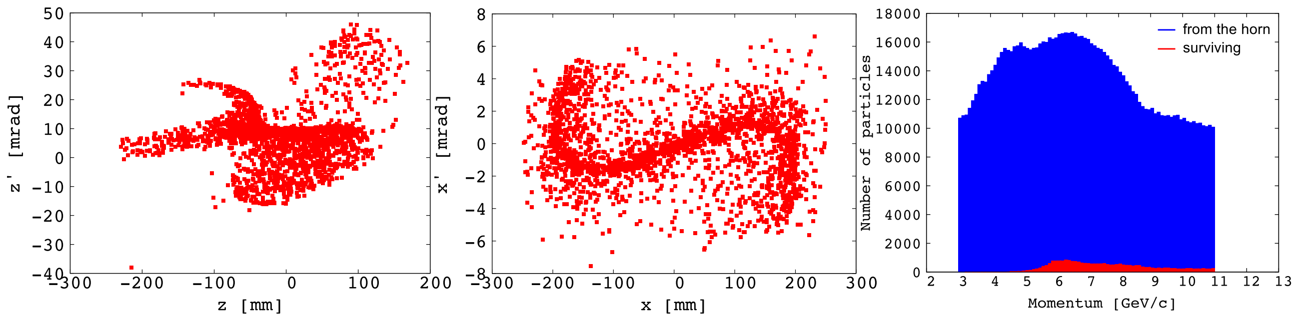

FIG. 9: Start (in blue) and surviving (red) pions π^- after the FFAG double achromat bend in the bending phase space plane (left), in the non-bending phase space plane (center), and the momentum distribution (right).

due to the limitation of the good field region. The results of the tracking are presented in Fig. 8.

The survival of the wrong-sign pions has also been investigated by tracking the distribution coming from the nuSTORM horn in the Runge Kutta code. The survival rate of the 1.1×10^6 initial particles is 2.38%, and the results of the tracking are presented in Fig. 9. The background coming from this beam is expected to be very small.

CONCLUSION AND FUTURE PLANS

The nuPIL concept aims to deliver a clean neutrino flux for the DUNE experiment. Preliminary results are promizing and the physics reach looks interesting. Furthermore, this configuration 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.

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