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DESIGN CONCEPT FOR NU-STORM: AN INITIAL “VERY LOW-ENERGY NEUTRINO FACTORY”

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Abstract

We present a design concept for a ν source from a STORage ring for Muons (νSTORM). In this initial design a high-intensity proton beam produces ~5 GeV pions that provide muons that are captured using “stochastic injection” within a 3.6 GeV racetrack storage ring. In “stochastic injection”, the ~5 GeV pion beam is transported from the target into the storage ring, dispersion-matched into a long straight section. (Circulating and injection orbits are separated by momentum.) Decays within that straight section provide muons that are within the~ 3.6 GeV/c ring momentum acceptance and are stored for the muon lifetime of ~1000 turns. Muon (and pion) decays in the long straight sections provide neutrino beams of precisely known flux and flavor that can be used for precision measurements of electron and muon neutrino interactions, and neutrino oscillations or disappearance at L/E= ~1m/MeV. The facility is described, and variations are discussed. In the initial concept up to ~10^{19} muons/year are stored.

INTRODUCTION

There have been a number of experiments that have demonstrated possible anomalies in neutrino interactions beyond the baseline 3-ν paradigm. These include anomalies in MiniBoone and LSND results. (Oscillation into a sterile ν at $\delta m^2 \sim 1 eV^2$ at ~5% could explain the anomalies.) Reactor experiments also see a deficit of ν events, and some cosmological models favour 3+N ν states. Most of these results are at the level of “3σ evidence”, and more definitive experiments are needed for confirmation or exclusion. In addition precision measurements of neutrino properties require accurate knowledge of neutrino interaction details; measurements with precisely known ν sources would facilitate this.

It has been recognized that a μ storage ring with long straight sections can provide precisely known neutrino intensities and flavors from the μ-decay in the straight sections. That property is used in the neutrino factory proposals. In this paper we present a simpler “low-intensity” version, suitable for an intial implementation of the concept and suitable for precision measurements of electron and muon neutrino interactions, and neutrino oscillations or disappearance at L/E= ~1m/MeV.

SCENARIO

The basic scenario concept is presented in figure 1. A high-intensity proton source places beam on a target, producing a large spectrum of secondary π’s. Forward π’s are focused by a collection lens into a transport channel. π decay within the transport produces μ’s which are injected into the storage ring. μ-decay within the straight sections will produce ν-beams of known flux and flavor. ($\mu^+ \rightarrow e^+ + \nu_\mu^* + \nu_e$) or ($\mu^- \rightarrow e^- + \nu_e^* + \nu_\mu$)

For this implementation, we choose a 3.6 GeV/c storage ring to obtain the desired spectrum of ~2—3 GeV ν’s. This means that we must capture π’s at a higher momentum (~5 GeV/c).

Proton source options

The proton source could be the Fermilab Booster (8GeV) or the Main Injector (60—120GeV) or some future upgrade facility. We prefer to use Main Injector beam, which will be capable of ~0.7MW beam power with 60--120 GeV protons. (i. e., batches of ~6×10^{13} 60 GeV p at 1.25Hz) The Fermilab Booster has 8 GeV protons with ~4×10^{12} p/pulse at 15Hz (75kW), but is too low an energy for 5GeV/c π production. It could be used in alternative versions with lower π/μ energies.

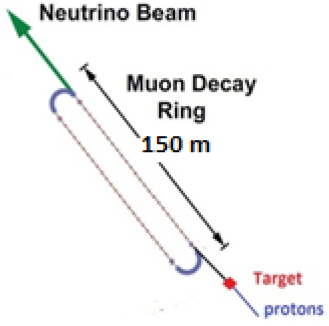

Figure 1: Layout of system.

Production Target

Target material and configuration for optimum acceptance are under study. To first order we could use a target configuration similar to that of the Fermilab Antiproton Source (FAS), which consists of a rotating Inconel target with a 1 cm radius Li lens to capture the secondaries. As we are collecting at ~5 GeV/c, the focusing strength should be somewhat less than the FAS, but a larger Li lens radius (2cm) would also be desired to improve acceptances. The Li lens will be followed by a sequence of quads leading into the storage ring. A magnetic horn (similar to that used in the NuMI and MiniBoone experiments[6,7]) could also be used as the initial acceptance lens, and could have a much larger geometric acceptance, but would have more nonlinear optics. The horn would be followed by a drift and a sequence of quads and dipoles leading into the ring. Simulations and comparison of acceptances will develop an optimum version.

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The choice of π collection energy and μ storage energy will be a subject of future optimization. The present values are driven by the energy sensitivity of μ-identification in the detector and the estimated π-production from 60 GeV protons. Lower energies (~1--2 GeV μ's) would reduce costs, but appear to have detector limitations. A 2 GeV ring option will be explored in further detail.

INJECTION OPTIONS

The scenario requires storage of μ's from π decay. The π-decay can occur either before injection or in the Ring. Decay before injection requires a separate decay transport line and full-aperture fast kickers matching the π beam pulse to the ring. For 5GeV/c π, the decay length is 250m; ~45% decay within 150m.

With π-decay within the Ring, non-Liouvillean "stochastic injection" is possible. In "stochastic injection", the ~5 GeV/c pion beam is transported from the target into the storage ring, dispersion-matched into a long straight section. (Circulating and injection orbits are separated by momentum.) Decays within that straight section provide muons that are within the~ 3.6 GeV/c ring momentum acceptance. With stochastic injection, μ's from a beam pulse as long as the MI circumference (3000m) can be accumulated, and no injection kickers are needed.

In a variant of the scheme, the target is internal to the ring, producing a broad spectrum of π's, some of which are accepted, and decay μ's that are within the ring acceptance are then stored. That variant is not favoured because of the large activation associated with internal targets, and a separate target with transport of π's toward the ring is presently used.

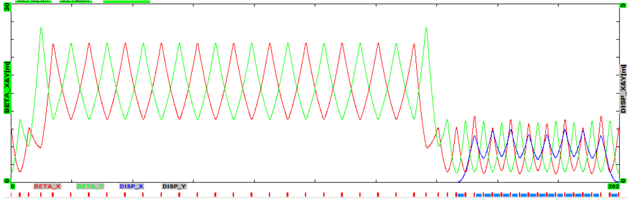

Figure 2 Betatron functions for a FODO half-ring. The half-ring is ~200 m long. The scale in $\beta_{x,}\beta_y$ is 0 to 30m and the maximum dispersion in the arc is ~1.5m.

Ring lattices

As an initial attempt, we have designed a FODO lattice with a missing-magnet dispersion suppressor. The basic cell length is 6m (β_{max} = 10m) with 0.5m quads and 2.0m dipoles, and we enable an aperture of ~12cm radius. The arcs are ~50m long, while we have straight sections of ~150m. FODO cells (12m, 45°) are used for the straight sections; variants toward optimizing acceptance will be developed. Fig. 2 displays betatron functions of the ring. The lattice will have a relatively large emittance and momentum aperture to enable maximum μ acceptance. At C=400m the μ lifetime is ~50 turns. (~70 μs)

The missing-magnet dispersion suppressor provides an ideal location for the implementation of stochastic injection. (See fig. 3.) With a dispersion of η~1.2m at the drift, the 5 and 3.6 GeV/c orbits are separated by ~30 cm; an aperture of ~±15cm is available for both the 5 GeV/c π and 3.6 GeV/c μ orbits.

Another option is the use of an FFAG-style lattice.[] The advantage is that a scaling FFAG lattice has a naturally small chromaticity and therefore could have a very large momentum aperture, which would be used to maximize acceptance of circulating μ's. Fast-kickers in the straight sections can be used for injection, or stochastic injection within the optics entering the straight section can be used.

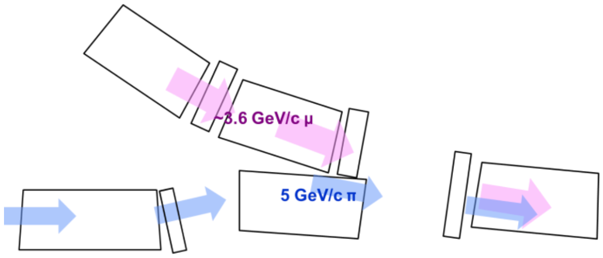

Fig. 3 Schematic view of optics for stochastic injection. Pions enter the ring from outside at the dispersion suppressor, joining with circulating lower-energy μ's. π's that decay to μ's within the ring acceptance join the circulating beam.

SIMULATION RESULTS

G4Beamline simulations of storage ring scenarios have been initiated.[5] Initial surveys indicate a momentum acceptance as large as ±20% in FFAG mode and at least ±10% in FODO mode should be possible. An integrated simulation including injection must be developed and cost/acceptance studies must be developed.

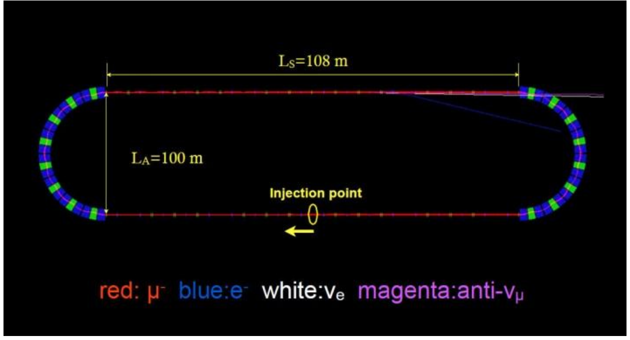

Fig. 4 G4Beamline of a μ storage ring (FFAG style).

DETECTOR OPTIONS

A complete facility will include a near detector (ND) immediately following the decay straight section and a far detector (FD) ~ 1km downstream of the decay straight section suitable for seeing $\delta m^2 \sim 1 eV^2$ oscillations.

Our initial concept for the FD is a modified MINOS detector [6], which consists of Fe plates with layers of scintillator between the plates. We would use 1cm thick plates and two layers of scintillator (for X and Y

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measurement) between plates, and include a superconducting transmission line coil through the center to provide B>1.8T within the active volume. The FD would be ~6m diameter with a total active weight of ~1kT. The ND will be adapted to precision measurement of ν cross sections. About 200T active mass is needed.

Other detector choices, such as a magnetized totally-active scintillator detector or a liquid Argon detector will be explored in search of an optimum version.

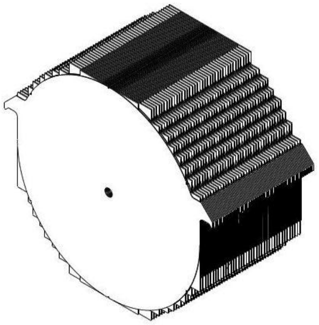

Figure 5: View of the body of the Far Detector, with iron plates, scintillator between plates, and a SCmagnetic coil to be inserted in the center

SENSITIVITY

A multi-year program should provide more than ~10^{18} neutrinos, from ~10^{21} protons. The 1000T far detector should see ~10^{6} ν interactions, enough for good sensitivity in appearance and disappearaince modes. (see fig. 6)

An important goal is setting limits on oscillation into sterile ν's, which can be seen as ν disappearance. For this goal, the ring beam intensity would be established using beam current monitors and decay $\mu \rightarrow e$ observation in the storage ring. Concurrent measurements of ν events in the near and far detectors will set limits on the degree and L/E dependence of ν disappearance; and better than 1% accuracy should be achieved.

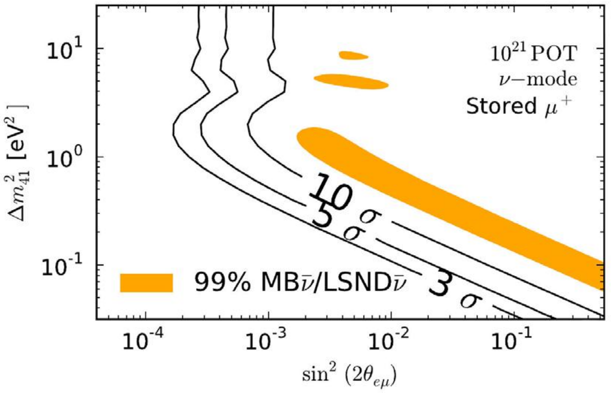

Figure 6. Sensitivity plot for observation of $\nu_e \rightarrow \nu_4$ oscillations in a VLENF scenario, compared with $\bar{\nu}$ observations consistent with that oscillation.[7]

VARIATIONS

The present example uses muons at ~3.6 GeV/c to maintain charged μ identification in the proposed detector. That choice is consistent with use of the 60 GeV MI, which is the highest-power p-source at Fermilab. A lower energy ring could be more affordable and could use the 8 GeV Booster or a possible 4 MW "Project X" upgrade as the p-source. This variant will be studied. A detector with broader particle ID may then be preferred.

The ring could also be used as the μ-storage ring for a future "neutrino factory", where the μ source would be intense bunches of captured, cooled and accelerated muons.[1] The neutrino factory could provide at least two order of magnitude more neutrinos, and would enable long baseline exploration of neutrino parameters.

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