

# $\nu$ STORM FACILITY DESIGN AND SIMULATION\*

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## Abstract

A facility producing neutrinos from muons that decay in a racetrack decay ring can provide an extremely well understood neutrino beam for oscillation physics and the search for sterile neutrinos [1][2]. The “neutrinos from STOREd Muons” ( $\nu$ STORM) facility is based on this idea. The facility includes a target station with secondary particle collection, pion transfer line, pion injection, and a  $\sim 3.8$  GeV/c muon storage ring. No muon cooling or RF sub-systems are required. The injection scenario for  $\nu$ STORM avoids the use of a separate pion decay channel and fast kickers. This paper reports a detailed description of the proposed injection scheme with full G4beamline simulations. We also present progresses on possible design options for a muon racetrack decay ring.

## INTRODUCTION

The possibility of using a muon decay ring with long straight sections to study neutrino interactions has been recognized and first proposed by Neuffer [1]. The stochastic injection scheme avoids using a separate pion decay channel and fast kickers. The injection scheme further eliminates the need of an additional beamline. However, the injected pions and the circulating muons have very different momenta, therefore, the “beam combination section”(BCS) that combines the two beams together needs to be carefully designed to accommodate both pions and muons. In this paper we present the realization of this injection via simulations.

## PION COLLECTION AND TRANSPORT

$\nu$ STORM is designed to use a 100 kW target station. A proton pulse with approximate  $10^{13}$  protons at 60 or 120 GeV with pulse length  $1.6 \mu\text{s}$  will be extracted from the Fermilab Main Injector and bombarded onto a solid target. The secondary pions are collected by a magnetic horn with  $5 \pm 0.5$  GeV/c momentum acceptance. The pions then go through a transport line and are injected into the ring.

### Target and Horn

We use a 95 cm graphite target (about two interaction lengths), with a radius of 3 mm. From MARS simulations, the number of pions in the 2 mm-rad transverse phase space acceptance after the target is 0.064 per 60 GeV Proton On Target (POT).

In order to collect the secondary pions with a large momentum acceptance, we use a NuMI-like, 300 cm long

magnetic horn and shift the target center inside the horn by 65 cm from upstream end of the horn (see Fig. 1). These numbers were optimized to collect 0.056 pions within  $5 \pm 10\%$  GeV/c per POT in the 2 mm-rad acceptance.

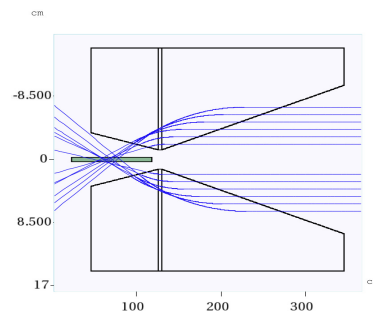


Figure 1: Schematic drawing of  $\nu$ STORM magnetic horn and target(middle rod). Protons hitting the target from left.

### Injection

We estimate that we need approximately 50 cm separation between the 5 GeV/c reference pion and 3.8 GeV/c reference muon to accommodate beam pipes and magnets at injection. The current design assumes that the reference muon trajectory goes through the centers of the magnets in the ring. The separation mentioned above can be done with a “beam combination section”(Fig. 2). The pions injected after the BCS start to propagate in the decay straight. Due to the large momentum difference, the focusing effects of the decay straight must be optimized simultaneously for both beams; otherwise the pion beam size will dilate.

The injection may be designed in three steps: 1. Periodic Twiss parameters for 3.8 GeV/c muon and 5 GeV/c pion are obtained for the same decay straight FODO cell; 2. Continued from the muon optics, the BCS is designed to have large dispersion,  $D_x$ , at the injection point. Then muon optics is matched from the FODO cells; 3. Keeping the magnets common, start from the pion’s periodic Twiss parameters obtained in step 1 and switch the reference momentum to 5 GeV/c. Then find the parameters at the injection point, and match them back to the downstream end of the horn. Fig. 2 shows that the defocusing quadrupole for muons in the BCS becomes a combined-function dipole for pions, with entrance and exit angles non-perpendicular to the edges. The sector dipole for the muon becomes one with the pion’s trajectory non-perpendicular to the pole-face.

### FODO Cell for The Decay Straight

To design the FODO cell, the requirements for a circulating muon beam in the decay straight are considered. On

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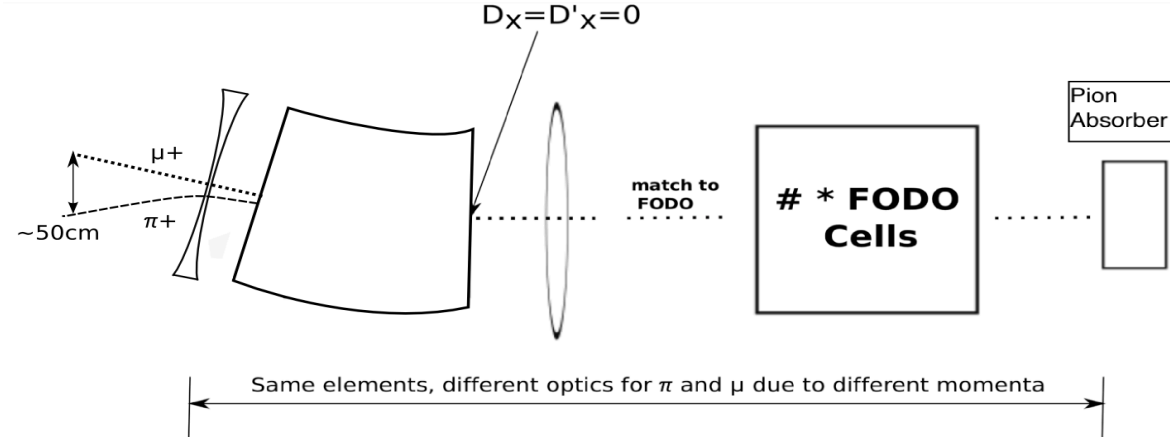


Figure 2: A schematic drawing of injection “beam combination section”(BCS) and the following decay straight in the ring. At the end of the straight, pions are extracted to an absorber along with muons in the same momentum band; lower-energy muons continue circulating in the ring.

one hand, larger optical  $\beta$ 's will dilate the beam size. This then requires larger aperture magnets. Moreover, as the maximum muon decay angle with respect to its parent pion solely depends on the pion energy, a large  $\beta$  in a FODO corresponds to a narrower divergence acceptance limiting the number of muons from pion decay in the straight that can be accepted. Conversely, smaller  $\beta$  increases the divergence of the neutrino beam obtained from stored muons, and the uncertainty in that divergence width. The  $\delta\sigma_{x'}$  and the percentage of decayed muons which can be accepted by the cell (both scaled to 1) versus  $\beta_{\max}$  of the cell are plotted in Fig. 3 on left and right vertical axes, respectively. Balancing the two criteria, we pick  $\beta_{\max}$  at 30 meters, and  $\beta_{\min}$  at 23 meters, which implies 38 and 32 meters for pion's  $\beta_{\max}$  and  $\beta_{\min}$ , respectively (Same for horizontal and vertical directions). The straight section is approximately 150 m long.

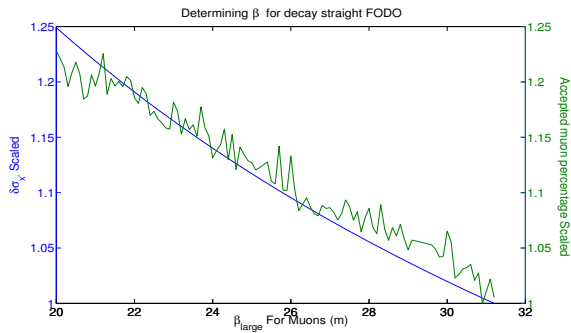


Figure 3: Determining the  $\beta$  function in decay FODO cells, where  $\beta_{large}$  means maximum  $\beta$ , or  $\beta_{max}$ , in the cell.

### Pion Transport Line

The optics of the 5 GeV/c pion is matched backwards from the FODO section to the downstream end of the horn.

At the injection point, the 2 reference particles are separated by 48 cm. The plot of the pion Twiss functions is shown in Fig. 4. The space between the two dipoles in the pion transport line was designed so that residual high-energy protons can be separated from the secondary pion transport line by the first dipole. Another dipole is used in the residual proton beamline to bend protons back to their initial direction, which points them to a  $4.3 \times 4.3 \times 10.7 \text{ m}^3$  proton absorber  $\sim 30$  meters after the first dipole.

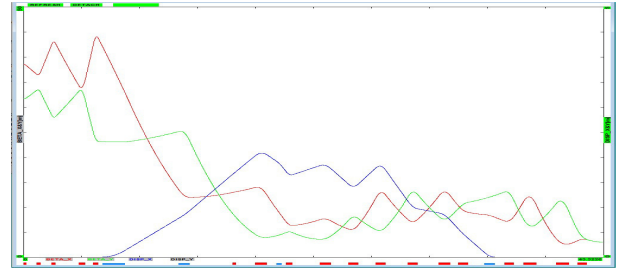


Figure 4: Transport optics for pions from the decay straight FODO cells back toward the production horn. Left vertical axis ( $\beta_x$ , red,  $\beta_y$ , green) division scale = 5m, Right vertical axis ( $D_x \rightarrow$ blue) division scale = 1 m.

## INJECTION PERFORMANCE

The performance of this scenario is gauged by determining the number of muons at the end of the decay straight using G4beamline [3], which is built based on Geant4. A script was written to automate the conversion from OptiM [4] lattice output to G4beamline input. The layout drawing of transport, injection and part of the decay straight is shown in Fig. 5. The  $\pi$  distribution used in G4beamline is obtained by MARS from a target and horn simulation. We are able to obtain **0.012 muons per POT** at the end of the decay straight, within a wide momentum spread (shown in Fig. 6) and thus partly accepted by the

ring. The green region in Fig. 6 shows the  $3.8 \pm 10\%$  GeV/c range for acceptance in the ring, and the red  $5 \pm 10\%$  GeV/c region shows the high energy muons that will be extracted with the remaining pions at the end of decay straight, in a mirror image of the BCS.

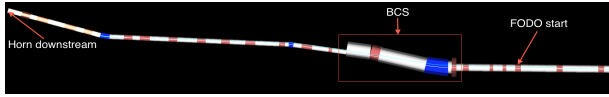


Figure 5: Layout in G4beamline, where dipoles are in blue, quads in red and the aperture defining beam pipes in white.

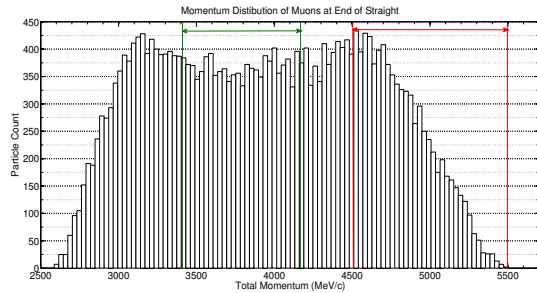


Figure 6: Momentum distribution of decayed muons at the end of decay straight.

## DECAY RING DESIGN

A FODO ring for such a large phase space acceptance and momentum spread has not been studied in detail to date. The  $\nu$ STORM decay ring has several challenges, which include the need for rather compact arcs, the limitations on beam size, and, most importantly, the nonlinear aspects such as tune chromaticity, higher order dispersions, etc. The muons at 3.8 GeV/c decay rapidly with an approximately  $80 \mu\text{s}$  lifetime in the lab frame. 15% remain after 100 turns for a 450 m ring. The optics and single turn loss pattern for a possible ring design are shown in Fig. 7, and its corresponding layout is shown in Fig. 8. Three Double Bend Achromat (DBA) cells are used in each arc to control beam size due to the linear dispersion term, and bend the reference  $\mu$  by 180 degrees. The survival for a Gaussian distributed beam with  $\epsilon_{\text{rms}} = 2/6 \text{ mm rad}$  and  $\frac{\Delta p}{p} \in \pm 10\%$  after 100 turns is around 60%.

Because of the large momentum spread, the orbit response due to momentum error can not be well approximated by only the linear term. Dispersion coefficients up to 3rd order can be corrected by sextupoles and octupoles. The correction effects and other chromaticity effects are currently under study.

An alternate FFAG decay ring described in the  $\nu$ STORM Letter Of Intent (LOI) [5] could achieve good acceptance for the muon beam, but it has injection scheme and cost uncertainty. An alternative arc consisting of FODO cells is also being studied.

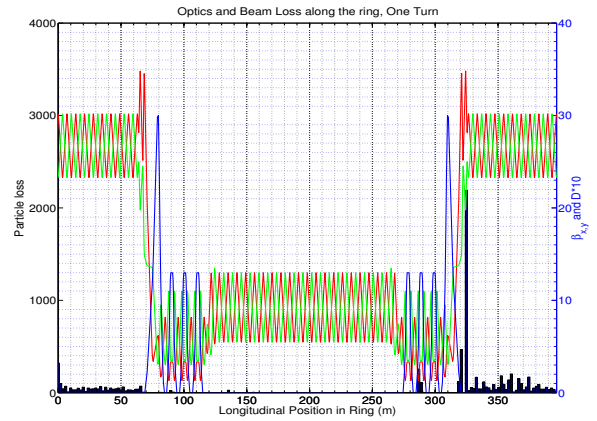


Figure 7: Optics and single turn loss pattern for a decay ring design. (Red curve:  $\beta_x$ ; Green:  $\beta_y$ ; Blue:  $D_x$ ; Histogram: beam loss versus longitudinal position)



Figure 8: G4beamline layout of the above ring.

## SUMMARY

The pion transport beamline and injection for  $\nu$ STORM have been designed and simulated. Our simulations show that the muon yield from pion decay in the first straight, within  $3.8 \pm 10\%$  GeV/c band, is about 0.004 per 60 GeV POT. A possible muon racetrack decay ring has also been designed. Our simulations show that the ring has a good momentum and phase space acceptance.

## ACKNOWLEDGMENT

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