# A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

## Part V: Booster Neutrino Beam

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## CONTENTS

# I. OVERVIEW

The short-baseline neutrino program described in this proposal makes use of the existing Booster Neutrino Beamline (BNB). The BNB is a conventional horn focused neutrino beam, fed with 8 GeV protons from Fermilab's Booster accelerator. The beamline was originally optimized for the MiniBooNE detector, the primary user of the beamline over the last decade. One of the considerations when designing the beamline was to have as large a flux as possible at 500 MeV, while keeping the flux at higher energies as low as possible. The higher energy neutrinos produce $\pi^0$s in the MiniBooNE detector through Neutral Current interactions and these present significant background for the $\nu_e$ appearance measurement. The LArTPC technology provides much better background rejection and so the constraint of reduced high energy neutrino flux can be relaxed. Maximizing flux at all energies should be generally beneficial.

In the existing beamline configuration the 8 GeV protons from the Booster are guided through the transport line to the target hall as shown in Figure 1. The primary beamline ends with a quadrupole triplet that focuses the beam on the target. The target is embedded within the 1.8 m long horn, and the target horn assembly lies just downstream of the final triplet. A 2.14 m long collimator about 3 m downstream of the target shields the entrance to the decay pipe region.

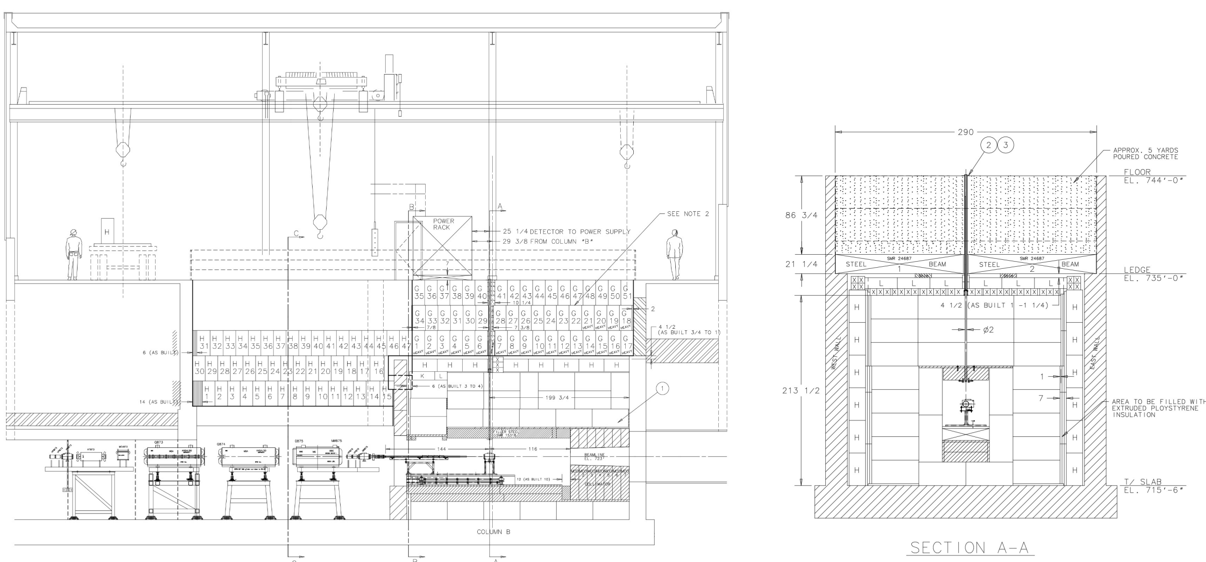


**FIG. 1:** *Side (left) and beam (right) view of the target hall region. Final focusing triplet (Q873, Q874 and Q875) can be seen in the side view. The MiniBooNE horn is inserted into the target pile just upstream of the collimator noted as section A in the drawing. This region is 2m high and 1.4m wide. [1]*

The Booster operates at the 15 Hz repetition rate with up to 5 Hz average rate delivered to BNB. The intensity per spill is typically about $4.5 \times 10^{12}$ protons. The time structure of individual beam spills is determined by Booster parameters. The harmonic number for Booster is 84 (81 buckets are filled with beam) and the RF frequency is 53 MHz. This results in 1.6$\mu$s long spill comprised of a train of 81, roughly 1 ns wide buckets mutually separated by $\sim$19 ns.

The next few sections describe how the neutrino interaction rate in the detectors can be doubled by replacing the existing single horn system with a re-optimized two horn system.

| | CC ($Events/t/10^{20}POT$) | | Flux ($\nu/m^2/10^6POT$) | |
|---|---|---|---|---|
| | MiniBooNE Horn | 2 Horn | MiniBooNE Horn | 2 Horn |
| $\nu_\mu$ | 302.0 | 636.6 | 7.02 | 12.6 |
| $\bar{\nu}_\mu$ | 2.6 | 2.9 | 0.44 | 0.41 |
| $\nu_e$ | 2 | 3.8 | 0.039 | 0.067 |
| $\bar{\nu}_e$ | 0.06 | 0.06 | 0.004 | 0.004 |

**TABLE I:** *Predicted neutrino event rates with a two horn system compared to the present BNB configuration with MiniBooNE horn. The rates were calculated using CC inclusive cross section on Ar. Significant increase in the event rate is expected with reoptimized 2 horn system.*

The additional space needed for this larger system can be made available in the BNB target building without any need for civil construction by condensing the final components of the proton beamline immediately upstream of the target.

## II. A RE-OPTIMIZED HORN CONFIGURATION

This section discusses the a reoptimization of the target and horn system to better match the capabilities of the LArTPC detectors, the future users of the beamline. In addition to the reoptimization motivated by the change in detector technology there is also a push to reoptimize that comes from better knowledge of the system components that is now available. Since the MiniBooNE horn was originally designed, precise measurements of pion production in the beryllium target have been made by the HARP experiment [2] and the kinematic distributions are much better known. These data additionally allow for better optimization of the shape of the inner conductor and the focusing system.

Preliminary studies have been made to estimate possible gains with a reoptimized focusing system. A fast Monte Carlo was developed and used to optimize the horn current, shape of inner conductor of horn 1 (and horn 2), horn position(s), and target position in order to provide focusing of pions that produces the most neutrino events in the on-axis detector(s). The geometry of the optimal design was then simulated using full GEANT4 based Monte Carlo (MC) used by MiniBooNE and other BNB experiments to calculate the neutrino flux. The detailed beam simulation was tuned to match HARP hadron production measurements. Comparing the predicted flux using the full beam MC enables a realistic comparison of the optimized system to the existing MiniBooNE horn focusing.

Figure 2 shows the shapes and locations of the current single horn system and the re-optimized two horn system. Figure 3 shows the fluxes that result from the same proton delivery to the current and re-optimized systems.

Table I shows the expected event rates with two horn system. It is important to note that the intrinsic $\nu_e$ component which presents irreducible background for $\nu_e$ appearance measurement remains fractionally the same.

It can also be seen from Table I that the optimized two horn system has a much smaller wrong sign component compared to the original MiniBooNE horn configuration. Both the longer first horn, and the additional second horn further defocus wrong sign (WS) mesons. In neutrino mode this results in a reduction of the WS component by a factor of ∼2. While this is not an important feature in the neutrino mode, similar reduction is expected in the antineutrino

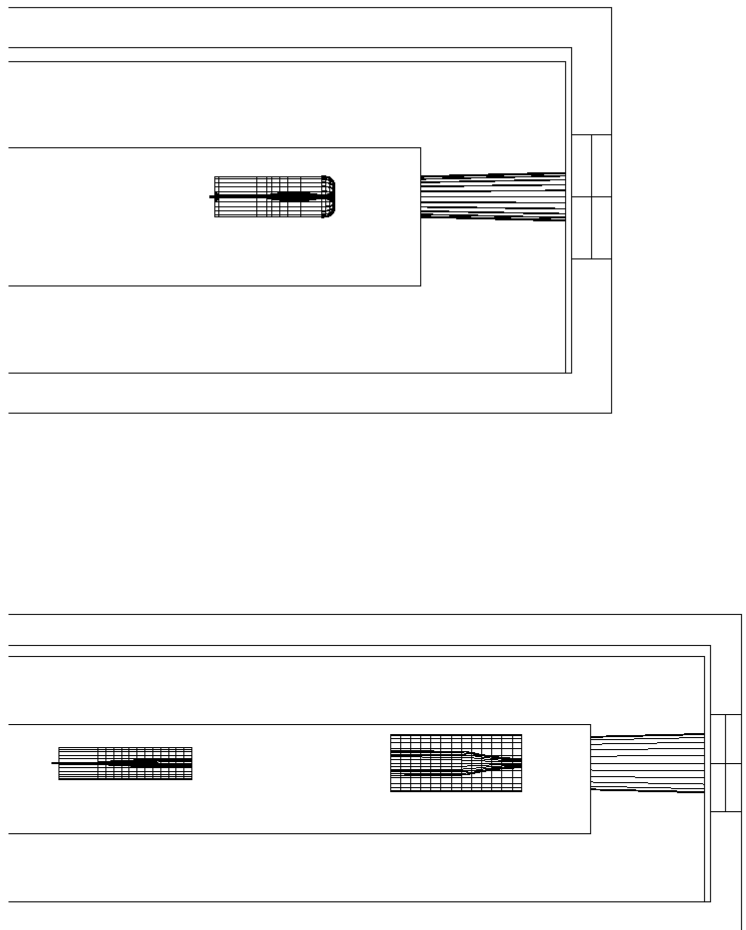

**FIG. 2:** *Two plan views of the target chase showing the shape and location of the current single horn (top) and optimized two horn (bottom) systems.*

mode where the WS component is significant. Hence, the two horn system would provide a much cleaner measurement of antineutrino oscillations as well as cross sections because the statistical and systematic uncertainties associated with subtracting the wrong sign component would be greatly reduced,

Further optimization of the system is possible. About 20% of the neutrino flux in the MiniBooNE configuration is lost due to pion interactions within the horn conductor. The thickness of conductors in these preliminary studies was taken to be the same as for MiniBooNE horn. Thinner inner and outer conductor could be used, further reducing the losses. The transverse size of the first horn was kept the same as the original MiniBooNE horn. The horn current was limited 250kA, the upper limit of the present MiniBooNE power supply, and both horns were pulsed with same current. All of these parameters could be modified to fine tune the system. The possibility of movable target and horn longitudinal positions will also be explored. This would allow the beam to be tuned to higher or lower energies. Future information from

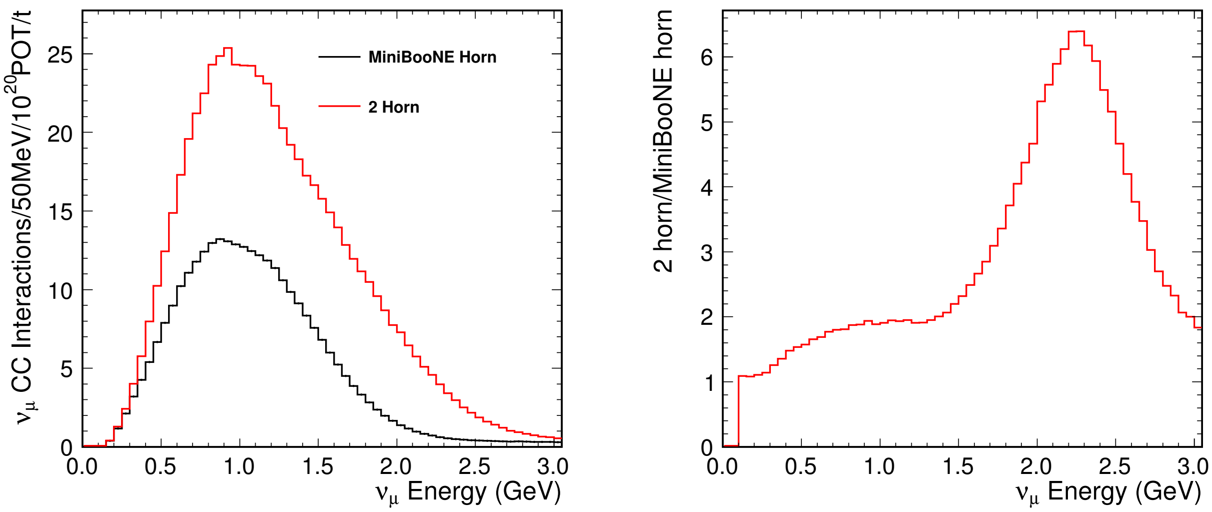


**FIG. 3:** *Comparison of the expected neutrino flux with a two horn system to the present MiniBooNE horn focusing. The two horns were optimized to give the most neutrino events, while fitting the constraints of the existing target hall.*

running of MicroBooNE or other experiments might make that a useful capability to have, just as it was for the NuMI target and horn system in the pre-NOvA era.

Physical constraints of the existing target hall were taken into account in these preliminary studies. The two horn system requires more room along the beam axis than is presently available (see Figure 1). Some modifications of the primary beamline and shielding within the target hall region would be necessary to accommodate the modified design as discussed in Section III.

The total length of the optimized system was limited to a realistically achievable size. The transverse size of the second horn was limited to the dimensions of the chase. To fully take advantage of the larger second horn, the opening of the collimator at the entrance of the decay pipe was enlarged from 30 to 50cm.

The preliminary studies demonstrate that it is feasible to build a new focusing system that would increase event rate by a factor of 2 or more. This system would provide a huge improvement in the statistics as it doubles the count rate of every detector in the beamline. Further optimizations are possible as well as fine tuning of the horn focusing to shape the spectrum and maximize the physics potential of the experiment.

The new system should be designed to take advantage of present and future accelerator upgrades. The present target/horn system and target hall shielding limits operations to 5 Hz average beam rate with up to $5 \times 10^{12}$ per spill. The first phase of Proton Improvement Plan (PIP) is presently underway and will allow Booster to deliver beam at a rate of up to 15 Hz starting in FY2016. Future improvements planned for PIP II will allow increasing booster rate to 20 Hz and spill intensity $6.5 \times 10^{12}$ protons. The design of an upgrade to horn system components should be made capable of handling the higher repetition rate and spill intensity.

## III. MAKING SPACE FOR THE NEW HORN CONFIGURATION

In order to accommodate the two-horn system, an additional 5m of space is needed in the Booster Neutrino Beamline.

The Booster Neutrino Beamline (BNB) has three sections. The first section is in the Main Injector tunnel, the second section is a carrier pipe transporting the beam under a road, and the third section points the beam toward the detectors and focuses the beam on the target. This third section is composed of optics to capture the beam from the carrier pipe, a regular lattice to transport the beam through the arc, a vertical dogleg to raise the beam to the height of the target, and a final focusing triplet. The third section is located in the MI12 tunnel and the target hall. The MI12 tunnel is ten feet wide, and the height is eight feet or nine feet, six inches. The tunnel changes height at the approximate center of the first magnet of the dogleg. The target hall, when all shielding is in place, is 23 feet wide, 24 feet deep, and 13 feet high ($7.0 \times 7.3 \times 4.0$ meters).

In order to gain the additional 5m the dogleg can be moved upstream, beginning in the last cell of the arc and ending at the transition to the higher enclosure. A slight adjustment of position of the quadrupole matching the lattice to the final focusing triplet is also required. A calculation using TRANSPORT [3] shows that a 1mm round beam can be focused at the center of the target with the quadrupole at acceptable currents.

In addition to changes in the beamline, the target pile must also be reconfigured. The present target pile consists of steel blocks filling the downstream half of the target hall. The steel is covered by concrete blocks above. The pile has concrete stacked in front, with an opening large enough to accommodate the horn. Adding an additional 5m of shielding upstream of the existing target pile should be possible.

Figure 4 shows the present and proposed beamline configurations indicating how the space needed for a two horn system can be recovered by adjusting the beamline components.

Figure 5 shows the line 5m upstream of the existing target pile. The new target pile would not occlude the door, although it would cover the sump. Shielding would have to be configured such that the pumps in the sump can be replaced. Existing utilities, such as the cooling skid for the horn, would have to be relocated, perhaps upstream, under the raised beamline.

Another option would be to reconfigure the target pile to allow for more space downstream of the target. This would entail removing all equipment from the MI12 service building, removing the existing shielding blocks, and handling the radioactive steel. However, enough space exists so as not to cover the sump.

## IV. SECONDARY BEAMLINE INSTRUMENTATION

In this section the current secondary beamline monitoring is described along with some possible upgrades. It should be noted that these monitoring upgrades are completely independent of the horn system upgrades of the previous three sections.

The present secondary beam has minimal instrumentation, consisting of a cross formed by 22 loss monitors located behind the 50m absorber. Twelve loss monitors are placed vertically, approximately six inches apart; and ten loss monitors placed horizontally, five on each side of the vertical column, also spaced approximately six inches apart. The loss monitors are read out through a segmented wire ionization chamber (SWIC) scanner, allowing one to see horizontal and vertical profiles.

The fifty meter absorber consists of 24 blocks of steel stacked roughly into a cube, ten foot on side. The steel is rough cut. This is followed by a ten foot square by three foot deep concrete block. The secondary monitor follows. A stack of steel, eight foot square by two feet deep, ends the absorber. The absorber is buried directly in the ground – no enclosure exists – eliminating the possibility of easily repairing the muon monitor. A steel pipe carries the signal wires to the

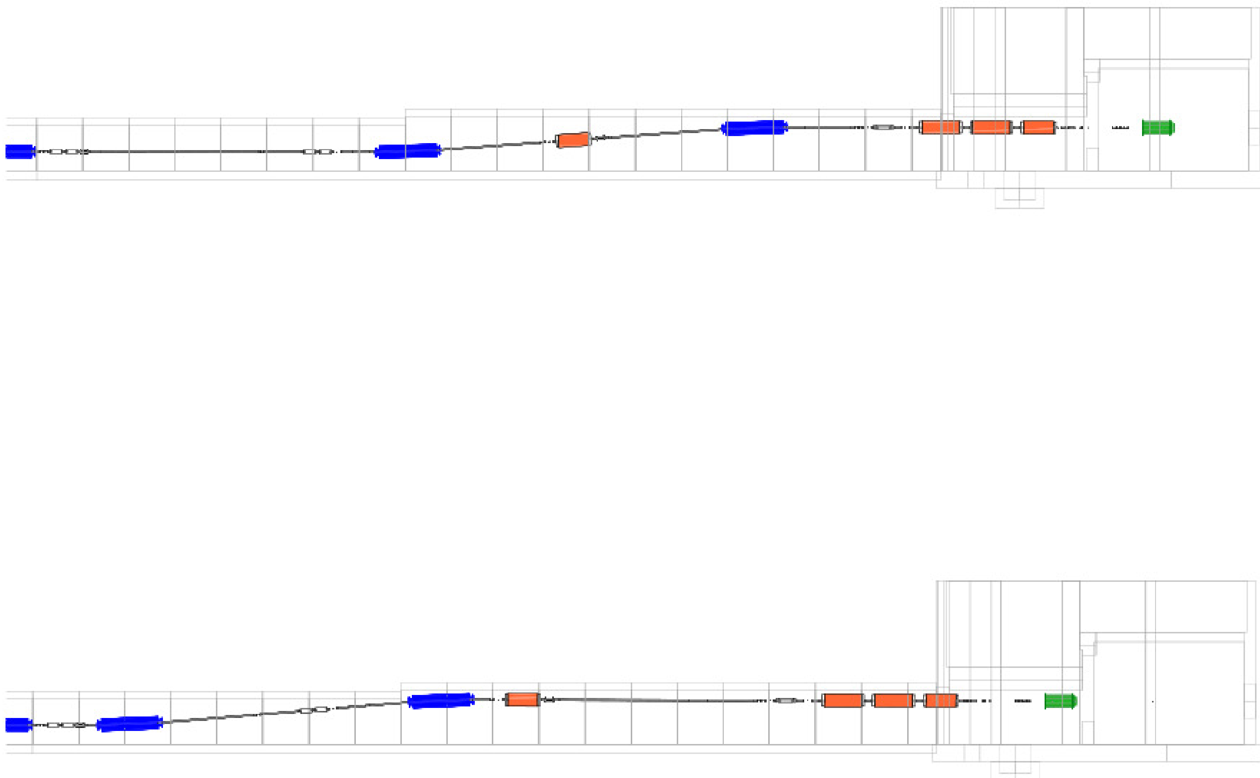

**FIG. 4:** *Side elevations of the Booster Neutrino Beamline (BNB). The present (top) and proposed (bottom) beamline configurations are shown. The dogleg dipoles are shown in blue, the triplet and matching quadrupoles in orange, and the horn in green. The new dogleg is initiated at the beginning of the last cell of the lattice and completed where the enclosure roof rises. The triplet and horn are moved five meters upstream. The location of the matching quadrupole is adjusted slightly.*

surface.

Ideally, one would replace the 50m absorber and provide better instrumentation. A hadron monitor would be placed at the upstream end and a muon monitor at the downstream end. The existing steel would be removed and replaced with more uniform steel plates, eliminating any transverse gaps. An enclosure would be provided to allow for the repair or replacement the hadron or muon monitor.

Constructing such a feature would entail digging into the berm and removing the present 50m absorber. Controls would be in place to manage the irradiated aggregate and steel. The existing water barrier would be breached and resealed around the new enclosure. Power would be run to the new enclosure. Adequate shielding would be placed between the absorber and enclosure, and a means of removing it thought about. Rebuilding the 50m absorber would require significant engineering.

Another option would be a retractable profile monitor at the 25m absorber. This absorber consists of a series of steel and concrete plates that can be lowered into the secondary beamline halfway down the 50m absorber.

In the autumn of 2014, the 25m absorber hatch was opened and the modules adjusted longitudinally to provide a 3/4 inch gap. A profile monitor, 5/8 inch thick, was inserted through this gap to nominal beam center. The monitor consisted of 48 horizontal wires and

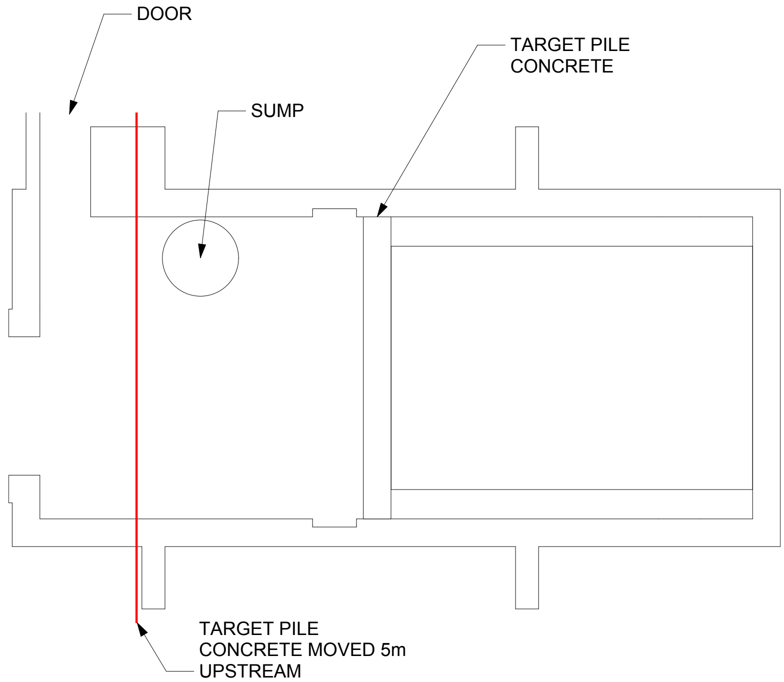


**FIG. 5:** *Plan view of target hall showing front face of existing target pile and location 5m upstream. The door is not blocked, but the sump would be covered.*

48 vertical wire, each plane having a 2mm pitch. The primary beam was steered around the target and observed on the monitor.

With moderate engineering effort, one could design a profile monitor which would be remotely inserted for alignment runs and retraced for normal runs. The monitor could be of adequate size to see both the primary and secondary beams. By appropriate choice of gain one may be able to distinguish between primary and secondary beam.

## V. REQUEST

Based on the preliminary studies outlined above we make the following requests

- A detailed study of the cost and schedule for conversion to a two horn system should be initiated immediately. This should include the cost of new horns, new or refurnished power supplies, and the necessary work for reconfiguration of the incoming beamline and of the collimator. The system should be capable of (or readily upgradeable to) operation up to 20Hz and of taking the beam intensities anticipated once the PIP II project is complete.

- A detailed study of the cost, schedule, impacts, and benefit of improving the secondary beamline instrumentation of the BNB should be initiated immediately. This should include studies of what instrumentation might be placed near the horn(s), at the 25m absorber, and in the 50m absorber. The instrumentation should be capable of (or readily upgradeable to) operation up to 20Hz and of taking the beam intensities anticipated once the PIP II project is complete.

[1] , “,” Fermilab drawing number 6755. 160-ME-416180.

[2] M.G. Catanesi *et al.* (HARP Collaboration), “Measurement of the production cross-section of positive pions in the collision of 8.9-GeV/c protons on beryllium,” Eur.Phys.J. **C52**, 29–53 (2007), arXiv:hep-ex/0702024 [hep-ex].

[3] David C. Carey, K.L. Brown, and F. Rothacker, “Third order TRANSPORT with MAD input: A Computer program for designing charged particle beam transport systems,” (1998).