The NuMI Primary Beam Technical Design Handbook

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I. Introduction

The purpose of this document is to collect together in one place the technical design features of the primary proton beam of the NuMI project. A NuMI Facility Technical Design Report[i] was written in 1998 as part of the process of establishing a baseline cost and schedule. That document concerned itself with the entire NuMI project including the hadron and neutrino beams. The present work concerns only the primary proton beam and can be thought of as Version 2.2 of the relevant parts of the TDR. Designs exist for all of the systems and subsystems of the primary beam and they are detailed herein. This document will serve as a guide for the construction and installation of the primary beamline components.

II. Beamline

A. Specifications

The scenario for production of neutrinos is as follows. The 120 GeV primary beam is extracted from the Main Injector ring and transferred through the MI Enclosure, a region known as the NuMI stub and a steeply inclined carrier pipe to the pretarget and target regions located deep underground in newly excavated caverns. There it strikes a newly designed two interaction length target in which a beam of hadrons is produced. The hadrons near zero degrees, of which π and K mesons are the most important, are focussed by a pair of horns and allowed to decay, into μ mesons and neutrinos, in a several hundred meter long shielded decay region. Those neutrinos induce the desired physics interactions in a near detector on the Fermilab site and the far detector in northern Minnesota.

This scenario sets specifications on the proton beam both in how it interacts with the hadron production target and the extent to which it leads the zero degree hadrons to be directed toward the far detector. The design of the target and the requirements it places on the primary beam are closely related to the number of protons to be delivered. The NuMI specification has, from the time of the experimental proposal[ii], been $4\text{x}10^{13}$ protons per 1.9 second Main Injector cycle. This value has been used in target and proton beam design; however it is larger than the baseline specification for the Main Injector itself[iii,1] - $2.5\text{x}10^{13}$. The Booster intensity record now stands at $5.75\text{x}10^{12}$ protons in one pulse, corresponding to $2.875\text{x}10^{13}$ delivered to NuMI.

The specifications established for the proton beam are as follows.

- Beam size The beam size on target is to be 0.7mm (horizontal) x 1.4mm (vertical), this being the 1σ value. There are different target locations, and thus tuning scenarios, depending on the desired energy range of the neutrino beam. In this document the so-called "low energy beam" is assumed. Note that it is not known with certainty the transverse emittance of the Main Injector beam at NuMI intensities. Quadrupole settings have been determined for values of 20π, 40π and 60π mm-mr.

[1] The MI intensity specification is $3\text{x}10^{13}$ protons per pulse. The precise scenario for sending beam is that 1/6 goes to pbar and 5/6 to NuMI. Thus the MI specification for NuMI beam is $2.5\text{x}10^{13}$ protons per pulse.

It is also necessary that the beam size not change significantly over the target length, either in becoming too small and endangering the target material or in becoming too large, permitting less beam to hit the target. With the parameters which have been determined the change in size is 2% over the target length in the vertical, and negligible in the horizontal. Thus clearly this parameter is not a problem.

- Positional precision and stability The target consists of rectangular fins of graphite with dimensions 6.4 x 6.4 mm^2, situated downstream of the second horn protection baffle with aperture 5.4mm (horizontal) by 10mm (vertical) and rounded corners. Thus for a perfectly centered beam, Gaussian tails only beyond 3.9σ (horizontal) will be intercepted by the baffle. This does not represent a serious problem; however any significant amount that the beam is off-center will lead to beam not reaching the target. The instrumentation specified will be adequate to maintain the beam center within ±100μ and the program Autotune will be used to maintain the position to high precision.
- Beam angle Assigning 10% of the total beam angle error budget to the primary beam yields a required precision of 60μrad. The final two instrumentation stations are located 14m apart, so that a 1mm relative position error between them will lead approximately to this 60μrad. The instrumentation itself will operate with a precision of an order of magnitude better than this 1mm value, so that the real limitation will be on the relative alignment of two detectors 14m apart.

There are separate specifications on the primary beam as regards losses. The number of protons traversing the beamline is large, the rate being, for instance, two orders of magnitude greater than that of the NuTeV experiment. Thus losses of order 1% are comparable to the total beam of large experiments of the past. Resonant extraction, which results in an irreducible beam loss of a few percent on electrostatic septa, was originally considered for NuMI. However this loss level leads to amounts and configurations of shielding so located as to be unfeasible at this time; thus single turn extraction is now specified. Losses are problematic as they lead to air activation, component residual activity and in extreme cases equipment damage. However the most stringent constraint in the case of NuMI is that of groundwater irradiation.

Groundwater irradiation and contamination have not historically been serious problems at Fermilab. This is because, at the elevations at which beamlines have been located, there are several feet of clay soil (glacial till) between any area which might be irradiated and the groundwater aquifer. In the time taken for the activity to reach the aquifer most of the harmful nuclides will have decayed away. This effect is often referred to as R_{till} - the reduction factor due to till migration. However NuMI is constructed at a much lower elevation, indeed being located, from the carrier pipe region onward, in the bedrock aquifer. Loss limits in different regions along the beamline have been determined[iv]. The most sensitive is that where the carrier pipe traverses the interface between soil and rock. The fraction of beam loss in this, rather limited, region must be kept below a few $x10^{-6}$, or a handful of full intensity pulses in the average water residency time of four months. Although this loss limit is the most stringent, any losses at or downstream of this region will be serious. The more downstream locations, in particular the pretarget hall with relative loss limit of 1.4×10^{-4}, are in some ways more worrisome in that smaller beam missteerings in the stub will lead to striking components there. A 0.28mrad angle error in the stub will lead to the first magnet in pretarget being hit with beam.

B. Layout and beam transport

In Figure 1 are seen elevation views of the beam layout in, from top to bottom, the MI-60 region of the Main Injector enclosure, the NuMI stub region and the pretarget hall. The components to be installed in those three regions are detailed in the following.

MI-60 region The first beamline elements encountered are Lambertsons and a C-magnet (V100) installed in a configuration similar to that in MI-52 where extraction to the Tevatron, Switchyard and Antiproton Source takes place. The method used to transport the beam through this region is shown in Subsection C. The quadrupole Q101 provides some focusing required to keep beam size under control over the rest of the MI-60 region. The string HV101 consists of standard beamline EPB dipoles, but installed in a rolled configuration. This string serves two purposes, first to set the horizontal bearing to the far detector, and second to level the beam vertically so that it can be transported to the stub region while remaining between the Main Injector below and the Recycler Ring above. This part of the line finishes with a quadrupole doublet, an instrumentation station and a trim magnet pair.

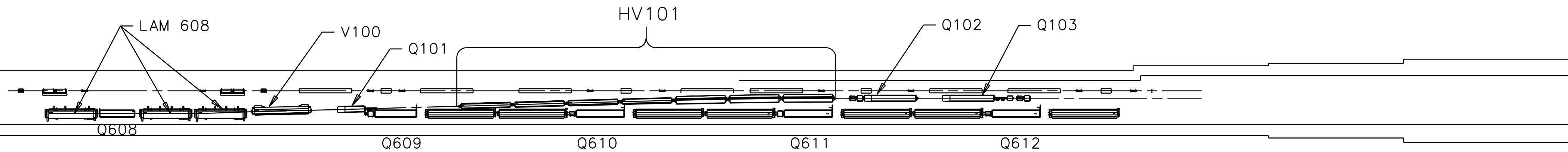
NuMI stub The goals of the design in this location are to provide the 146mrad of downbend required to reach the proper depth in the target hall and to provide focusing for the beam before it passes through the critical carrier pipe region. Most of the required bend is provided by the string V105, made of Main Ring B2 magnets serving as vertical benders. Additional bending is provided by the pair of EPB dipoles noted as V104. There are also three instrumentation stations and three trim magnet pairs in this region.

Pretarget hall The function of the line here is severalfold. As to steering, this is where the pitch angle to the far detector is established. This is accomplished by string V109, consisting of three 6-3-120 large aperture dipoles, and string 110, consisting of six EPBs. The focusing here establishes the α, β and η functions (i.e. beam sizes) at the target. The instrumentation just downstream of Q110 and at an additional station just upstream of the target is used to measure the beam position and angle at the target. There has arisen a concern that the beam energy spread may be difficult to control. The vertical dispersion function is made zero at the target (the horizontal dispersion is small everywhere), preventing beam motion as the MI energy changes.

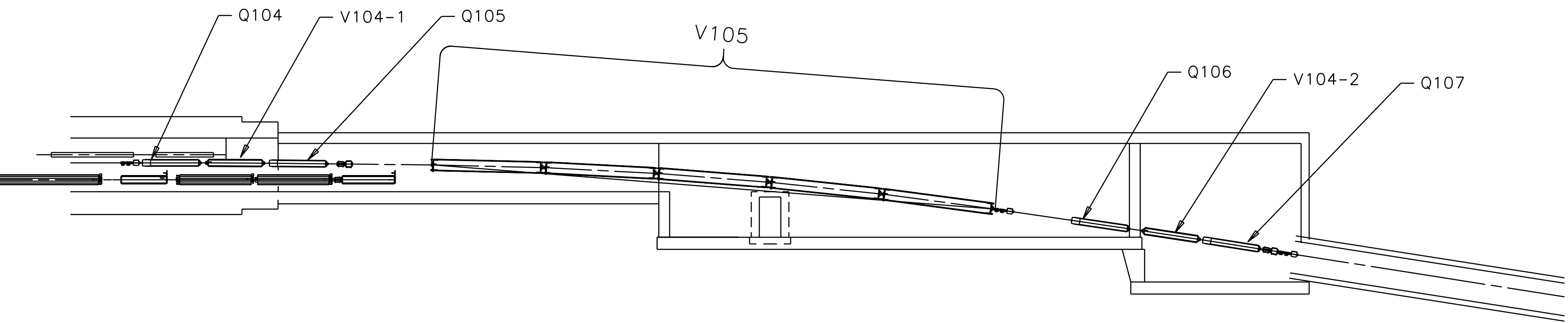
All of the magnets of this line except for the trims are recycled from previous installations. They have been refurbished and measured in the Technical Division.

C. Extraction region

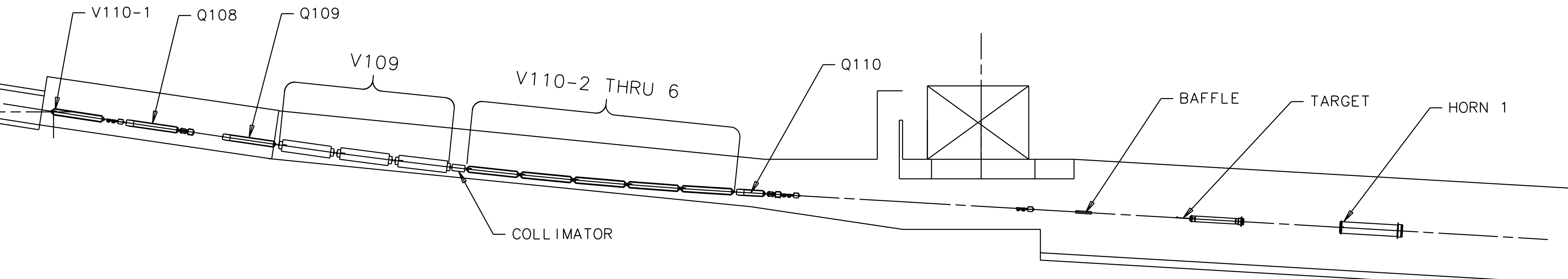
The MI60 extraction region has been reworked several times. The extraction mechanism was originally proposed to be resonant with a 1ms spill[iii,v]. However, due to losses on the septa[vi] this option was discarded in favor of a kicker induced single turn mode[vii,viii]. It



MI 60 REGION AT THE MAIN INJECTOR (ELEVATION VIEW)



NuMI STUB (ELEVATION VIEW)



PRETARGET TUNNEL (ELEVATION VIEW)

has been decided to produce kickers based on those at MI52, and a location for them has been selected in the region downstream of MI quad 602. Installation in this location will involve moving elsewhere equipment currently there. Alternate locations have been found for these pieces - horizontal Schottky, resistive wall and wideband pickups and pinger magnet - and their associated hardware.

The extraction mechanism is a horizontal kick, leading to Lambertson magnets which deflect primarily in the vertical. The extracted beam is to lie, at the Lambertson magnets, to the outside of that circulating. Since the phase advance from kickers to Lambertsons is near to 270°, it is required that the kicker deflect beam inward. The half-width of a beam with normalized emittance of 40π mm·mr at the Lambertson magnet entrance is 3.6 mm. We choose to keep the edge of this beam at least 4σ from the Lambertson steel and this requires a minimum kick of 0.553 mrad.

As is indicated in Figure 1, there is a complication in the Lambertson magnet region in that a Main Injector lattice quad, Q608, is located between the first two Lambertsons, its field and aperture having an essential impact on the extraction process. At extraction a bump is required to fit the circulating beam cleanly through the Lambertson field free regions and the extracted beam through Q608. Displacements of MI quadrupoles are used for an inward orbit displacement; the displacements required are presented in Table 1. The phase space centroids of the beam through the extraction elements are presented in Table 2. Figure 2 shows the beam orbit induced by the kickers, that of the bump and the combination of the two. In Figure 3 are shown the beam envelopes at injection, for high energy circulating beam and for extracted beam at the entrances to the three Lambertsons, at Q604, at the exit of Q608 and at the entrance and exit of C-magnet V100. The envelopes shown correspond to an emittance of 40π mm·mr. The indication is that all apertures are appropriately respected.

It is found that at injection a bump must be applied to the beam to fit it cleanly through the field free regions of the Lambertson magnets. This bump is produced by Main Injector horizontal correction magnets, running at quite low currents. The resulting orbit through the extraction region is shown in Figures 4 and 5. As the energy increases and the beam size shrinks, the need for this bump vanishes.

Recent changes have involved reducing slightly the current through the Lambertson magnets and making the rolls of those magnets all the same. This latter change reduces the maximum roll and slightly improves the MI acceptance in this region. With minimal changes in rolls of C-magnet V100 and three elements of the HV101 string it is possible to match the phase space exiting that string to that used in downstream design.

Element	dX, mm
Q602	1.130
Q606	-1.403
Q610	-1.220
Q612	0.042
Q614	1.100

Table 1: Displacements of MI quadrupoles for horizontal bump excitation.

Element	X, mm	X', mrad
first Lambertson entrance	-10.573	-0.524
Q608 exit	-12.202	0.545
second Lambertson entrance	-11.936	0.545
third Lambertson entrance	-10.076	0.545
V100 entrance	-8.151	0.545

Table 2: Circulating beam locations at the Q608 exit and at the entrances of Lambertsons and magnet V100.

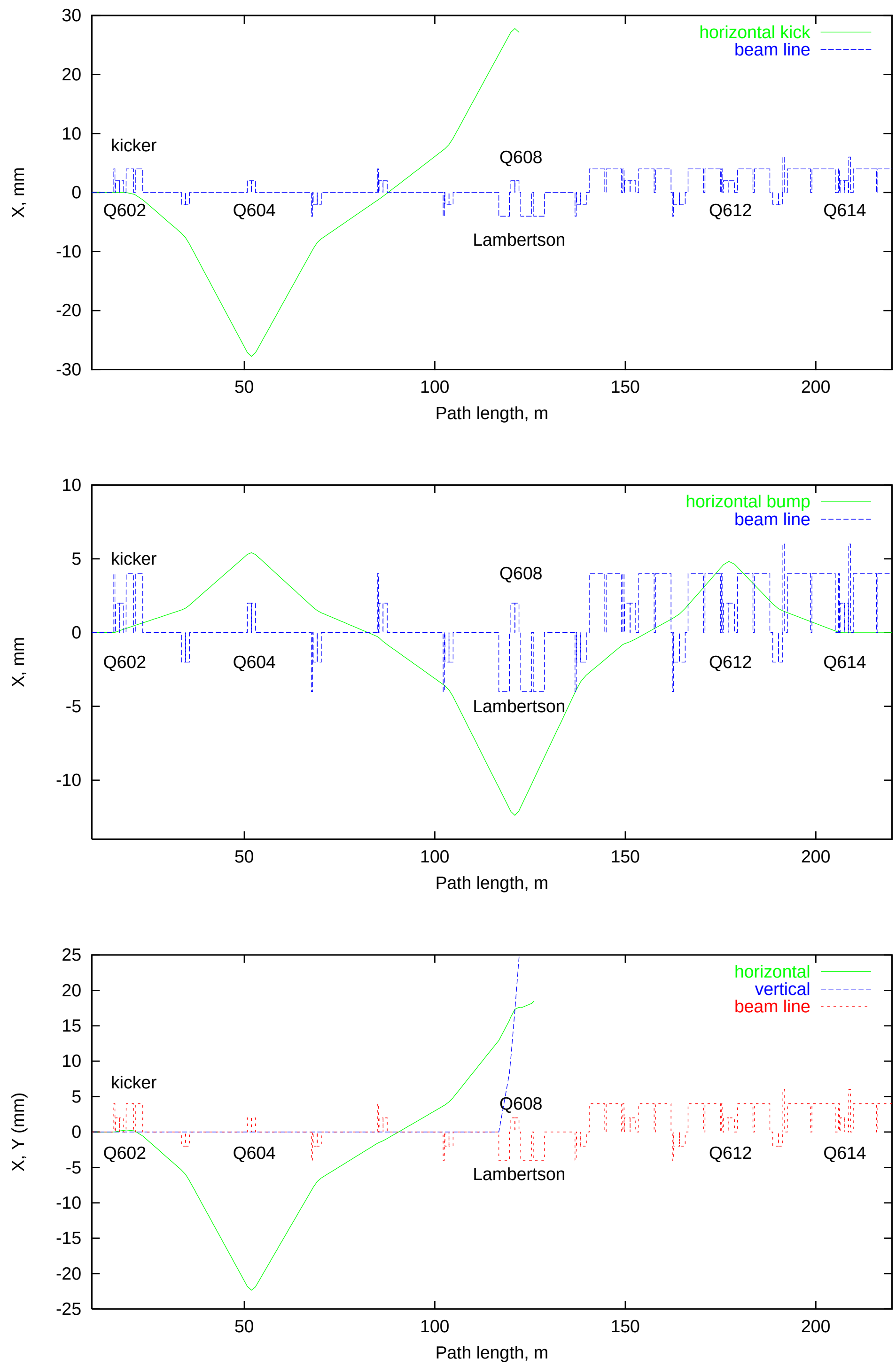


Figure 2: Horizontal kick (top), horizontal bump (middle) and resulting kick from kicker magnet, horizontal bump and Lambertson LAM60A (bottom) at extraction.

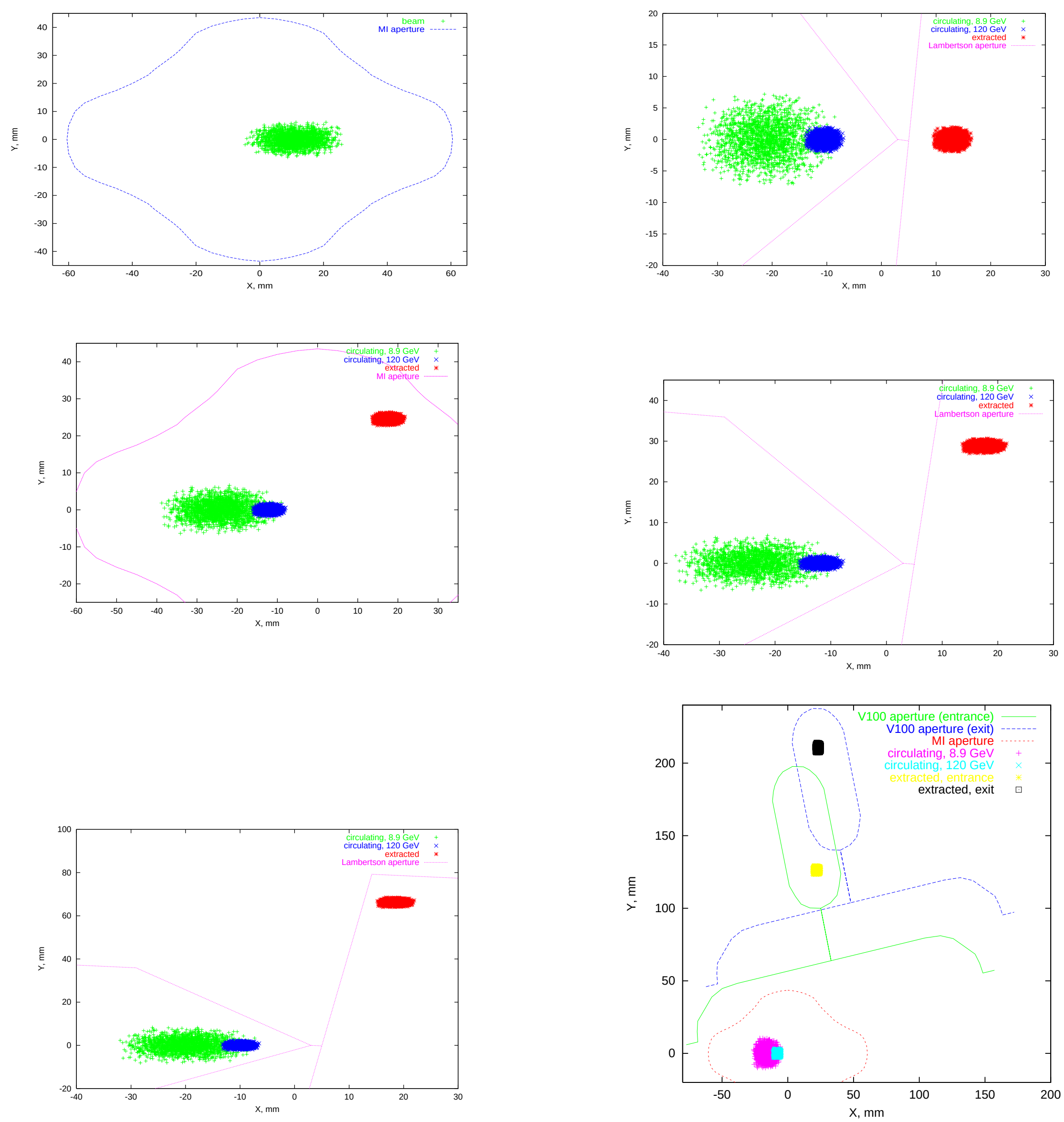


Figure 3: Circulating and extracted beam locations at the first (top right), second (middle right) and third (bottom left) Lambertson entrances, at quadrupoles Q604 (top left) Q608 exit (middle left) and at the C-magnet entrance (bottom). The beam size corresponds to a normalized emittance of 40π mm·mr.

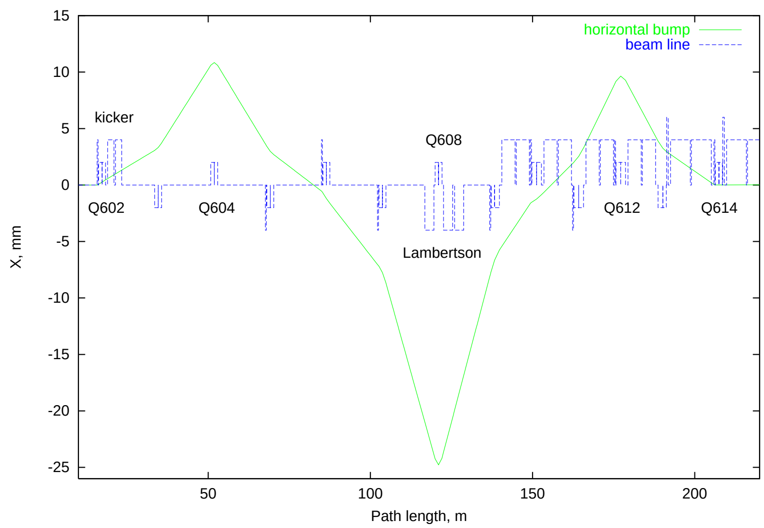


Figure 4: Horizontal bump at injection.

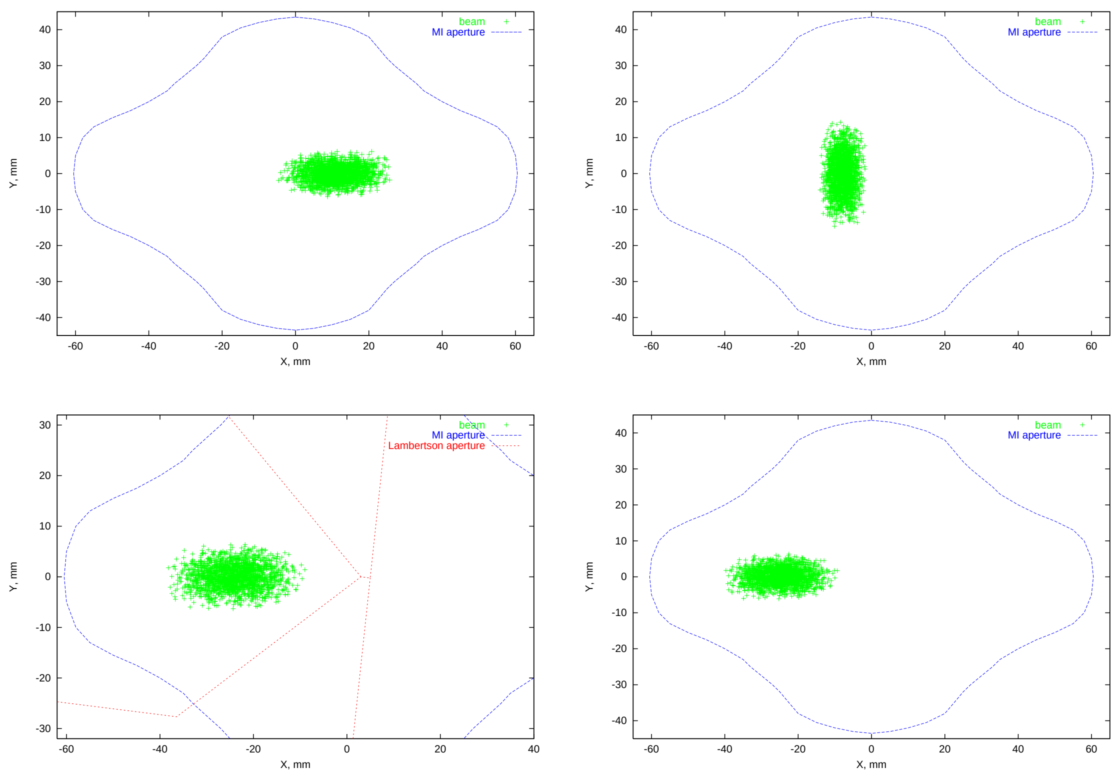


Figure 5: Circulating beam locations in the quadrupoles Q604 (top left), Q607 (top right) and Q608 (bottom right) and at the first Lambertson exit (bottom left) at injection. The beam size corresponds to a normalized emittance of 40 π mm·mr.

D. Apertures

Due to the groundwater constraint it is imperative that all means of scattering beam particles be minimized or eliminated. This requirement has led to use of multiwires instead of SWICs, as is discussed in Section IIIB and in elimination of carrier pipe baffles, see below. It also leads to the statement that no vacuum windows, which scatter beam, will be installed in this beamline.

Much work has gone into comparing beam sizes with apertures. For this purpose a beam emittance of 40π mm·mr with a momentum spread of 2 x 10^{-4} (σ_p/p) has been used. The comparison of this profile with the magnet apertures led to the decision to place three 6-3-120 magnets in the line, replacing EPBs which had been specified earlier. The comparison of the apertures with beam sizes is shown in Figure 6. The first region shown, at low station values, is that of the Lambertsons and the figure continues to and past the target, ending with the three possible locations for the second focusing horn. The three large aperture dipoles are indicated just downstream of station 300m. The vertical profile is seen to have contributions arising both from the beta function and from the dispersion (eta function). There is no way to inhibit the growth of the eta function in the carrier pipe region, and thus a constraint on the magnitude of the momentum spread is imposed. Some preliminary measurements on bunch length, related to momentum spread, in the Main Injector have indicated that by appropriate RF manipulations that spread can be made somewhat smaller than the value used in making this figure.

An aperture question which has been revisited several times in the course of the design effort is that of baffles, collimators, installed to protect downstream locations from accidental direct hits by the primary beam. Originally there were two pairs of baffles, the first to protect the carrier pipe region from beam and the second to protect the horns. The first one continued to present aperture problems and was finally ruled out in favor of current interlocks on all magnets in the stub region, allowing essentially no way for the beam to be grossly missteered. A recent development (March 2001) is that the horn protection baffle pair also be designed to protect the hadronic hose. The concept of this protection is that the target plus baffle together intercept all primary beam particles, guarding against the possibility that some will get beyond the target and be focussed into the hose wire over the length of the decay pipe. The downstream member of this pair of baffles will be located within the target region shielding pile and will have cooling provided by a radioactive water system. The upstream member restricts the vertical aperture to the same extent that the horizontal is naturally restricted by vertically bending EPBs. It is located between the last 6-3-120 dipole and the first EPB of the V109 string. (Recent changes to target dimensions may obviate the need for this upstream baffle.)

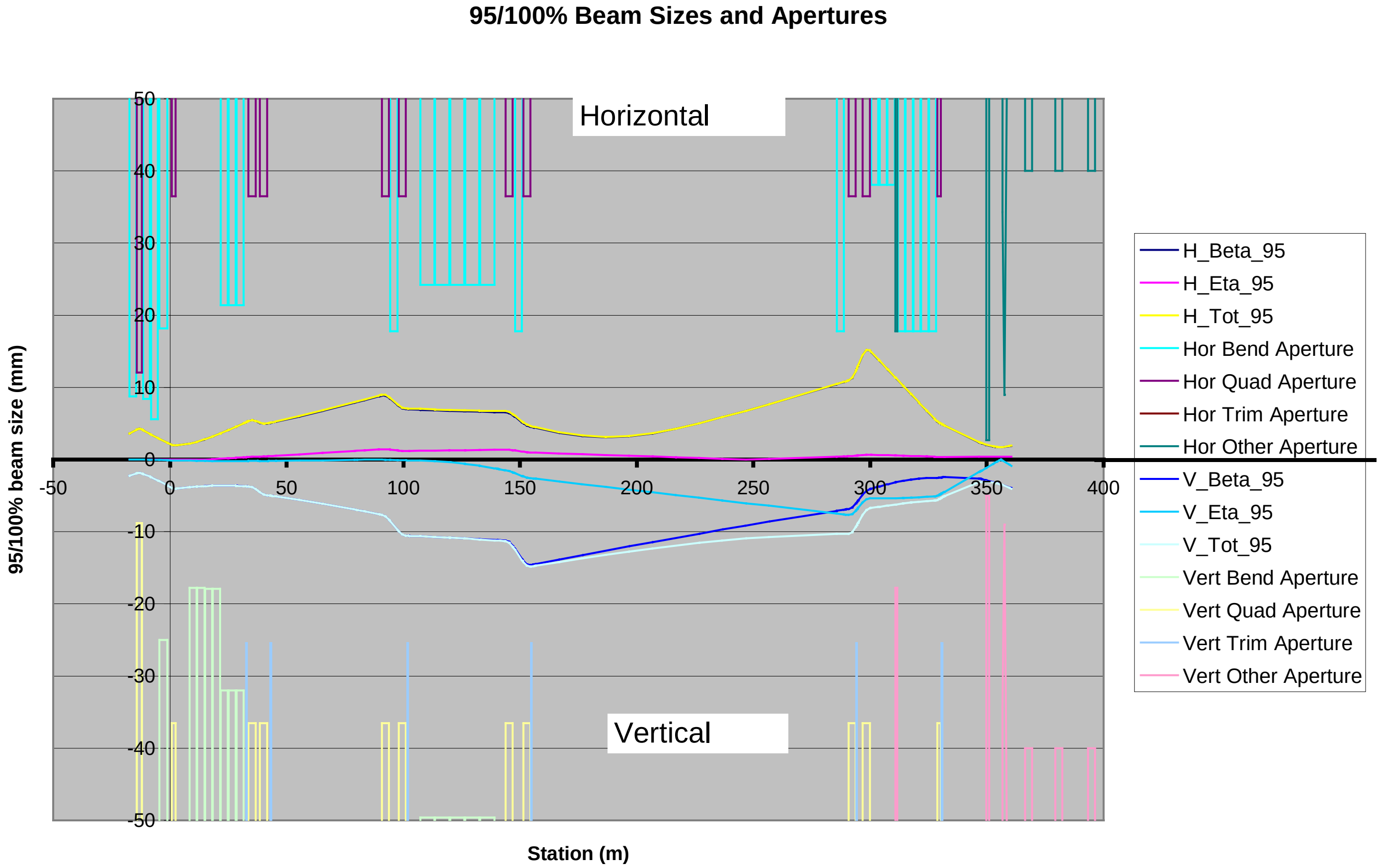


Figure 6: Beam sizes compared with apertures

III. Instrumentation

A. Overview

The instrumentation of this beamline is designed to serve two purposes. The first is to assure that the beam is accurately on target and is directed accurately toward the far detector. The pointing requirement on the primary beam, 60μrad as noted above, is about as stringent as those requirements of other fixed target experiments. However any new long-baseline experiment will have a burden of assuring that neutrinos are indeed being directed at its distant detector. The second purpose of the instrumentation is to aid in the effort to keep any losses at an absolutely minimum level. It will do this by providing position information to assure that the beam is in the center of its vacuum chamber, profiles to allow unexpected beam tails and halo to be observed, sensitive loss measurements to allow beam problems to be immediately addressed and intensity measurements in the ring and in the line to serve redundantly with the loss monitors in the case of large losses.

All of the instruments specified are of types which already exist in either the Main Injector complex, the Tevatron or the Switchyard. However NuMI will utilize unprecedented beam intensities at this energy. Thus a particular requirement placed upon the instruments is that they be functional over a wide range (at least two orders of magnitude) of intensity. This will allow all beam tuning to be done at low intensities, high intensity only being run after all beam properties are declared nominal.

B. Profile Monitors

All profile monitors will be of the type known as multiwires. The operational principle is that of secondary electron emission from wires which are placed in the beam. There are neither gas nor gas containment windows which would provide additional material in the beam beyond the wires themselves, which intercept 10% of the beam and scatter 10^{-4} of it. There are seven of these devices, each having 48 horizontal and 48 vertical wires. The wire spacing is 1mm for the upstream five units and .5mm for the last two, which are used in targeting the beam.

All units will have motion control into and out of the beam as directed through the control system. They will be in the beam during high intensity running only on rare occasions when a particular measurement needs to be made, but in general will be left out as they provide scattering of beam particles. A multiwire unit with its motor drive is shown in Figure 7.

The amplifiers which produce the readback signals will have gains variable in steps over two orders of magnitude, to facilitate the operation at different beam intensities. Typical intensity profile readouts from a series of multiwires are seen in Figure 8. Changing amplitude and dispersion functions affect profile widths significantly.

C. Position/intensity monitors

There are specified eight position/intensity monitors, each with horizontal and vertical readout. These intercept no beam and will provide all position information during normal operation. The position specification for the upstream six is a fairly standard .2 mm RMS. For the last two, those used in targeting, .05 mm RMS is specified; this is more challenging but comparable to what has been achieved by the collision point position monitors in the Tevatron collider. For the six upstream units, standard analog RF modules will be used to develop the positions/intensities. For the targeting units there will be more sophisticated equipment, such as a digital four channel oscilloscope with LabView computer interface. All units have intensity, as well as position, readouts.

As for the profile monitors, there will be switchable gain amplifiers to facilitate running over a wide range of intensities. It will be particularly important to confirm in this case that a gain change does not lead to an apparent position change. It is being considered whether these units, or perhaps only the targeting ones, should have high bandwidth readout which allows the position to be measured multiple times in the 10 μsec spill time.

D. Toroid intensity monitors

Toroids are often used for intensity measurements as they provide better accuracy than BPMs, are stable, reliable and subject to absolute calibrations. There is a toroid in the MI ring - observation of the change in ring intensity obtained from it over NuMI extraction provides a measure of the beam delivered. There will be two similar devices in the NuMI line to assure that all beam removed from the MI indeed enters the line and arrives in the vicinity of the target.

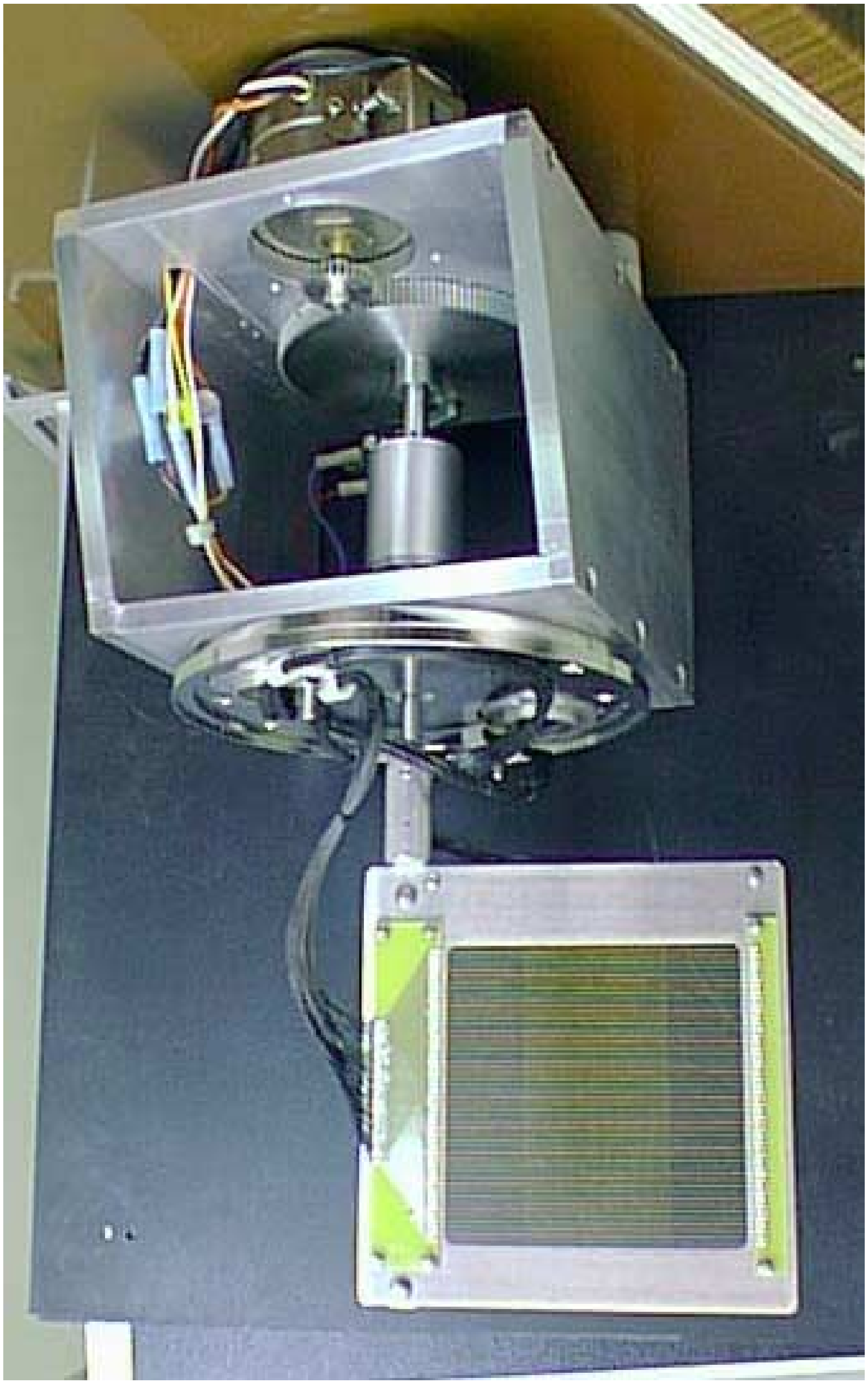


Figure 7: A multiwire system assembly. The motor drive is shown at the top, the wire plane beneath it.

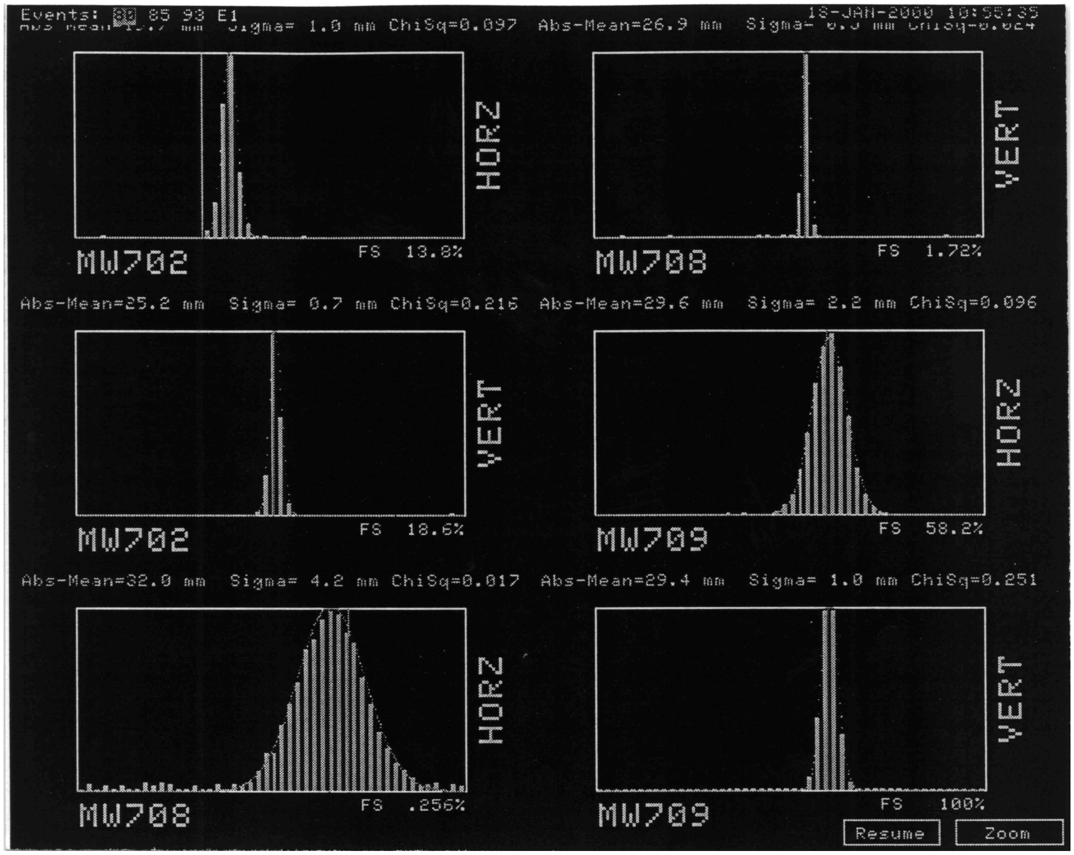


Figure 8: Horizontal and vertical profiles for a series of three multiwire monitors

E. Loss monitors

Two types of loss monitors will be used, both copies of existing equipment. First there are standard sealed units, thirty-five in number. These are placed at every location along the beamline where the aperture becomes smaller, as well as at every second magnet in bend strings. A photograph of a sealed unit, indicating the dimensions, is shown as Figure 9. The second type is known as total loss monitors. The present plans are for three of these - two in the carrier tunnel covering separately soil and rock regions, and one covering the length of the pretarget hall. The total loss monitors are sensitive in a calibrated fashion to any and all losses over the region covered.

The electronics to be used for the loss monitors will be like that developed for the Main Injector beamlines, where several decades of linearity have been demonstrated, see Figure 10. These monitors will likely provide the first warning of many types of beam delivery problems. The intensity monitors will see losses at the level of a few percent, but the loss monitors will be several orders of magnitude more sensitive and will provide a primary means of troubleshooting.

Figure 9: A standard sealed unit loss monitor.

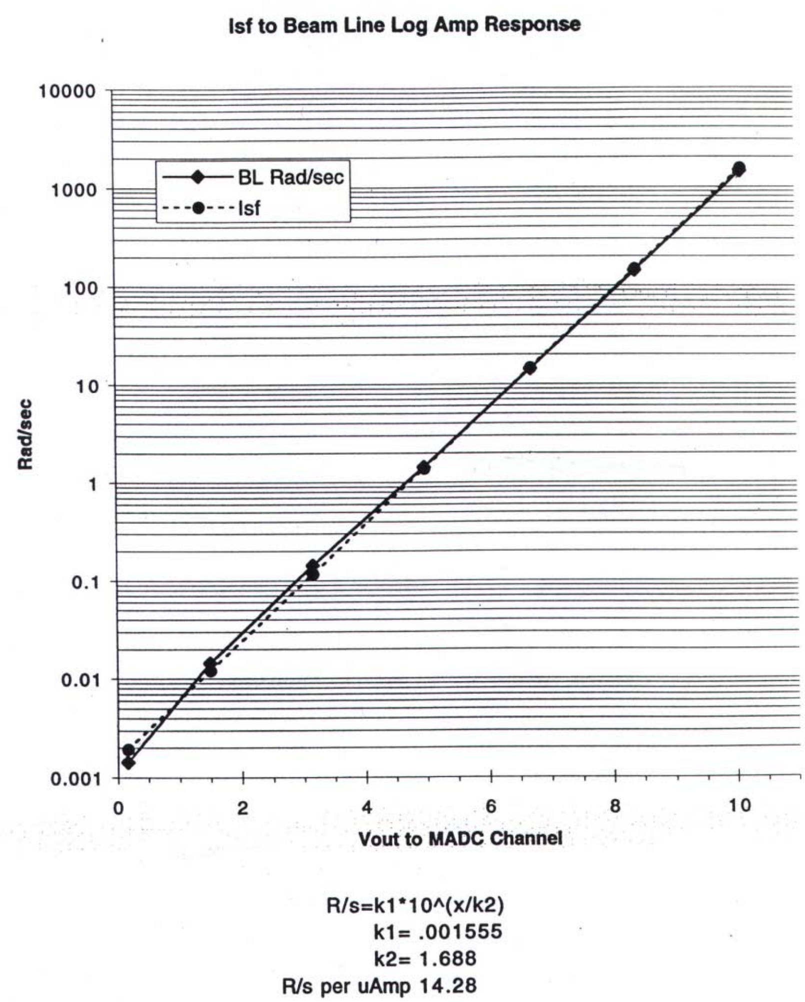


Figure 10: Measurement of the range and linearity of a standard loss monitor.

IV. Extraction kicker

The requirements on the extraction kicker are similar to those of the long-batch kicker, which is operational at MI52. The normal operating mode will be one in which five Booster batches, each consisting of 84 18.9nsec bunches, are extracted, a single Booster batch having previously been sent to the antiproton source on the same accelerating cycle. However for periods when antiproton is not in a stacking mode it will be desired to extract six Booster batches to NuMI. This latter mode has essentially the same requirements as does six batch extraction to the Tevatron, which is effected by the MI52 device. The specifications for the kicker system are given in Table 3 with specific requirements on the magnets and power supply given in Tables 4 and 5. There are two major change required in designing this device as compared to the existing ones. The rapid cycling of the kicker (1.9 second repetition rate) combined with the long pulse time lead to a high heat load in the magnet load. The high repetition rate means more pulses per year than the MI-52 kicker. A polarity change is also required due to a 180 degree change in the phase advance from that used previously. A cross-sectional view of a kicker magnet is given in Figure 11. The magnets are to be located in the region downstream of quadrupole Q602 with the power supply upstairs in the MI60 South Power Supply Room.

A measured kicker waveform is shown in Figure 12. It is seen to satisfy the given specifications. However it is noted that there is no criterion given for fall time and that there is ringing after the pulse is completed. This feature implies that there can be no beam left in the Main Injector after NuMI extraction and thus that this kicker design is not satisfactory for any scenario in which NuMI beam is extracted first on any given cycle, with extraction to antiproton following.

V. Utilities

A. Vacuum

The specification for primary beam vacuum is 10^{-6}Torr at the regions of instrumentation, which are essentially the whole line except for the long drift before the stub and for the carrier pipe. In these regions vacuum must be good enough so as not to jeopardize the 10^{-6} for the rest.

B. Water

Cooling water at Fermilab falls into three categories - Industrial Cooling Water (ICW), Low Conductivity Water (LCW) and RadioActive Water (RAW). These systems are needed to remove directly or indirectly the heat generated by the operation of electrical devices and to dispose of the energy deposited in various components by high energy beams. Without functional cooling systems, many beamline components would be damaged and fail due to excessive thermal buildup.

Ultimately the energy absorbed by a cooling water system of any type is transferred to the ICW system and thence to the atmosphere. This ICW system is part of the Fermilab infrastructure and includes cooling ponds, cooling towers and pumps. The pond water circulating through the ICW system is not suitable for direct use in beamline components such as magnets or power supplies due to its high electrical conductivity. Therefore a

Table 3 - Extraction Kicker Specifications

(Most physics specifications from MI Note #258, 1/6/00 D.E.J.)

Minimum Integrated Field:	2.24 kG - m
Physical & Good Field Aperture:	81 mm H x 33 mm V elliptical shape
Kick Angle @ 120 GeV:	563 µrad to inside of ring
Field Rise Time (1%-99%):	1.30 µs
Field Fall Time:	N/A
Field Flattop Time:	9.78 µs minimum(6 batches)
Flattop During Pulse:	± 1%
Flattop pulse to pulse:	± 1%
Repetition Rate:	1.9 seconds
Required Charging Time:	1.5 seconds

Magnet Location: Immediately Downstream Q602

Power Supply Location: MI-60 Service Building, South Power Supply Room

Table 4 - Single Turn Extraction Kicker Magnet

Two Traveling Wave Magnets (Magnetic Length 2.02 m each), Peak Current for Minimum Kick (550 G) 2300 A / magnet

Same magnet as used at MI-52 for Extraction from MI to TeV/P-Bar.

Different Kick Direction (to inside at 602 *vs.* to outside at 520)

Higher average power (390 W *vs.* 250 W) in load resistors requires significant design effort. Water manifold/heat exchanger required in tunnel for cooling.

Small modifications in components to improve manufacturing.

Table 5 - Single Turn Extraction Kicker Power Supply

Design modifications to change polarity of supply. Significant design effort.

Pulse Forming Network driving two magnets in parallel.

PFN has 32 sections, 33 nF/section, 825 nH/section, 46 kV at minimum kick

Increase coupling of Pulse Forming Network (versus MI-52)

Longer lifetime capacitors for PFN (versus MI-52)

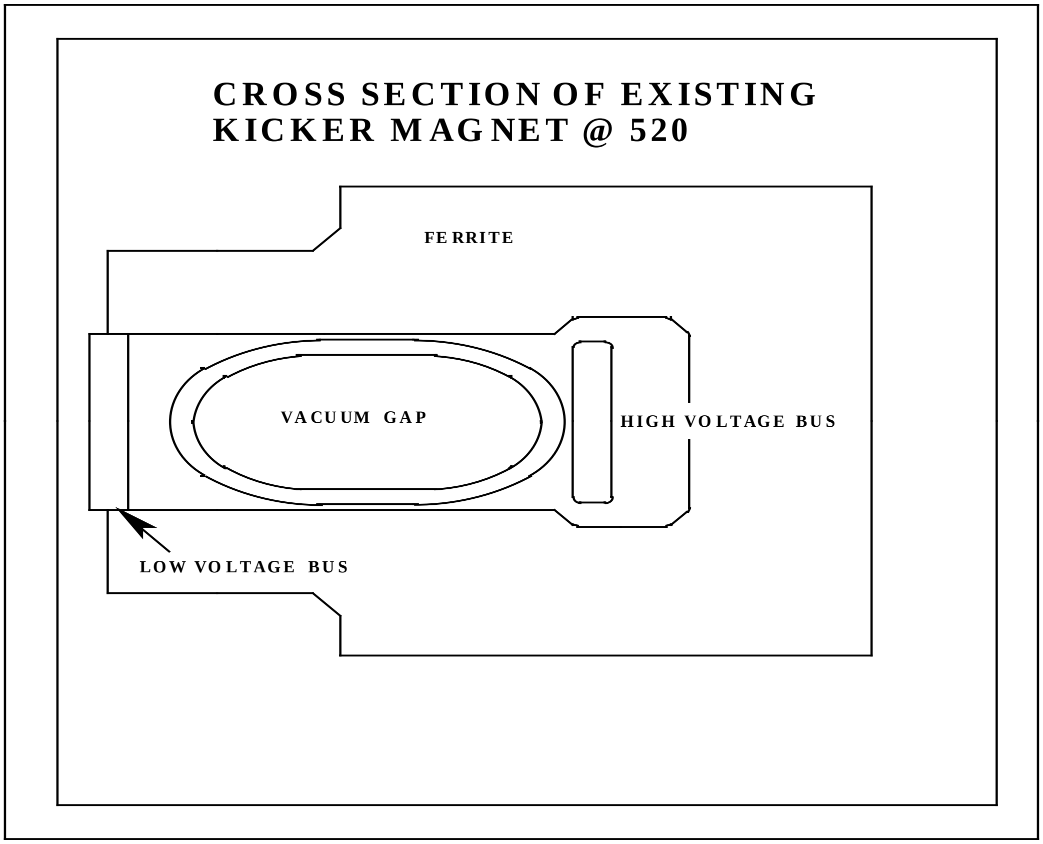


Figure 11: Kicker magnet cross section

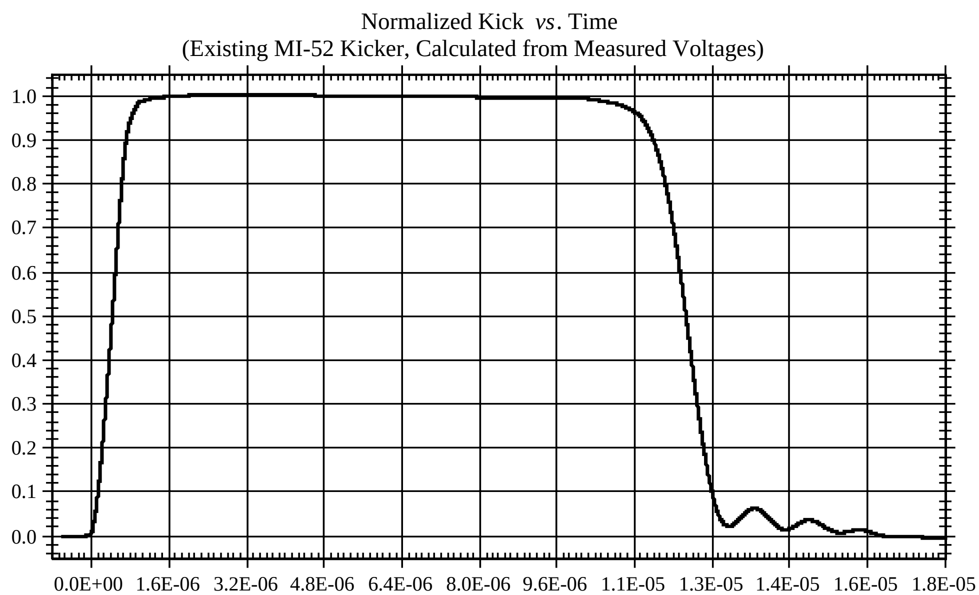


Figure 12: Measured kicker waveform

separate system, of LCW, is required. The LCW system forms its own closed loops and includes heat exchangers, LCW pumps, DeIonization (DI) bottles, plumbing and the components to be cooled. The DI bottles bring the electrical conductivity of the LCW to a low enough level that it is suitable for use within electrical conductors.

Of the primary beam devices, the downstream horn protection baffle operates in an extremely high radiation level environment. The radiation level is potentially high enough both that the device must be cooled against radiation induced heating and that this water itself becomes activated, particularly with tritium. Therefore a special RAW system is required to cool this component, together with the target and horns which are nearby. A RAW system contains many of the same pieces as are found in an LCW one but forms its own isolated closed loop. The heat that is absorbed by a RAW system is transferred through a heat exchanger to an LCW system, from there through another exchanger to an ICW system and finally to the atmosphere.

Fermilab has had long experience with ICW, LCW and RAW systems. However NuMI will contain the first Fermilab beamline operated deep underground. Since some parts of the cooling system will be on the surface while others will be at beamline level, the piping, pumps, heat exchangers and instrumentation will have to be designed to handle the higher pressures caused by this hydraulic head.

The objective of the water system as it pertains to the primary beam is to provide sufficient heat rejection for the following devices:

- magnets (LCW)
- magnet power supplies (LCW)
- downstream horn protection baffle (RAW)
- vacuum pumps (if cooling is needed) (clean ICW)

A further requirement is that the system be sufficiently robust to be fully functional, and responsible for absolutely minimal downtime, during scheduled operations.

The technical requirements of the LCW and RAW systems can be stated in terms of the flow rate and pressure differential for each of the components to be cooled. For the magnets these values are given in Fermilab-TM-623. As an example EPB dipoles, the most frequently used magnets in the line, require a flow rate of 1072 liters/hr at a pressure of 7.03 kg/cm^2. The values for the various power supplies to be employed are similarly available (see Appendix V of the Tevatron II Facilities Handbook Vol. 2 and the manufacturers' name plate data). For other devices to be cooled similar requirements must be determined as part of design.

The ICW must ultimately be able to remove all the energy created in the beamlines by both electrical and radiation heating. To set the scale, the magnet power during operation is 628kW. Details of water pressures and flows for all circuits and elements are given in Table 6.

All of the heat removed will end up in the main injector pond H. The existing pump vault near MI-62 was originally installed to provide pond water from H pond to MI-8 for the cooling of the 8 GeV transfer line magnets. Changing the 8 GeV transfer line to permanent magnets eliminated the need to provide cooling water to MI-8. So, this pump vault will be re-piped to provide pond water to NuMI. The pond size is found to be adequate for the NuMI loads, although spray nozzles to increase evaporation will need to be added.

C. Magnet power supply system

The extraction/primary beam power supply system consists of the power supplies for the beamline elements, the cables and connections from the power supplies to the 480 VAC power panels, and the cables and connections from the power supplies to the devices that they drive. A major new item is the kicker power supply, which needs to be constructed. All other supplies will either be refurbished from existing Fermilab spares or bought off the shelf.

The power supplies must provide reliable, stable power to beamline elements while minimizing power consumption. The NuMI facility is expected to be operational for of order ten years, and the power supply system has been designed with this in mind. Power supplies must accommodate a repetition period of 1.9 seconds. Personnel safety must be assured from possible electrical, mechanical and radiological hazards during installation and operations.

Voltage and current requirements for the various beamline elements determine what power supplies and cables will be needed. Table 6 summarizes these requirements and indicates the chosen power supply for each case. For beam tuning and focusing, each trim and quadropole magnet has its own power supply. On the other hand the bend circuits use several 500 kW supplies in series (or for the V105 circuit a Main Ring Power Supply) in order to obtain the desired voltage levels.

Magnet Power Supplies Description

Existing power supplies from decommissioned fixed target areas and the Main Ring is utilized for all but the kicker and perhaps some correctors. The recycled power supplies will require some upgrades and refurbishment.

In order to reduce power consumption, all but the quadropole and trim magnet supplies will be ramped. There will be eight high-current bend circuits: the kicker magnet (I:KPS6N), the Lambertson magnets (I:LAM60), the C-magnet (E:V100) and five bend circuits (E:HV101, E:V104, E:V105, E:V109, E:V110).

The kicker power supply was covered in Section IV and thus will not be covered further here. The combined (3) Lambertsons and the C-magnet will each be powered by a 500 kW supply. The first bend string (E:HV101) consists of seven EPB magnets powered by three 500 kW supplies in series. The second bend (E:V105) consists of five B2 magnets powered by a Main Ring type power supply. The circuit E:V104, the two EPB magnets, is powered by a single 500 kW supply. The string E:V109, three 6-3-120 magnets, is powered by a two 500 kW supplies. There will also be ten quadropole circuits, and twelve low-current circuits for Main Injector corrector magnets. The critical devices will be the E:HV101 and I:LAM60 circuits, and appropriate circuit breaker hardware has been bought, installed on them. The testing has yet to be done.

Table 7 lists the power supply circuits (except for the kicker), corresponding magnet types, numbers of magnets, their resistance, inductance, cabling information, current and voltage information, power supplies required and their corresponding voltages, currents and power. There is also included information about passive filters and regulation electronics. NuMI will use filters on all the bend strings (seven). Present plans also include a HOLEC transductor and FNAL regulation electronics in order to achieve the beam stability needed.

Construction Plan and Installation Plan

The recycled supplies will need to be refurbished and modified to allow invert operation. The kicker power supply will be designed base roughly on that of the long batch kicker at MI52.

All installation work, including that of power supply cabling, in the MI enclosure including the NuMI stub must be carefully planned to take place during scheduled MI shutdowns. Thus the refurbishing of the power supplies associated with these areas has been accelerated to allow early installation during some shutdown before 2004. Workers in this area may need specialized training due to radiation levels or other safety concerns.

Power supplies will be located in the MI60 service building, the MI62 service building, and the target hall service building as is given in the table. It is seen that most of the supplies are located in existing buildings (MI60, MI62) as this allows much of the work to happen early, rather than waiting for beneficial occupancy of the target hall service building. The power supplies for the Lambertson, C-magnet and bend circuits will need to be rigged in place and thus their installation will have to be planned not to interfere with other service building work. The quadrupole and MI corrector supplies are small and can be installed by hand. The installation of these supplies in MI-60 service building is complete. Installation in MI-62 is underway and will be completed in 2001.

Pre-Commissioning Plan

All supplies will be AC power tested once they are refurbished, built or bought. They will also have an extensive power test after the DC connections are made, before commissioning beam. These tests will point out any problems with power supply cables, power supplies and power supply monitoring devices and cables. Water for magnet cooling will have to be operational before such power testing can occur. The control system will be fully functional before commissioning, with data-logging, alarms and power supply adjustment available. This will allow further pre-commissioning of the power supplies and cables. Once in place in MI60 South and connected to the kickers themselves the kicker supply will be tested and monitored.

Performance Monitoring Plan

For the kicker and magnet power supplies, Autotune will correct slow drifts. All power supplies will also be continually monitored by the ACNET alarm system (with tolerances set appropriately). These alarms plus logged data will point out required power supply repairs. All large bend supplies will have current error detectors which will prevent extraction if the supply is not tracking the ramp. Supplies critical to beam motion on target or along the beamline will be part of the Beam Extraction Permit system such that beam is not extracted if they have not reached an appropriate current at flattop before extraction.

D. Controls

A description of the control system to be used is given in the NuMI Technical Design Report, Section 3.8.3; that information will not be repeated here. What is given below is a listing of all primary beam devices thus far identified as requiring control system interfaces. The devices to be located in the MI ring will be given names beginning with I: while those in the external line will be E:. All beam sheets thus far distributed have referred to the beamline locations from upstream to downstream as 101-110. This convention will be retained with the target region denoted as 111.

- Power supplies with ramp control as appropriate
  - Kicker K602
  - Lambertson string LAM60, C- magnet V100
  - Dipole strings HV101 (EPBs), V104 (EPBs), V105 (B2s), V109 (6-3-120s), V110 (EPBs)
  - Quadrupoles Q101-Q110
  - Correction dipoles, horizontal and vertical, at locations 102, 103, 105, 107, 108, 110
- Instrumentation
  - Horizontal and vertical positions and intensities from BPMs at locations 101, 103, 104, 106, 108, 110 and target. Perhaps readbacks over different parts of the spill for two downstream monitors
  - For wire scanners at locations 103, 104, 106, 108, 110 and target motor control and motion system status readback, horizontal and vertical profile, position means, position sigmas and apparent intensity
  - Readbacks for total loss monitors LLMCPU, LLMCPD and LLMPTG and for 35 sealed units
  - Toroid intensity values INU103 and INU110
  - Temperature monitor readouts for magnets as required
- Vacuum pump status and gauge pressures
- Water pump status, flow rates and pressures for LCW and ICW systems
- Position motor control for target baffle
- NuMI beam permit system

- Beam Loss Budget Monitor (software devices)

Much of the equipment will require events on Tevatron clock and MI beam sync clock and timing channels based on these. In particular are noted power supply ramps and instrumentation triggers.
The software required for dealing with the primary beam is database entries for all of the devices listed above and entering them logically onto standard parameter pages. Also specified are an interactive (synoptic) beamline display to give a modern look and feel to beamline operation, an appropriate configuration of Autotune and an application which provides a user interface for the Beam Permit system.

VI. Radiation safety and beam permit

Personnel protection from radiation will be similar to that installed in all other beam enclosures. The NuMI stub is already protected as part of the MI; the pretarget and target halls will need a new system, which will include critical devices LAM60 and string HV101. This system will be built by the BD/ESH Department and reviewed as for all other enclosure access controls. However NuMI, due to high instantaneous and integrated beam intensities, must protect all beamline equipment from radiation damage, and, due in addition to transporting beam through the aquifer region, must also look to protecting the groundwater resource. Implementation is under way of a separate NuMI beam permit system based on the capabilities of the Beam Switch Sum Box (BSSB).

Some conditions will give clear indications that beam cannot be sent to NuMI and will used to prevent NuMI beam from ever being accelerated. Foremost among these will be the fact that the permit has been withdrawn on a previous pulse and a reset not yet given by an operator. This is the same procedure followed for beam aborts in circular accelerators, except that NuMI beam cannot be aborted during delivery. Several other conditions have also been identified:

- the MI measure of beam delivered on the previous pulse does not match the NuMI measure of beam received on target;
- the position or intensity signal from the previous pulse of any BPM is off-nominal;
- any loss monitor was above threshold for the previous pulse;
- any quadrupole or trim dipole (DC supply) current is off nominal
- any vacuum valve is closed or vacuum reading above nominal;
- any water instrumentation indicates a cooling problem;
- any multiwire device is in transit between its fully inserted position and its fully extracted position (a possible future extension is to insist that if high intensity is being delivered all multiwires must be in their extracted positions);
- an off-nominal condition is being reported by some device downstream of the primary beam (target monitor, horn power supply, hadron beam monitor,…)
- any operator has "taken" the NuMI beam switch.

If beam has successfully been accelerated there are further conditions which can prevent it from being extracted to NuMI:

- current in any dipole string has failed to ramp to the correct value;
- extraction to antiproton has failed to occur or has indicated problems;
- internal measures of MI beam quality are off nominal.

In addition to these active measures there are also administrative controls on beam delivery. There may be limits set on the beam which may be extracted over a given period of time and this will be monitored by the standard Beam Budget Monitor. However it is envisioned that for NuMI there will be an extension known as the Beam Loss Budget Monitor. The principle is that catastrophic losses will trigger the active beam inhibit, but chronic low level losses will not. However in some regions the low level losses cannot be allowed to increment to too high a level, and the operators' heads-up display will indicate the onset of problems.

It is also noted that beam permit/inhibit conditions have a complication in the NuMI era which have not been faced previously. The intended mode of operation is that beam of individual pulses will be shared between antiproton production and NuMI. If the permit is removed for either beamline this must not in general cause an inhibit of beam to the other. There will also be limitations on beam intensity which are intended to apply to only one or the other of the users.

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[ii] P-875: A Long-baseline Neutrino Oscillation Experiment at Fermilab, February 1995, p33
[iii] The Fermilab Main Injector Technical Design Handbook, November 1995
[iv]"NuMI Primary Beam Groundwater Protection", S. Childress and P. Lucas, November 1999 (Revised December 1999)
[v] J. A. Johnstone, "A Simplified Analysis of Resonant Extraction at the Main Injector", Fermilab-MI-Note-91 (1993)
[vi] A. I. Drozhden et.al, "Radiation Environment Resulting from Main Injector Extraction to the NuMI Beam Line",Proceedings of the 1999 Accelerator Conference, p2614
[vii] A. Drozhden, "Kicker Location and Bump Configuration for Fast Extraction from the Main Injector to NuMI", Local NuMI Note, 1999
[viii] D. Johnson, "Single Turn Extraction for NuMI", Fermilab-MI-Note-0258, 2000