Technical Design Report
for the
8 GeV Beam

The BooNE Collaboration

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Chapter 1

Overview

The 8 GeV Beam consists of the beamline enclosures and the technical elements (magnets, power supplies, vacuum systems, water cooling systems, etc.) required to bring 8 GeV protons onto a target in a Target Hall.

The purpose of this document is to describe the technical design of passive and active components of the 8 GeV Beam. Figure 1.1 gives a more detailed view of the 8 GeV Beam enclosures.

This report follows the Work Breakdown Structure (WBS), with a reference at the head of each chapter and each relevant section. Table 1.1 gives the highest level WBS for the 8 GeV Beam.

1.1 Project Description

The 8 GeV Fixed Target Facility has been placed in a green-field site to accommodate growth within the low-energy FNAL program. The facility will transport beam from the Booster to a new area dedicated to external beam physics, and MiniBooNE will be the first experiment that will be carried out in this area. The Booster primary beam will be extracted from the MI-8 beamline near MI-10 into the 8 GeV beamline. The 8 GeV beamline will transport the beam under Main Injector Road, to a point where the beam can be split to service several experiments. The position of the site was chosen because it is a green-field, with few wetland areas, and avoids archeological sites, yet has enough space for future detectors. Possible future experiments include muon cooling studies required for technical development of the First Muon Collider [1].

In accordance with the expectations of Beams Division management, the 8 GeV Facility is designed to be compatible with the existing Booster, and can accommodate future upgrades associated with long-term plans for Booster improvements. The most likely improvement is a 16 GeV Booster associated with the muon collider. Injection to the main injector (MI) will occur at MI-10, therefore any new facility must deliver beam to this point. Tunnels have been

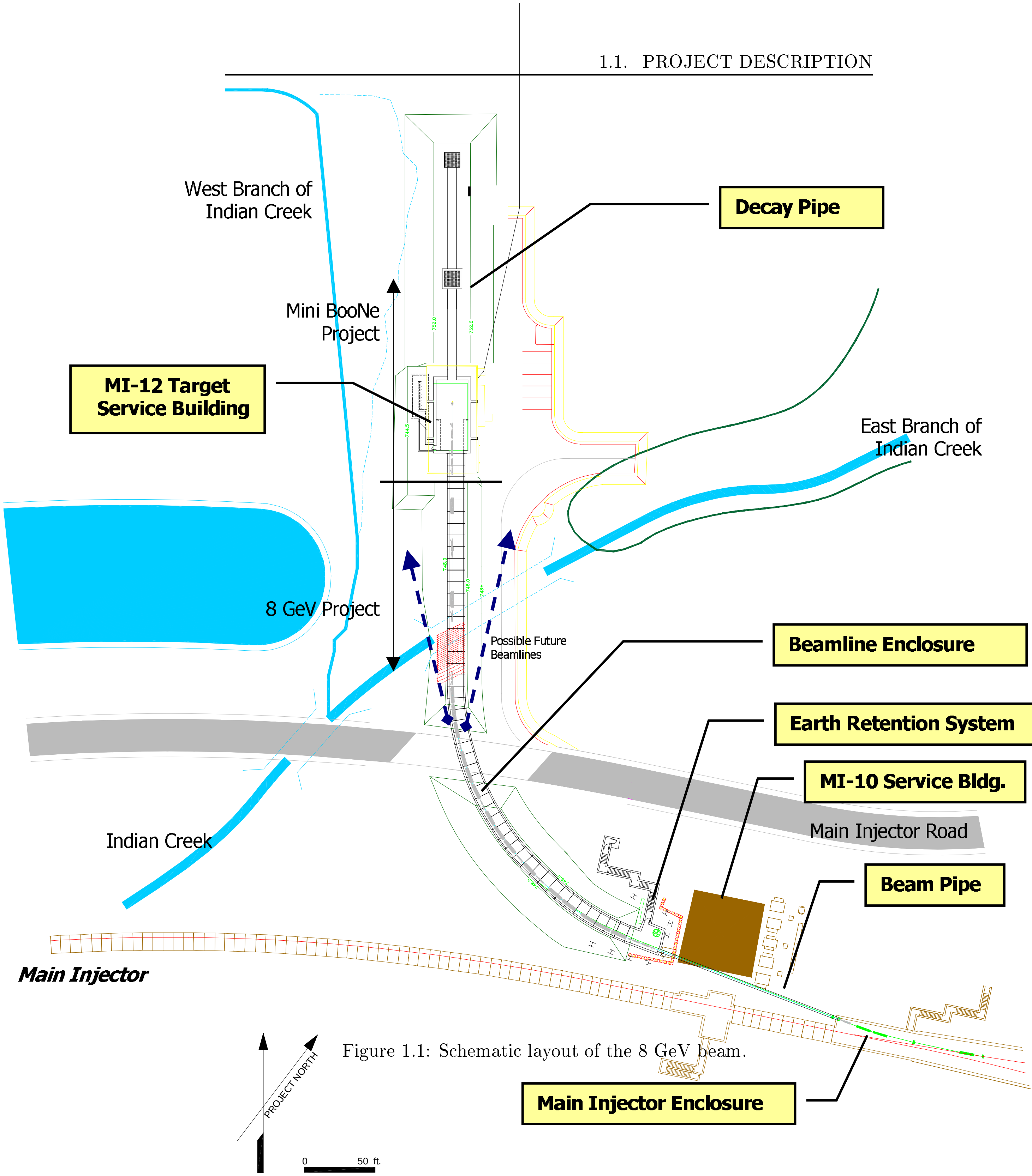

Figure 1.1: Schematic layout of the 8 GeV beam.

Table 1.1: Level 3 WBS for projects associated with MiniBooNE 8 GeV Beamline

WBS	Name
1.	8 GeV Beamline
1.1.	8 GeV Beamline Technical (AIP)
1.1.1	Magnets
1.1.2	Dipole Power Supplies
1.1.3	Quadrupole Power Supplies
1.1.4	Correction Elements Supplies
1.1.5	Kicker Power Supply
1.1.6	Cables
1.1.7	Vacuum Systems
1.1.8	Water Systems
1.1.9	Instrumentation
1.1.10	Controls
1.1.11	Safety System
1.1.12	Alignment
1.2	8 GeV Beamline Civil (AIP)

made sufficiently large to upgrade beamline elements for higher energies. To reach higher intensities, shielding can be added.

1.2 Other Supporting Materials

This document focuses entirely on beamline elements. Other supporting materials for the 8 GeV Beam are:

- *Booster Operation for Run II, Run II+ MiniBooNE and Beyond* [2] which places the MiniBooNE proton requirements within the context of the FNAL program.
- *The Environmental Assessment (EA)* [3] which describes the environmental impact of 8 GeV beam operations. In this document, project areas 1 and 2 (the 8 GeV Beam and the BooNE Neutrino Beam) are considered together, under the title, "The 8 GeV Fixed Target Facility," because of their geographic proximity and inter-related environmental issues.
- *The Conceptual Design Report (CDR)* [4] which describes the civil construction of the beam tunnels.
- *The Preliminary Safety Assessment Document (PSAD)* [5] which contains hazard analyses for the 8 GeV Beam.

- *The Project Management Plan (PMP)* [6] which describes the organization and responsibilities for the construction, including technical beam elements.
- *The Cost Books* [7] which contain the most up-to-date cost and schedule information.

1.3 Physics-driven Beam Design Requirements

High intensity is a crucial design goal for the 8 GeV beam and will drive shielding and absorber design.

The Booster is a high-intensity proton source. MiniBooNE requires protons from the Booster at a rate of 5 Hz with 5×10^{12} protons per pulse at 8 GeV for 2×10^{7} seconds of Booster running (66% of one calender year). As described in ref. [2], these goals are relatively conservative and should be achievable. The initial run will begin in mid 2002 and end before the start of the NuMI run, currently scheduled to begin in early 2004.

Chapter 2

The 8 GeV Beam Technical Design (WBS 1.1)

Beam is extracted from the Booster at 8 GeV kinetic energy (momentum, 8.9 GeV/c). The 8 GeV beamline transports the proton beam from MI-10 to the MiniBooNE target. At the target, the design requirements to maximize the flux are:

- Beam position and stability on target: < 1 mm
- Targeting angle and stability: < 4.6 mrad
- Beam spot 1/2 size: $< 4.$ mm

The beam position and stability requirements are driven by Monte Carlo ν_μ flux studies. The targeting angle and size limitations maintain the primary beam within the target. These are conservative estimates of the requirements.

In this chapter, the technical design for the 8 GeV Beam is described. This extends from the Booster to Main Injector 8 GeV Beamline (the P8 line) to the MiniBooNE target.

2.1 Primary Beam Devices & Transport Design (WBS 1.1.1)

The primary elements in the 8 GeV Beamline are identified in Figure 2.1, a schematic representation of the beamline. Beam from the Booster is transported along the P8 beamline through quadrupole Q851. A pulsed magnet, B8511, located downstream of Q851 deflects selected Booster batches into the MiniBooNE channel. B8511 is off except when beam is being sent to MiniBooNE. Quadrupoles Q860, Q861 and Q862 capture the beam and focus it for transport through the 42 m drift under the MI-10 service building. Quadrupoles Q864, Q865 and Q866

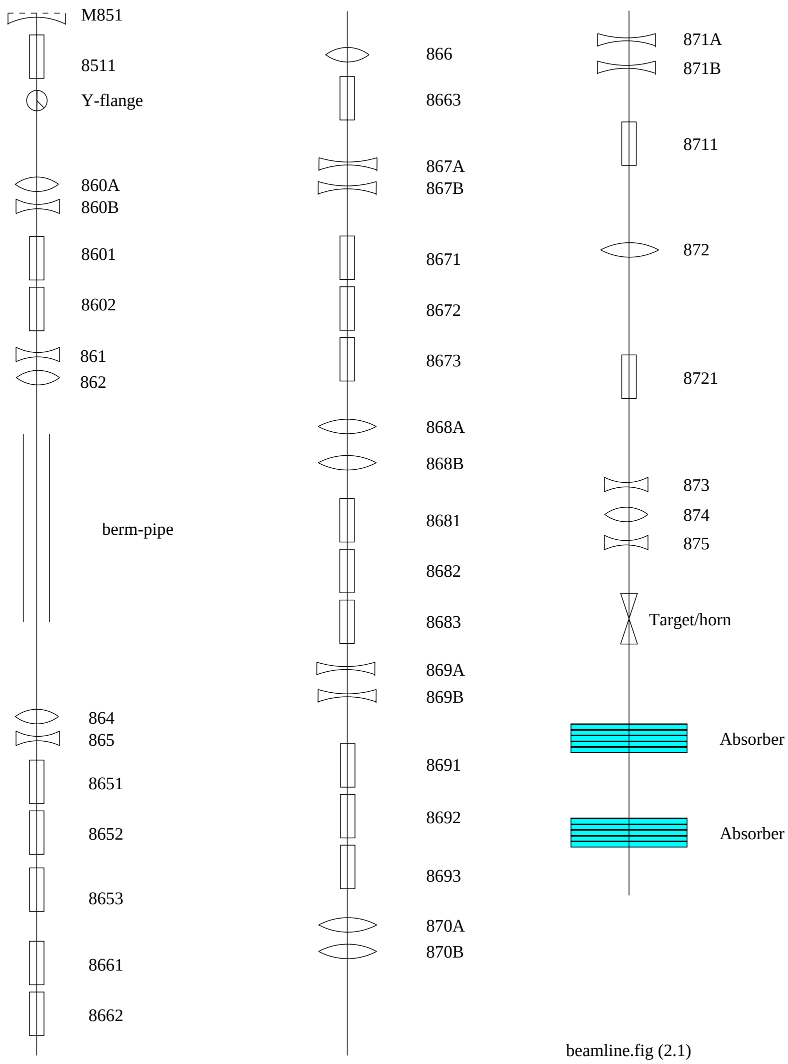

Figure 2.1: Beamline schematic and function. Elements are listed in Table 2.1.

match the beam into the FODO cells of the arc that provides the major bend to direct the beam toward the experimental area.

The heading of the beam at Q851 is -150.29°. The ray from target to detector is at heading -230.73°. The total bend is -80.45° (-1.404 radians). B8511 bends the beam by -40 mr (-2.29°). Seventeen 6-3-120 dipoles B8601 – B8693, each bending ~ -80.4 mr, (-4.61°) direct the beam toward the target.

To reduce civil construction costs the beam is raised approximately 0.69 m between downstream B8602 and upstream B8651, a distance of 54.2 m, including 42 m in the drift pipe under MI-10. The vertical bend up is provided by rolling B8601 and B8602 by $\sim 5°$. The bend down required to restore the beam to horizontal for transport through the arc comprising twelve 6-3-120's and 8 permanent magnet quads is provided by rolling B8651, B8652 and B8653 by $\sim -3°$. The total rise is 0.795 m (2.6′) from Q851 to downstream of B8653. To center the beam on the detector, the beam and target are raised a further 1.4 m by a dog-leg using B8711 and B8721. The beam elevation is 218.193 m (715.855′) at Q851; 218.826 m (717.933′) at entrance to the MiniBooNE enclosure; and 218.983 m (718.448′) in the arc. The final elevation of the beam at the target is 220.311 m (722.803′).

Focussing is provided by a combination of electro- and permanent magnet quadrupoles. Where tuning capability is not required (in the FODO channel) permanent magnets are convenient and provide significant cost savings. Matching from the P8 line into the 8 GeV Beamline is acomplished by powered quadrupoles at Q860 through Q866. 3Q60s are used at Q861–Q866; Q860 is a hybrid composed of Q860A (an RQMB) and Q860B (a CQA). Most of the focussing strength is provided by the permanent magnet RQMB; the tuning capability, by the powered CQA. Matching into the FODO structure is provided by quads Q864, Q865 and Q866.

A short quadrupole section, consisting of 2 permanent magnet quads and a LEP MQ quad, transports the beam from the end of the arc to the final focusing section. The final focus is achieved using a quad triplet consisting of an MQ and two MQA large aperture LEP quads.

The beam is focussed to a spot of ~ 6 mm diameter at the target by Q872–Q875. The small spot size implies a relatively large beam in the quadrupoles which comprise the triplet, Q873–Q875. We plan to use large aperture type MQ and MQA quadrupoles acquired from LEP in this application. We expect to take delivery of the LEP quads in the summer of 2001.

Tables 2.1 and 2.2 summarize pertinent information for the magnets, including nomenclature, type, strength, current, etc.

The beam passes out of the Main Injector enclosure near MI location 101 and travels 42 m (138′) under the MI-10 service building to the MiniBooNE beam enclosure, rising at an angle of 12.7 mr. To minimize the impact on the MI-10 service building a 24″ diameter carrier pipe extending from the exit from the Main Injector enclosure to the beginning of the MiniBooNE beam enclosure was inserted under it using directional drilling techniques. This pipe is a drift space and contains only electrical and signal conduits, LCW cooling water pipes and a 6″ diameter beampipe. The conduits and pipes have been installed in the carrier pipe and are supported in place by suitable fixtures ("spiders"). A cross-sectional sketch of the pipe is shown in Figure 2.2. It does not contain any magnetic elements or instrumentation, Figure 2.13, other than the total loss monitor.

Table 2.1: Beamline magnets, 8511 to 8692

		Quad			Dipole		
Loc	Type	F/D	k1 $[m^{-2}]$	I [A]	angle [mr]	I [A]	Comment
8511	IDC				40.000	1479	Note 1
860A	RQMB	F	0.07475				Note 2
860B	CQA	D	0.	0.			Note 3
8601	6-3-120				80.013	505.9	Rolled 5°
8602	6-3-120				80.013	505.9	Rolled 5°
861	3Q60	F	0.10457	16.7			
862	3Q60	D	-0.10723	-17.1			
864	3Q60	F	0.11419	18.2			
865	3Q60	D	-0.11016	-17.6			
8651	6-3-120				80.013	505.9	Rolled 3°
8652	6-3-120				80.013	505.9	Rolled 3°
8653	6-3-120				80.013	505.9	Rolled 3°
8661	6-3-120				80.402	508.4	
8662	6-3-120				80.402	508.4	
866	3Q60	F	0.07336	11.7			
8663	6-3-120				80.402	508.4	
867A	RQRA	D	-0.09228				Note 2
867B	RQRA	D	-0.09228				Note 2
8671	6-3-120				80.402	508.4	
8672	6-3-120				80.402	508.4	
8673	6-3-120				80.402	508.4	
868A	RQRA	F	0.09228				Note 2
868B	RQRA	F	0.09228				Note 2
8681	6-3-120				80.402	508.4	
8682	6-3-120				80.402	508.4	
8683	6-3-120				80.402	508.4	
869A	RQRA	D	-0.09228				Note 2
869B	RQRA	D	-0.09228				Note 2
8691	6-3-120				80.402	508.4	
8692	6-3-120				80.402	508.4	

Table 2.2: Beamline magnets, 8693 to 875

		Quad			Dipole		
Loc	Type	F/D	k1 [m^{-2}]	I [A]	angle [mr]	I [A]	Comment
8693	6-3-120				80.402	508.4	
870A	RQRA	F	0.09228				Note 2
870B	RQRA	F	0.09228				Note 2
871A	RQRA	D	-0.09228				Note 2
871B	RQRA	D	-0.09228				Note 2
8711	6-3-120				76.38	482.9	
872	MQ	F	0.07058	112.2			Note 4
8721	6-3-120				-76.38	-482.9	
873	MQA	D	-0.14212	-112.9			Note 4
874	MQA	F	0.21280	169.1			Note 4
875	MQ	D	-0.06856	-108.9			Note 4

Total beamline magnet power load, DC [kW] 255.0

Notes:

1. - The pulsed dipole splits the beam into the BooNE beamline. A Main Injector style IDC dipole has been selected for this application. See reference [8]

2. - Magnet type RQRA is a recycler style permanent magnet quadrupole. The nominal integrated gradient is 1.39 T·m/m and G = 2.74 T/m. Polarity is determined by the orientation in which they are installed. Magnet type RQMB is similar to the RQRA quadrupoles but trimmed to a nominal strength of 1.1259 T·m/m (81% of 1.39 T·m/m.)

3. - Magnet type CQA is the large aperture Electron Cooling Ring quadrupole. Design has this quad at zero current. Included to provide tuning capability.

4. - The final focus is achieved using 4 independently powered quadrupoles, Q872 – Q875. LEP style MQ and MQA quadrupoles are used for the large (125 mm diameter) aperture they provide.

Figure 2.3 shows the horizontal and vertical beta functions and Figure 2.4 gives the corresponding dispersion functions.

The design admittance of the Main Injector (and P8 beam line) is 40π mm·mr. However, based on data from emittance versus intensity measurements [9] shown in Figure 2.5 we expect that the emittance will not exceed 20π mm·mr for the beam conditions required by this experiment, 5×10^{12} protons/pulse at 5

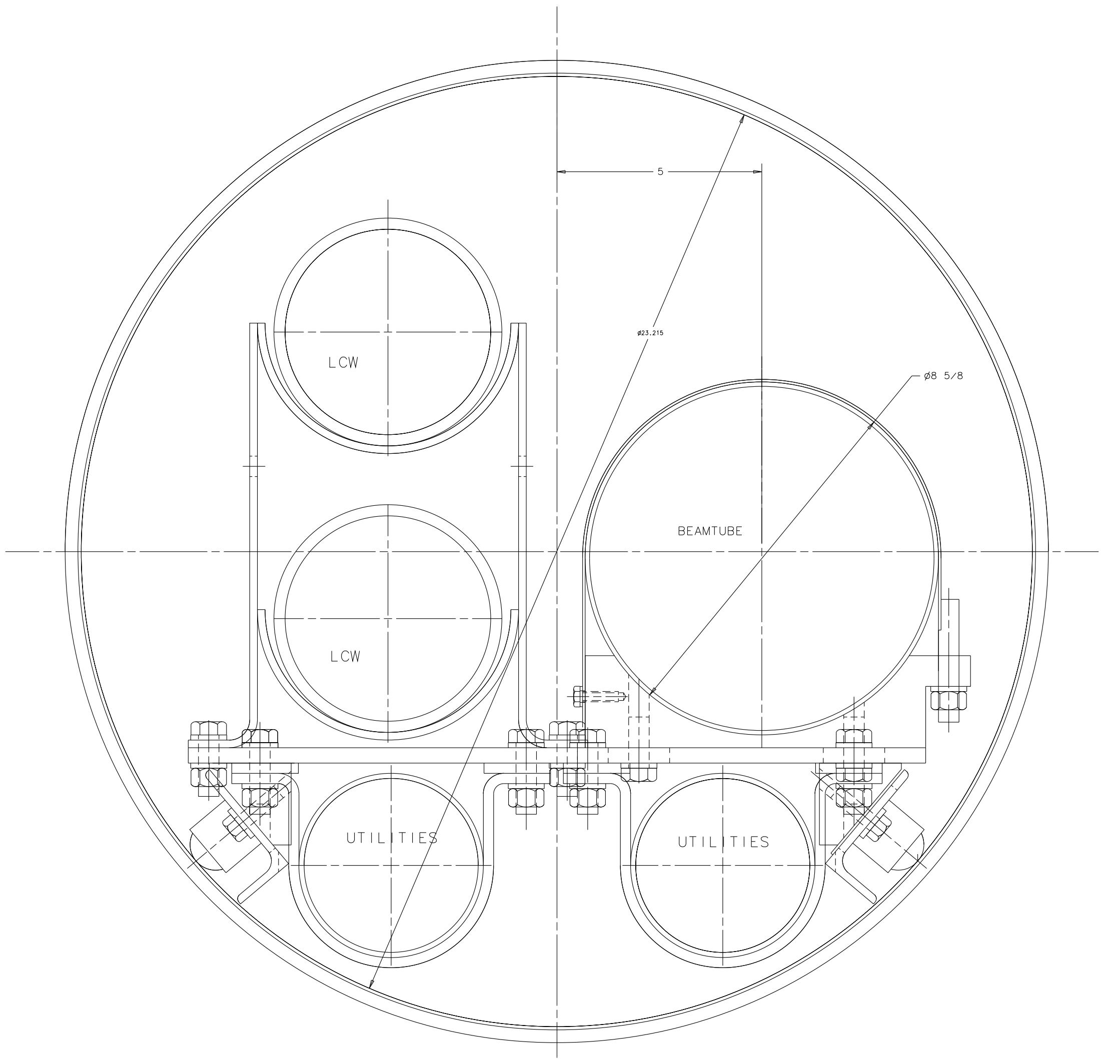

Figure 2.2: Layout of utilities inside the 24″ carrier pipe under MI-10, looking downstream. The beam vacuum pipe is located in the right region, supported and held in place by the locating fixtures ("spiders"). Two 4″ PVC electrical conduits are suspended in the bottom portion, and two 4″ pipes for LCW supply and return occupy the left hand space. The spiders are afixed at intervals to the beamtube and utility pipes and carry them as they are inserted into the carrier pipe.

Hz. The expected beam envelopes for a 20π mm·mr (40π mm·mr) beam are shown in Figure 2.6 (2.9). Horizontal and vertical aperture clearances for 20π- (40π) mm·mr) beam are shown in Figures 2.7 and 2.8 (Figures 2.10 and 2.11). The beam parameters at the target are summarized in Table 2.3.

Table 2.3: Beam parameters at the target. The contribution due to dispersion is calculated assuming $\Delta p/p = 0.001$ and is added in quadrature in the third row.

Beam parameters at Target	20π Emittance	40π Emittance
divergence	1.0 mr	1.0 mr
1σ spot size	1.0 mm	1.0 mm
half-size, 95% spot	2.45 mm	2.45 mm
half-size, 95% with dispersion	2.5 mm	2.5 mm

We are planning to use the MQ and MQA quadrupoles from LEP primarily because of the capability afforded by their large (125 mm diameter) aperture to do target scans. To ensure that the beam is correctly centered on the target we will use the trim dipoles [10] to sweep the beam across the target. This will necessarily displace the beam in the final focus triplet where the beam is large. A simulation [10] shows that with the large aperture of the LEP quads we can safely perform this procedure.

2.1.1 Trim dipoles

A total of fifteen horizontal and vertical trim dipoles will be placed along the beamline, Figure 2.13. Four trims are FNAL 4-4-30 vernier dipoles and eleven will be large aperture trims from LEP. The trims are used in general for tuning to minimize losses and for the specific case of centering the beam on the target.

2.1.2 Pulsed Switch Magnet (WBS 1.1.5)

A short (4 m length) Main Injector dipole is used for the switch. Magnet IDC058-0 has been installed in the beamline. IDD054-0 is available as a spare. These magnets have 8 turn coils and a gap of 2″ (0.0508 m). The effective length is about 160″ and the inductance is 1.3 mH. Using the IDC we achieve the required 40 mr deflection with 1479 A. The sagitta for this bend is 0.80″, whereas the good field region (to the required 1%) is nearly 2″ × 4″. The horizonal beta is smaller than the vertical at this point so the beam size, even including a contribution for the momentum, is smaller than the vertical size. At the downstream end, the separation from the undeflected beam is 81 mm (3.2″) and the horizontal beam size is 13.7 mm (0.5″). The 8 GeV Line beam pipe has only a 3.75″ horizonal aperture so a special pipe is required. A tapered stainless pipe was fabricated with a support web between the two beam apertures in the

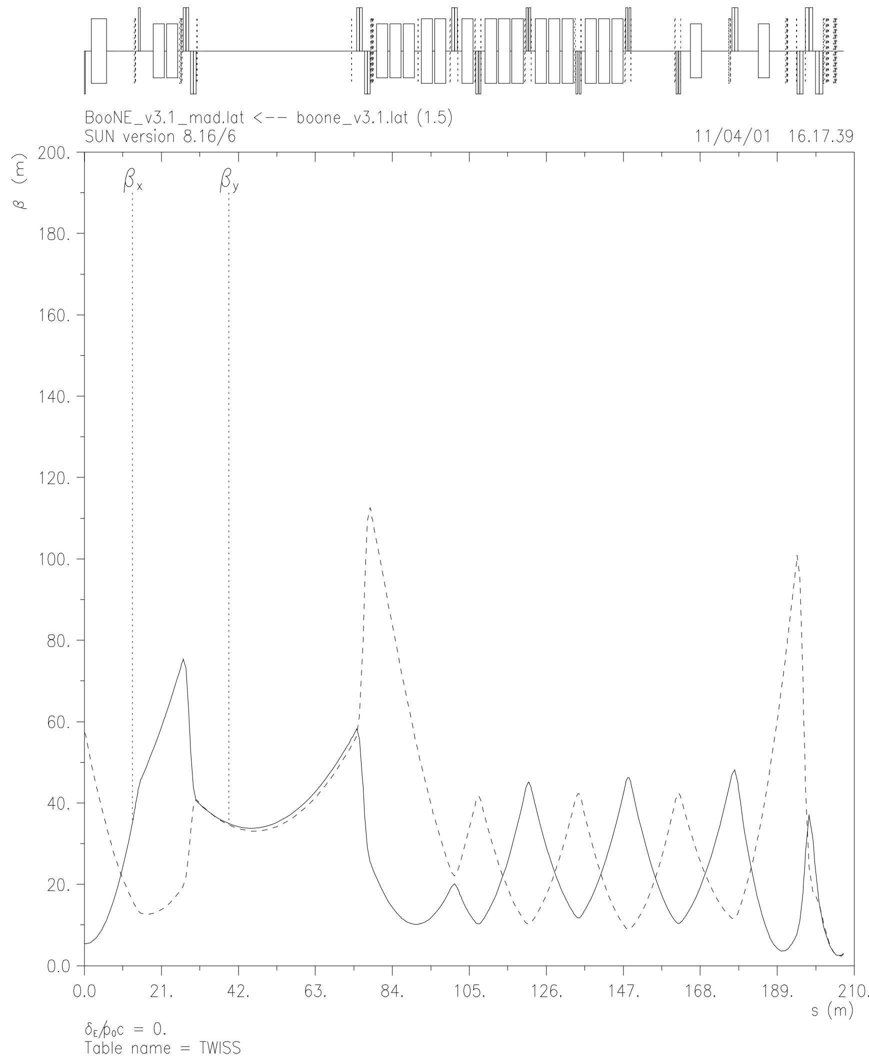

Figure 2.3: Beamline beta functions.

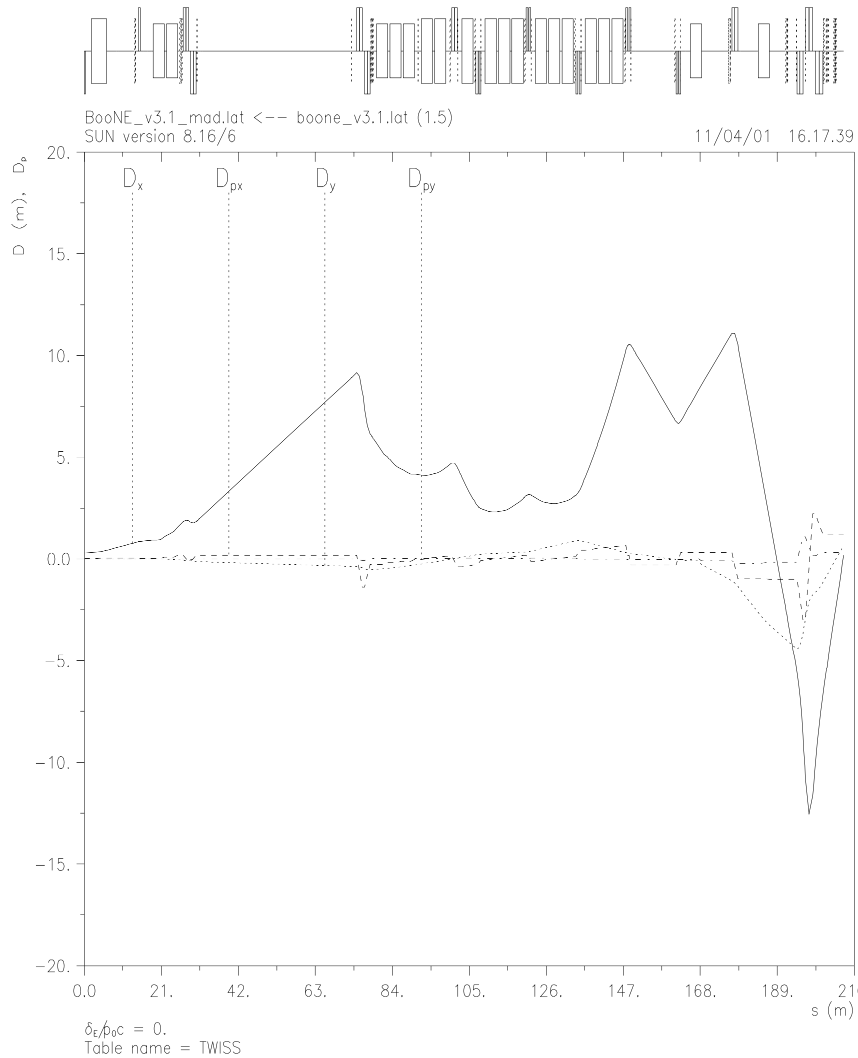

Figure 2.4: Beamline dispersion functions.

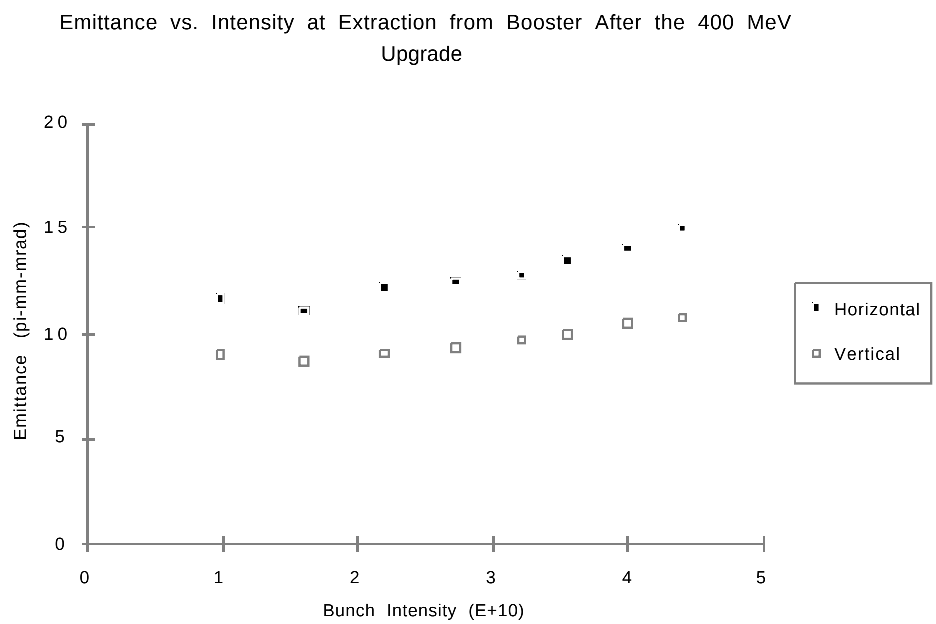

Figure 2.5: Booster emittance as function of bunch intensity [9]. A Booster batch contains ~ 80 rf bunches. (The Booster circumference contains 84 rf buckets. Four are normally empty to facilitate extraction.) The required intensity is 5×10^{12} protons per batch, or about 6×10^{10} protons per bunch. Extrapolating from the data, the invariant emittance is expected to be less than 20π mm$\cdot$mr.

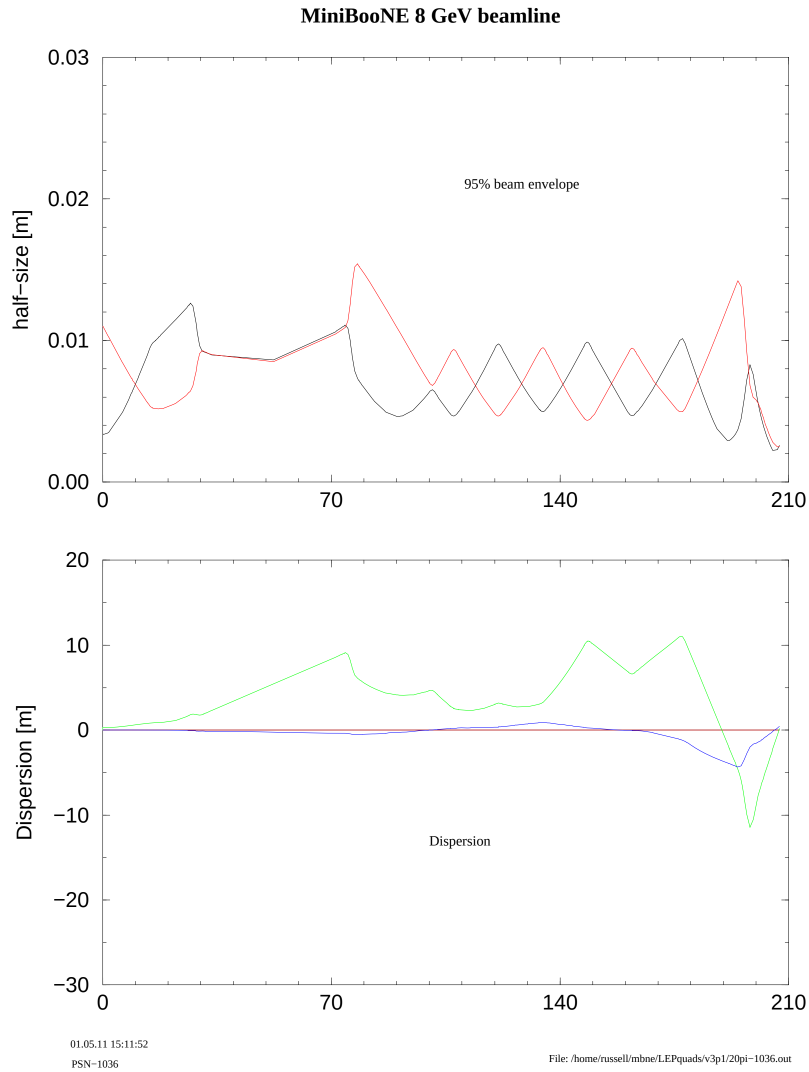

Figure 2.6: Beam envelopes assuming beam from the Booster has 20π mm$\cdot$mr emittance.

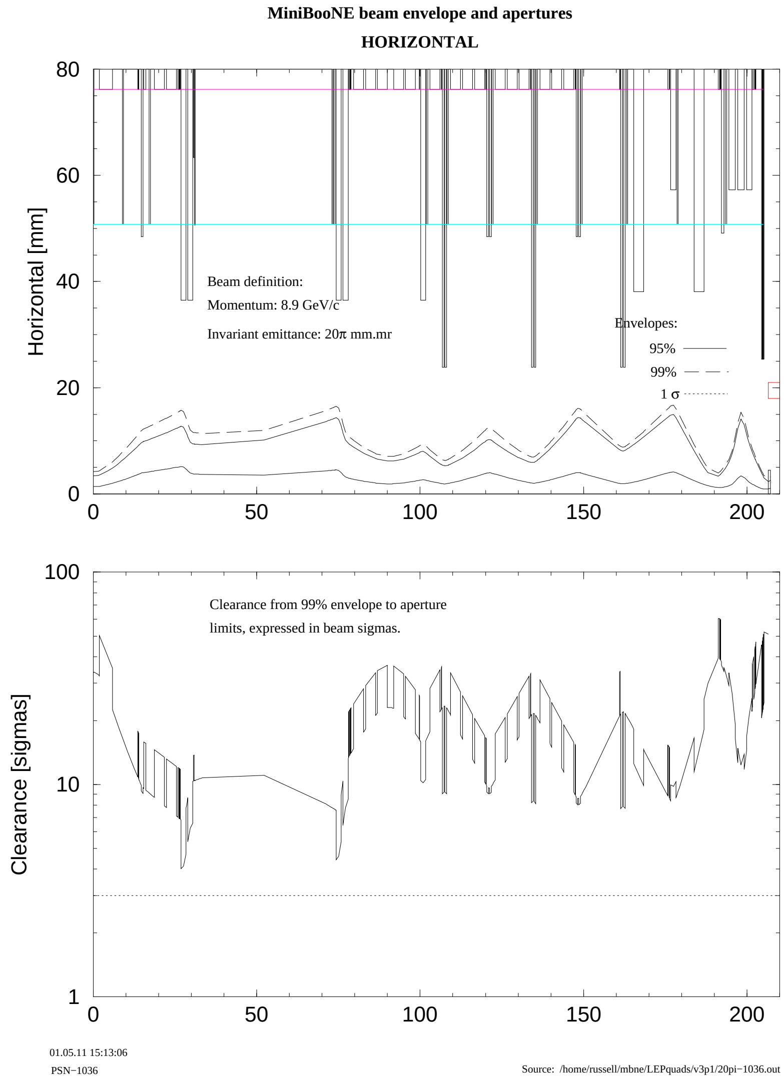

Figure 2.7: Beam separation from magnet and other apertures in sigmas for 20π mm·mr beam emittance. Horizontal plane.

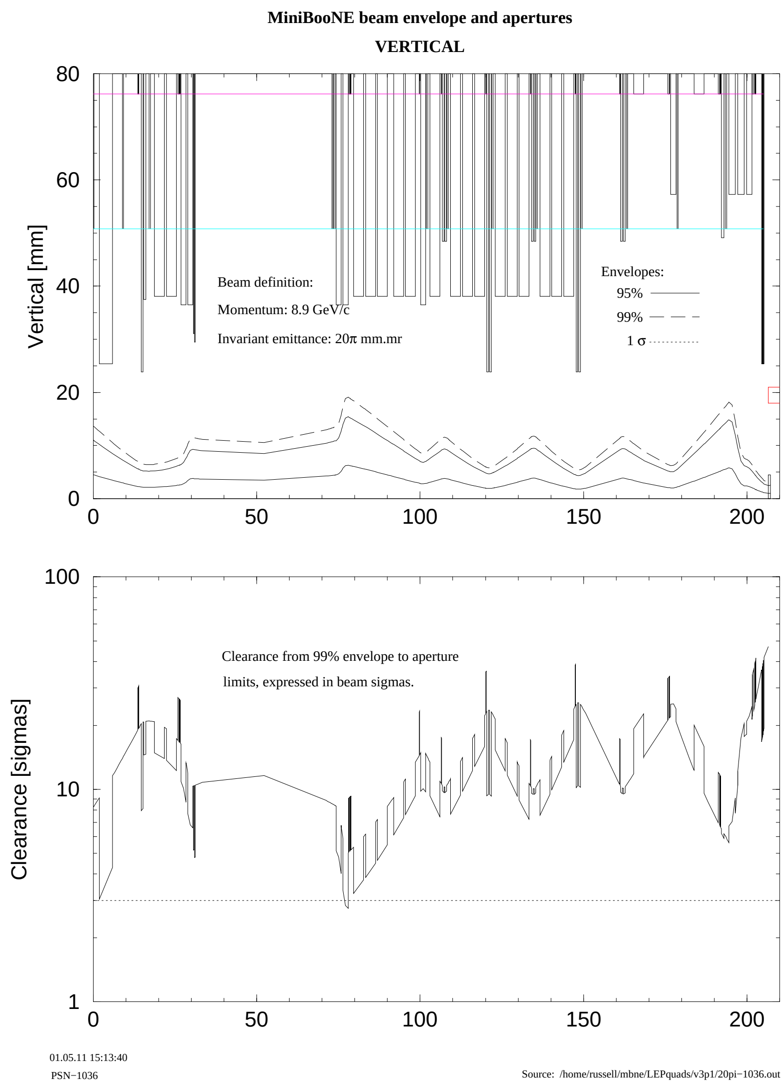

Figure 2.8: Beam separation from magnet and other apertures in sigmas for 20π mm·mr beam emittance. Vertical plane.

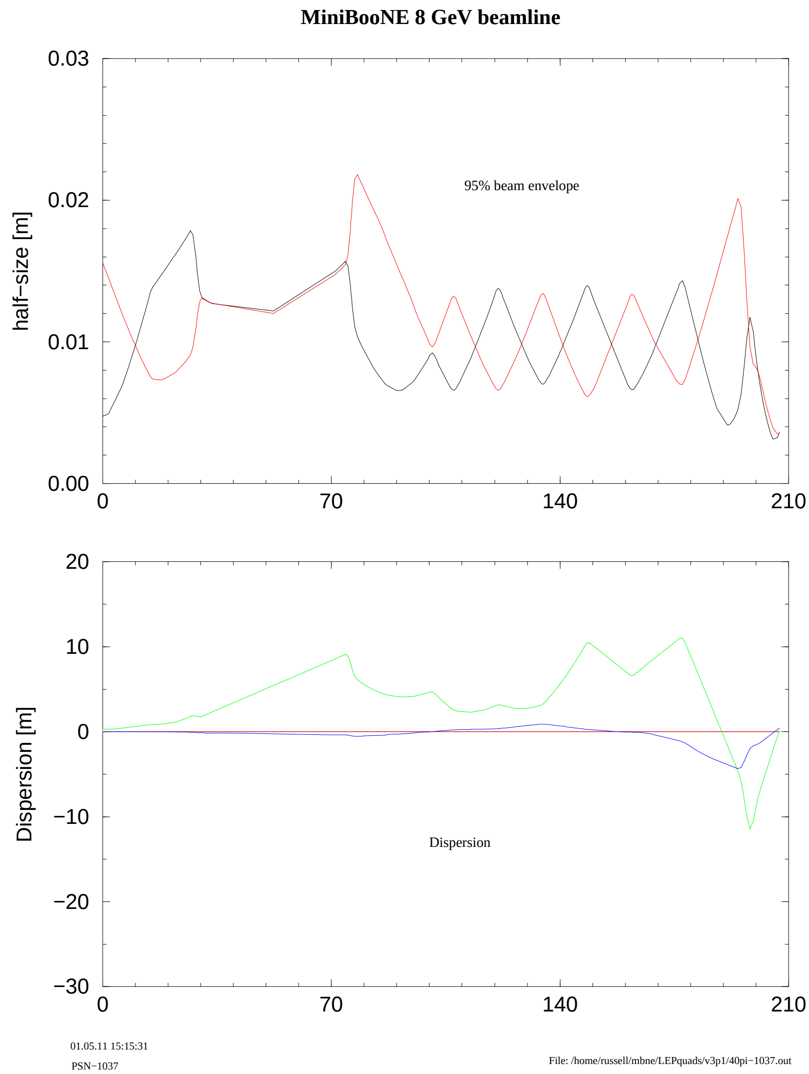

Figure 2.9: Beam envelopes assuming 40π mm·mr emittance (nominal admittance for the Main Injector).

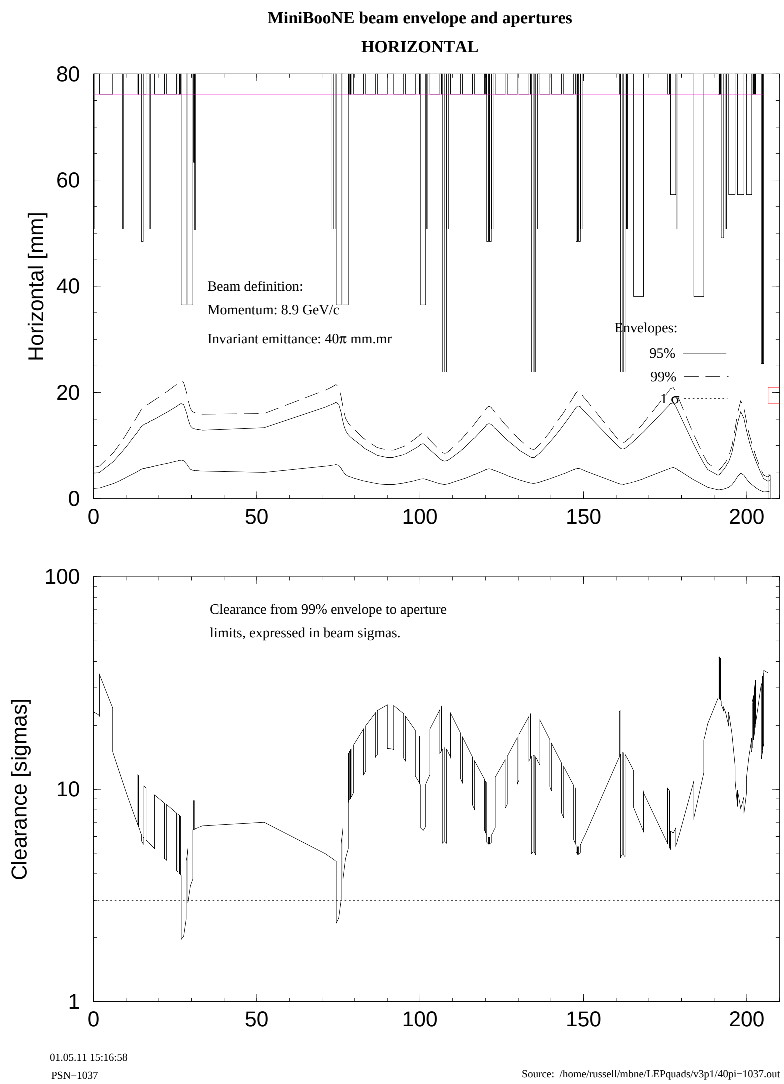

Figure 2.10: Beam separation from magnet and other apertures in sigmas for 40π mm·mr beam emittance. Horizontal plane.

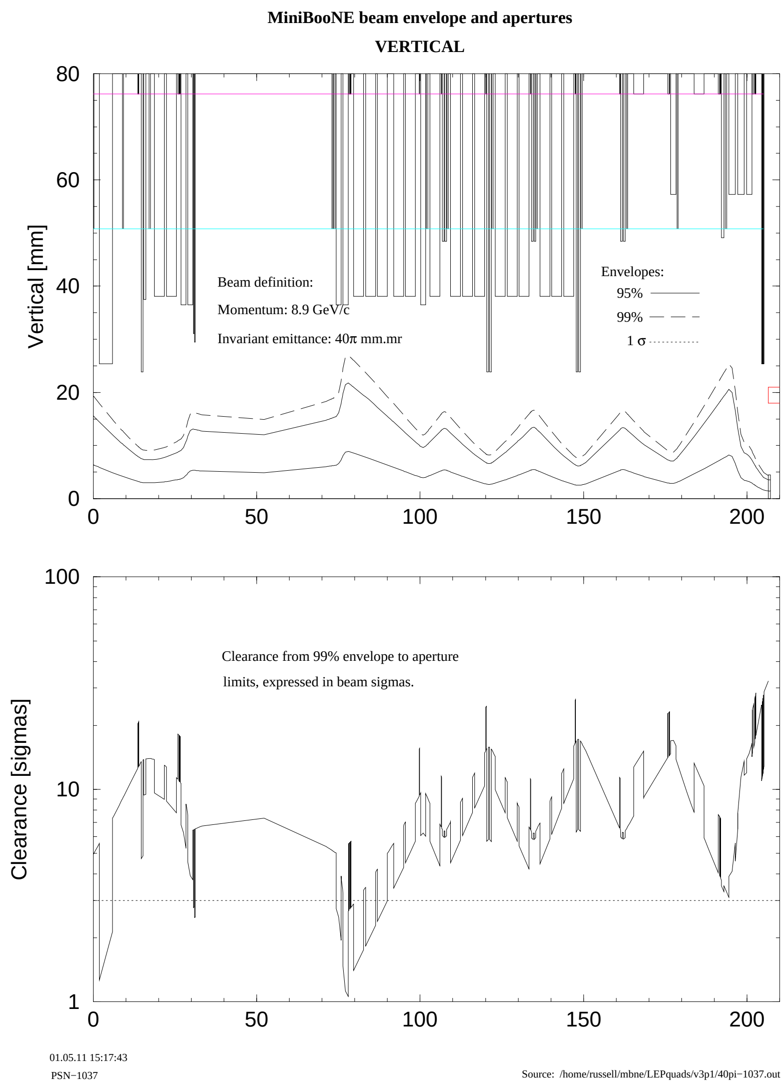

Figure 2.11: Beam separation from magnet and other apertures in sigmas for 40π mm·mr beam emittance. Vertical plane.

downstream end. A copper cooling tube is attached to provide cooling for the eddy current losses.

We propose an 8.5 ms rise time excitation using a half-sine waveform. The switch power supply will require an 18.9 millifarads capacitor charged to 460 volts and storing 1984 joules of energy. Corrections to these power supply estimates to account for losses in the cables are expected to be small. A supply will be constructed to meet these requirements. It will need to provide 1% regulation of the pulses for MiniBooNE. This will be achieved without pre-pulses.

2.1.3 Magnet Stands (WBS 1.1.1)

It is planned to use existing designs and hardware for as many magnet stands as possible. A standard Main Injector dipole stand will be utilized for the 6-3-120 dipoles. Appropriate modifications will be made to reflect beam to floor elevations, roll required for 5 magnets, and the vertical dogleg configuration. 3Q60 quadrupole and LEP quadrupole magnets will use a slightly modified design of an existing magnet stand. The final focusing quadrupole triplet requires a floor stand that accommodates the 90 inch high beamline. These stands also have to be designed to reflect projected movement for horn replacement. Permanent magnet quadrupoles, trim magnets, and instrumentation will utilize existing designs as well. Some of these stands will be mounted on a common beam to allow for ease of installation.

2.2 Power Supplies (WBS 1.1.2, 1.1.3, 1.1.4)

Some of the power supplies for the MiniBooNE beamline will be located in MI-10 and some in MI-12, the Target Service Building. The MiniBooNE supplies to be located in MI-10 are those for the pulsed magnet, the quads, the trims and the two 6-3-120 dipoles located in the Main Injector tunnel. The power supplies for the 6-3-120s are in MI-10 for both safety and operational reasons.

Power supplies for the vertical dogleg, for the four final focus quads and for the 6-3-120 dipoles in the beamline enclosure will be located in the MI-12 Service Building. This minimizes the congestion in the MI-10 Service Building and avoids the difficulty of getting additional DC power cables from the MI-10 Service Building to the MiniBooNE enclosure.

Distributing the power supplies in this way permits the use of service building floor space and of cable runs to be optimized.

Power supply tolerances have been calculated using the beamline optics [10], and the constraints that the beam must remain within 1 mm of the target center and vary in angle by no more that 4.6 mr. Table 2.4 lists the tolerances for the bend strings; all powered quadrupoles have a tolerance of $\Delta I/I = \pm 1 \times 10^{-3}$. These tolerances are easily achievable.

Dipole string	$\Delta I/I$
B8511	110.119×10^{-4}
B8601–B8602	5.885×10^{-4}
B8651–B8653	39.152×10^{-4}
B8661–B8693	4.514×10^{-4}
B8711–B8721	19.501×10^{-4}

Table 2.4: Dipole-string power supply stability needed to achieve targeting requirements. Magnets are grouped according to power supply.

2.3 Vacuum System (WBS 1.1.7)

A schematic overview of the vacuum layout for the 8 GeV Beam is depicted in Figure 2.12. The first item is a special vacuum chamber in the switch magnet which allows the MiniBooNE beamline to split off from the P8 beamline. Immediately following the split a gate valve is installed to allow the MiniBooNE beamline to be isolated from the P8 beamline. Six 300 ℓ/s ion pumps are distributed along the beamline and two 600 ℓ/s ion pumps are located at either end of the berm-pipe. Pirani gauges and gate, let-up and/or roughing valves are included at some of the pumping stations. The vacuum in the beamline is expected to be about 10^{-8} Torr, except in the berm-pipe and near the multiwires where it is expected to be about 10^{-7} Torr. The vacuum pipe ends after the instrumentation downstream of the final-focus triplet.

2.4 Water Systems (WBS 1.1.8)

The cooling water for the magnets and power supplies will be provided by the Main Injector LCW system. The MI water system was designed to handle the heat load associated with a 1-second slow spill from the Main Injector, with a safety factor of approximately 20%. The "available" flow at MI-10 is estimated at 317 GPM (MI Technical Design Handbook [11], Figure 3.9-4). The near term plans for the MI facility anticipate fast spill for NUMI, which requires only 45% of the power for slow spill, and under these conditions the safety factor is much larger.

The power consumption in the MiniBooNE beamline is dominated by the 6-3-120 dipoles, which account for approximately 200 kW. About 150 GPM of LCW is required for a 10° F temperature gradient. Other magnets that require LCW flow totalling approximately 70 GPM are the 3Q60, MQ, and MQA quadrupoles, and 4-4-30 trim dipoles. The power supplies, the horn RAW system, and cooling for the beam absorbers will require an additional 50 GPM. The total heat load imposed by the 8 GeV Beamline and the MiniBooNE experiment is estimated to be less than 250 GPM and represents about a 10% increment to the slow-spill cycle cooling requirements at the MI-10 service building, and less than 2% of the total heat input to the cooling ponds from the ring. The incremental cooling required can be accomodate by the existing systems.

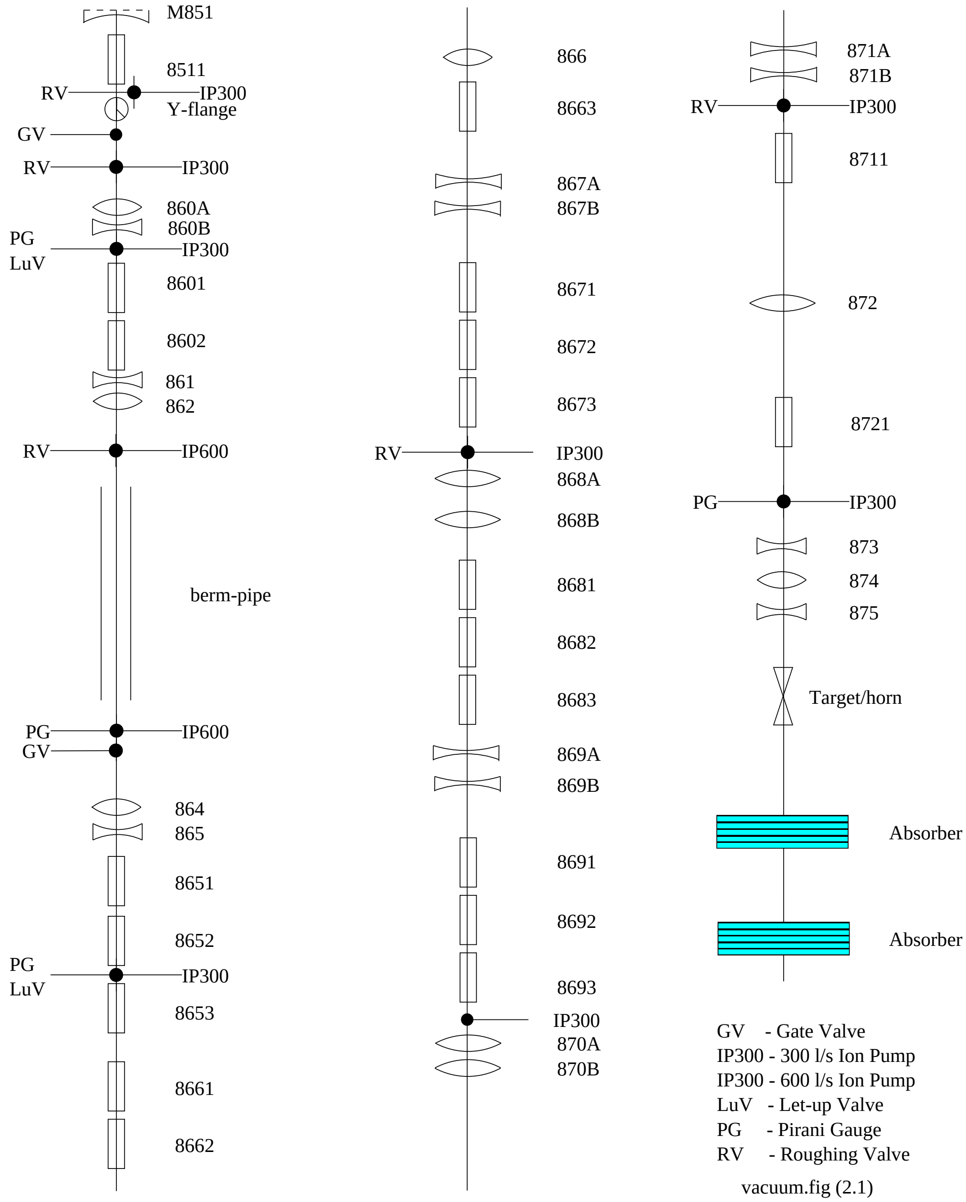

Figure 2.12: Schematic overview of the vacuum layout for the 8 GeV Beam.

Providing LCW for the magnets within the Main Injector enclosure is straightforward. Taps into the 6″ headers at Q-101 feed a secondary mainfold that distributes LCW to the magnets in the 8 GeV Intersection area (upstream of the berm-pipe.) To keep the water velocity below 7 fps, 4″ lines feed the remainder of the beamline. This comprises the magnets downstream of the berm-pipe, the target hall, power supplies located in MI-12, and the RAW system. These lines tie into the MI 6″ headers at Q-100, and have valves located at both ends of the berm-pipe. Installation required a brief shutdown of the MI LCW, and was accomplished in the spring of 2000. The berm pipe was pushed under the MI-10 service building from the upstream end of the MiniBooNE beamline enclosure into the MI tunnel during the fall 2000 shutdown. LCW pipes, electrical counduits and the beam pipe were installed in the berm-pipe at the same time.

The 4″ lines run opposite the aisle side of the tunnel, above and behind the magnet string, until B-8711, whereupon the lines tee. From here, a set of $1^1/_2$″ lines will continue along this wall to the triplet magnets and girder, connected to the 4″ lines with hoses and ball valves. Also from here, the 4″ lines reduce to 3″, cross the tunnel overhead, and continue down the aisle side to the first two of the four vertical penetrations to MI-12. Feeds to the RAW skid and the stripline Fan Coil Units (FCUs) are split off at this point.

2.5 Primary Beam Monitoring (WBS 1.1.9)

The primary beam position, profile, and intensity will be monitored to maintain the highest possible flux, to constrain beam simulations, and to prevent losses. Multiwires will be used to measure beam profiles. BPMs will be used to measure beam position, and a beam current toroid will measure beam intensity. (BPMs also measure intensity, but the toroid is necessary for absolute calibration.) Since all the devices used in MiniBooNE are also used in other beamlines, spare components will be maintained by the appropriate Beams Division departments as part of the general inventory. A schematic overview of the location of beamline instrumentation is given in Figure 2.13.

2.5.1 General Primary Beam Monitors

Twenty-two BPMs will be placed in the beam line (See Figure 2.13.) for beam tuning. Eight x,y BPM pairs are needed. The first pair is placed at the beginning of the 8 GeV Beamline, between B8511 and Q860. Another is upstream of the doublet at the entrance to the berm-pipe under MI-10. A pair is located at the end of the berm-pipe and upstream of the doublet which sets the optics going into the arc and FODO channel. Another pair is located at Q870. (The end of the arc.) There will be a pair at each end of the final focus. Two redundant pairs will be located upstream of the target. Six individual BPMs will be placed in the beamline. The last two BPM pairs upstream of the target will be of special design to fit in the tight space between the stripline. Special electronics is being designed for better accuracy near the target where tolerences are

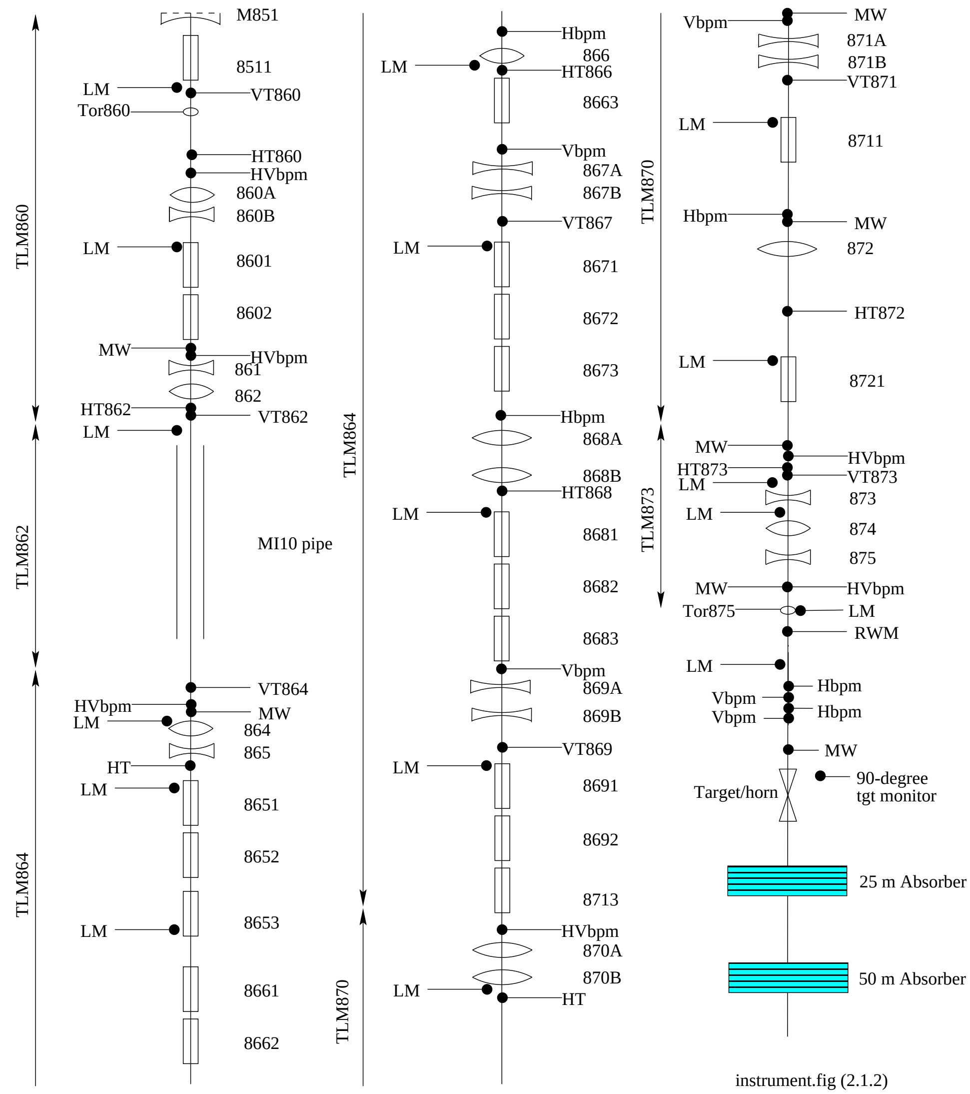

Figure 2.13: Schematic overview of location of instrumentation in the primary proton beamline. Key LM: – loss monitor, VT – vertical trim, HT – horizontal trim, MW – multiwire, Tor – toroid, bpm – beam position monitor, TLM – total loss monitor, RWM – resistive wall monitor.

smaller. The rest will be the same as in the P8 transfer line. The 8 GeV style BPM electronics is compatible with 15 Hz operation. The electronics may be upgraded to provide better accuracy and stability.

The BPMs do not interact with the beam in any way that degrades its quality and thus may be used to monitor the beam position continuously. Beam position data and the lattice definition will be used as input to a beamline autotune program that will monitor the beam position and make corrections spill by spill.

Seventeen loss monitors will be placed along the beam line to monitor beam losses. The preferred type is the sealed unit which is commonly used at Fermilab. The loss monitors will inhibit the beam permit when a prescribed threshold is reached, thereby preventing equipment damage. This is especially crucial in the target/horn region. The loss monitor electronics will be modified to respond to the beam pulses at 15 Hz.

Five total loss monitors (TLMs) provide coverage over the length of the beamline, including through the berm pipe. They will detect beam losses that occur anywhere along the length of the beamline. Beam will be inhibited if total losses exceed a threshold value.

A beam halo monitor will be installed downstream of the final focus to measure changes in beam quality.

A resistive wall monitor will be used to detect individual buckets and transmit this information to the experimental electronics for timing purposes.

2.5.2 Technical issues of the e-Berm

We are planning to have continuous loss monitor coverage of our beam line with a total loss monitor (TLM) system. However this will not be a fail safe and redundant system. We will have some individual loss monitors on selected elements but it will be possible to lose some beam on unprotected devices. Therefore there will be a system to trip the beam permit if significantly more beam is detected at the upstream end of the beam line than at the downstream end. This is more commonly known at Fermilab as an "e-Berm" (electronic berm). This prevents beam from being lost upstream of the target for more than one or two pulses. These systems have been used successfully at Fermilab in the past (M-east) and allow for the use of less dirt overburden while maintaining the same level of safety.

Because of the high beam intensity toroids will be used in place of SEM's in this system. The design goal is to have a trip level at 6% beam loss on a single beam pulse (remember we have 27,000 pulses/hour so a single beam loss of 6% or greater is not a problem when coupled with the e-berm and administrative controls) and to have a trip level at 2% beam loss on a ten pulse average. The 2% limit is the reduction factor that we will use in our shielding assessment.

The comparison of the intensities will be done in a fail-safe manner as was done in the previous applications of the e-berm method at the Laboratory. However, there is a question of knowing that we are timed in properly, *i.e.* both toroids could be looking outside of the beam window. We propose to use a nearby BPM in order to determine if the timing is correct. The intensity signal from the BPM will be sent into a discriminator, the output of which will be sent to a splitter. One of the outputs from the splitter will be sent into a gate module which is closed for a period of time determined by the width of the toroid timing window pulse. If a signal passes this gate we know that it was out of time with respect to the toroid timing window. A signal from this gate will disable the safety system in the same manner that a mismatch in intensities would. The other output from the splitter will be used to verify that the discriminator has not failed. The details of making the system fail-safe need to be engineered; however, only the first toroid needs to be safe-guarded in this manner.

Further discussion of the e-Berm is found in Section 2.9.

2.5.3 Monitoring of Primary Beam on Target

Six low precision retractable wire SEMs or multiwires will be located at strategic places in the beam line to monitor beam shapes and to help calibrate absolute position on some of the BPMs. These devices are more radiation hard than the standard beamline SWIC and present less material to the beam. Also, no gas lines are required. These devices have been used successfully in high intensity 8 GeV Booster beam for years and have been upgraded recently to provide better reliability and reproducibility. Multiwires are typically built with wire spacing of 0.5, 1, or 2 mm. Since these devices will be open to beampipe vacuum levels, it is assumed that levels of at least 10^{-6} Torr will be maintained. The vacuum, as discussed in Section 2.3, exceeds this requirement. The most downstream multiwire and BPM pair will be used to determine the targeting angle of the primary beam.

The beam current toroids will be located at either end of the beamline to measure the beam intensity as part of the e-berm system. Highly accurate (1-4%) beam current toroids[1] including electronics are commercially available. Typical signal strength from these toroids is 0.5 volt per ampere. This would yield about 250 mV for one beam pulse at nominal intensity.

A 90° target monitor may be employed to verify targeting efficiency. Preliminary MARS modeling shows that this device would need to be insensitive to neutrons coming out of the steel. Neutron source tests on a high rate ion chamber developed for NuMI are being proposed. Costing for this monitor has been included in the WBS.

2.5.4 Protection of Horn from Mistuned Beam

A "donut collimator" near the upstream end of the Target Pile, together with a loss monitor mounted on the front face of the Pile will be used to trip off the beam when it moves away from center. The purpose of these devices is to prevent mistuned beam from depositing large amounts of energy in the horn. Given the specified maximum spot size at the target, an 8 GeV beam has a maximum

[1] The Manufacturer's specifications claim 1% accuracy. Measurements in the Tevatron using locally constructed electronics show 4% accuracy.

energy deposition in aluminum of 0.03 GeV/cm^3. One pulse at 5×10^{12} would give a temperature rise of 10°C. Consider the case where the beam is mistuned in such a way that it completely misses the target. At the narrow neck of the Horn, where the beam size is roughly doubled because the beam is diverging, this implies a temperature rise on the conductor of 2.5 °C per pulse. Limiting the number of mistuned pulses to four, using the loss monitor, would keep the maximum temperature on the aluminum at a manageable level. The donut collimator will consist of a 5 cm long piece of copper. The outer geometry will be square, with 10 cm sides. A 3 cm diameter hole, which shadows the target, allows beam to pass through the collimator.

2.6 Controls (WBS 1.1.10)

The beam line magnets will be controlled through CAMAC modules (mostly CAMAC 453 ramp modules) and read out via CAMAC MADC's. Both of these will be connected to the Main Injector CAMAC link. The horn will be controlled and read out through an Internet Rack Monitor (IRM). BPM's and loss monitors will also be read out through IRM's. A "local application" running on an IRM will collect the BPM measurements and other time critical data (e.g. horn data) on a pulse-by-pulse (15 Hz) basis, time stamp each pulse with a GPS derived time so that the data can later be correlated with MiniBooNE detector data, and buffer this data for later access through the control system.

Multiwires and the Muon Monitor will be read out via Switchyard style SWIC scanners. These will connect like the Switchyard system to VME front end computer systems via ACNET. The VME systems will buffer the data on a pulse by pulse basis for later access through the control system. Each pulse will be time stamped with a GPS derived time stamp.

The beam line vacuum system will be controlled and monitored through the standard vacuum CIA crate. There will be one CIA crate in MI-10 which will service the entire beam line. The CIA crate will be connected to the MI vacuum front end.

Operator monitor and tuning facilities that will be needed include a BPM position display, a BPM intensity display, a loss monitor display, a multiwire display, and a ramp card setup and modification program. Many of these will be straight forward extensions to already existing code. In addition, an autotune program will be needed to keep the beam line tuned with minimal operator intervention. This program is being developed as a general facility for fixed target experiments (MiniBooNE, NUMI, 120 Gev MI fixed target). For MiniBooNE this program will read the buffered IRM BPM data and/or the buffered Multiwire data as input for its tuning algorithm.

Another fixed target facility program which is being developed and needed by MiniBooNE as well as NUMI and the 120 Gev fixed target experiments is a fixed target ACNET data EXPORT program. This program reads ACNET spill data (BPM's, Multiwires, SWIC's, magnet currents, etc.), time stamps the data, and sends the data to the various experiment's Data Acquisition systems via ethernet. For MiniBooNE this program will read the buffered IRM data, the buffered SWIC system data, and other non time critical ACNET data during non beam pulses and send this data to the experiment's DAQ system.

2.7 Safety Interlocks (WBS 1.1.11)

A Safety Interlock System is required to prevent individuals from entering the enclosure while the beam is present. All requirements for personnel safety interlock systems (electrical and radiation) are stated in the Fermilab Radiological Control Manual (FRCM) [12], and the Fermilab Environmental Safety & Health Manual [13]. Issues of radiation safety are considered in detail in Section 2.9 of this TDR.

Critical devices are used to protect individuals from accidental exposure when entering the enclosures during periods when beam is present in the accelerator or in other remote areas. Critical devices must provide redundancy. That is, at least two critical beam elements are turned off upon access to an enclosure. For the 8 GeV beam transport to MiniBooNE, the first critical device is the set of two dipoles at 862 that bend the kicked beam into the 24″ berm-pipe under MI-10. These magnets must be energized to send beam into the 8 GeV line. The second critical device is a refurbished beam stop from the Meson Area. Either of the critical devices is sufficient to keep beam from entering the 8 GeV Beam tunnel to MiniBooNE. Hence, this set of critical elements is more than sufficient to protect individuals upon entry to the enclosure or the Target Hall.

Poly-bead bags are used around the outside of the beam pipe at the up- and downstream ends of the 24″ berm pipe to provide neutron shielding. One foot of poly beads provides about $\times 1000$ reduction of the flux of low energy neutrons. We plan to load about 2′ of poly-beads at each end of the berm pipe.

The interlock system will require that the controlling power supplies are not only set to zero current, but actually turned off to allow entry. Controls for the safety interlocks will be housed in the MI-10 and Target Service Buildings.

2.8 Installation Plan and Alignment Requirements (WBS 1.1.12)

The 24″ diameter berm-pipe was installed under the MI-10 service building during the fall of 2000. The shielding and interlocks needed to allow work to proceed downstream in the beamline enclosure have been installed. The beam tube and utilities pipes have been installed in the berm-pipe. Final alignment of the beamtube will be done after we occupy the beamline enclosure. To protect the Main Injector tunnel environment pending completion of the 8 GeV Beamline enclosure the downstream end of the berm-pipe has been securely sealed.

Several of the beamline components have been installed in the MI tunnel. The switch magnet, B8511, dipoles B8601 and B8602 and quadrupole Q860A have been installed. A survey control network exists for the P8 beamline and was used to align these elements. The beam tube through B8511 is common to the P8 line and the 8 GeV line and therefore B8511 was carefully aligned to ensure there is no interference with normal delivery of beam to the Main Injector. The other elements were rough aligned. Quadrupoles Q861 and Q862 could not be installed at this time; their slots are occupied by temporary shielding.

After beneficial occupancy of the beamline enclosure and MI-12 building is obtained, the MI-12 crane will be used both to move the beamline elements into the enclosure and to erect the target pile. Careful coordination will be required to complete both tasks efficiently. A detailed time line has been started and will be completed as the civil construction schedule firms up.

The general requirements for the alignment are to establish control for the civil construction, establish precise control for the beamline elements, provide rough alignment of the stands, and provide precision alignment of the beamline elements. Initial establishment of control for the civil construction should take a crew week (where a crew is defined to be two persons), however quality control for the construction will probably average 1 crew day per week for the duration of the construction. Establishing precise surface control to one sight riser and the installation hatch will take 6 crew days. Establishing a precision control network for the beamline and the Target Hall will take a total of 30 crew days. Inside the beamline enclosure it should take 3 crew days to lay out the stands and then 15 crew days to align the beamline elements. The desired accuracy in the transverse planes is 30 mils for the 6-3-120's and 10 mils for the quadrupoles.

Alignment and installation are iterative tasks. Alignment crews lay out the control grid and the stand locations; the installers put in the stands and the magnets; the alignment crew puts the beamline elements in their precise positions; the installers then hook up the vacuum, water, and electrical connections; and then the final alignment is rechecked.

We will develop a drilling template to facilitate the fastening of the stands to the concrete floor for the 6-3-120's. The quads in general are short enough that we will not need a template. The expected rate of stand installation is at least six stands per day. The permanent magnet quadrupoles and the correction dipoles should go in at a rate of nine per day since they are light enough to be transported by golf cart. The 6-3-120's and powered quads will take longer. Taking into account transportation from the Magnet Facility, dropping down the installation hatch, and starting installation from the upstream end of the enclosure so that interferences are kept to a minimum, the average rate of installation should be three to four elements a day.

2.9 Radiation Shielding Criteria for the 8 GeV Beamline

To determine the amount of shielding needed over the pre-target portion of the beam, we have used Dugan's criteria [14]. These criteria provide two methods for determining the amount of shielding necessary for prompt radiation: (1) an amount for passive shielding and (2) an amount for active shielding, that is shielding which includes beam trip detectors that detect an accidental beam loss (this option will be referred to here as an “e-Berm” [15]). The requirements are quite different for the two methods.

The passive shielding assumes an undetected continuous beam loss for an hour. For MiniBooNE, this means a loss of 1.35×10^{17} protons at 8 GeV for each accident. Line 2 of Table 2.5 gives the amount of dirt shielding over various portions of the beam that would be necessary for unlimited occupancy under this scenario.

Table 2.5: Comparison of required earth equivalent shielding for accidental beam loss conditions for a case of active shielding (e-Berm/interlock detectors) and passive shielding (no e-Berm).

	over magnet in enclosure	over beam pipe	over buried beam pipe
w/e-Berm	17ft	14ft	18.4 ft
w/o-e-Berm	26ft	23ft	27 ft

On the other hand, for an e-Berm, an accident would consist of all the beam that could be lost between the time that the loss is detected and the time that the beam is shut off. For this analysis, we assume that the beam will be shut off in one second (or after 4×10^{13} protons). In reality, we expect that the interlocking mechanism will be able to inhibit the beam in the next booster fill after such an accident has been detected, *i.e.* $\sim$66 msec. Thus our assumption includes a safety factor of 7.5. Line 1 of Table 2.5 gives the shielding requirements for our e-Berm.

We must next consider the possibility of a 2% loss at a single point in the beamline which would not trip the e-Berm given the above design. This would generate a dose of 2.4 mrem/hr over most of the beamline which has $24.5'$ of shielding. The regions which have less overburden are being studied and additional steel will be added in several places. Identifying and mitigating/removing such loss points is an area of active investigation by the collaboration.

The leakage of radiation through labyrinths and penetrations which connect the region of beam-loss points and that of personnel access areas is under study at present. Appropriate precautions will be taken to meet the criteria set by reference [12].

Chapter 3

Project Management

The Project management Plan for the 8 GeV Beam Project is posted on the WWW at:http://www-ppd.fnal.gov/stefanski.Myweb/. Additional management concerns are discussed in this chapter.

3.1 Performance Requirements

The 8 GeV Beam must meet the physics driven requirements given in section 1.3.

3.2 Baseline Cost and Schedule

The schedule presented here is the baseline schedule approved at the Director's Review on May 16, 2001. The schedule will change subject to availabily of funds, and resources.

Table 3.1 gives the schedule start and finish dates for each WBS element in the technical part of the AIP. The costs given in Table 3.1 are the base costs. For additional information on the cost and schedule, see the cost book.

3.3 Methods of Performance

Overall project management, quality assurance and supervision of design and construction of the 8 GeV Fixed Target Beamline will be the responsibility of Fermilab through the Beams Division. Development and installation of all hardware associated with this task will be accomplished by Beams Division or their sub-contractors.

Table 3.1: The project Milestones as determined in the Project Baseline (as of 4/30/01).

WBS	Description	Duration	Start	Finish	Cost
1.1	8 GeV Beamline Technical	806 d	3/12/99	4/12/02	$1,345,712
1.1.1	Magnets	578.5 d	10/26/99	1/11/02	$ 195,024
1.1.2	Dipole Power Supplies	757.89 d	3/12/99	2/5/02	$ 67,579
1.1.3	Quadpupole Power Supplies	385.35 d	4/3/00	9/24/01	$ 35,347
1.1.4	Correction Element Supplies	265.78 d	4/3/00	4/9/01	$ 28,673
1.1.5	Kicker Power Supply	480 d	4/3/00	2/1/02	$ 173,684
1.1.6	Cables	701.5 d	3/12/99	11/19/01	$ 140,214
1.1.7	Vacuum Systems	770.5 d	3/12/99	2/22/02	$ 163,427
1.1.8	Water Systems	774.5 d	3/12/99	2/28/02	$ 169,044
1.1.9	Instrmentation	565.5 d	1/10/00	3/11/02	$ 91,732
1.1.10	Controls	806 d	3/12/99	4/12/02	$ 106,894
1.1.11	Safety System	344.5 d	12/1/00	3/28/02	$ 163,412
1.1.12	Alignment	730 d	3/12/99	12/27/01	$ 10,682

3.4 Requirements and Assessments

3.4.1 Security and Safeguards

Direction for security issues related to this project will be provided to the Beams Division by the Fermilab ES&H Section.

3.4.2 Safety

A hazard analysis was done for the project and is contained in the 8 GeV Beam Preliminary Safety Analysis Document (PSAD) dated October 20, 1999. The PSAD was approved by the ES&H Section, and contains a review of all safety issues pertinent to the project.

3.4.3 Environmental Protection

An Environmental Assessment was carried out for the 8 GeV Fixed Target Facility (DOE/EA-1267), and a Finding of no Significant Impact (FONSI) was issued on April 23, 1999.

3.4.4 Quality Assurance

All aspects of this project will be periodically reviewed with regard to Quality Assurance issues from conceptual design through to completion. The Quality Assurance requirements for this project are given by the following four elements:

1. The 8 GEV Beam Project Management Plan (PMP) [6] includes the identification of staff assigned to this project with clear definition of responsibility levels and limit of authority, as well as delineated lines of communication for exchange of information. The Project Management Group (PMG), chaired by the Deputy Director, Ken Stanfield, provides review of the project for conformance to Laboratory policies and standards. The PMG also reviews and approves changes as they occur, providing a means of change control for the project. The Beams Division Head has appointed Ray Stefanski as the Project Manager, and Craig Moore as the Project Leader for the 8 GeV Project. The External Beams Department, headed by Craig Moore is the lead department for the Technical elements in the project and provides direction to FESS with regard to the civil construction elements in the project. The Project Leader will form a team as needed to carry out the technical components of the project. The execution of the requirements for civil construction is given in the Construction CDR developed by FESS. The Beams Division Head has unlimited signature authority for this project consistent with the project budget. The Project Manager's signature authority is further limited to $25,000 on any one transaction. The Project Leader must review and initial all purchase requisitions, but has no signature authority. This holds for both the Technical and Civil elements in the project.

2. The PMP provides the criteria and provisions for control and recording of design changes. The means of control involves review and approval by the Project Management Group, for engineering change requests that conform to applicable standards.

3. In order to provide assurance that the execution of the project proceeds according to the design criteria established in the PMP, and that drawings and specification comply with these criteria, the Project Manager or the Project Leader will establish meetings with the project's team as deemed necessary.

4. To provide controls for project updating and compliance with the approved construction schedule, the Project Manager will provide written monthly reports to the Beams Division Head, and written semi-annual reports to the Associate Director for Accelerators.

3.4.5 Maintenance and Operation

A comprehensive maintenance program for the 8 GeV Beam will be developed as part of this project. Preventive maintenance, normal equipment service, and emergency repairs will be done by the Beams Division.

The operation of the beamline will follow the normal start-up and operational procedures of the Beams Division.

3.5 Contingencies

The design criteria that have been generated for this project are based on an on-going laboratory process that has been operating for over 20 years. The contingency that has been included in the cost estimate is that deemed appropriate for the nature of the design criteria. A contingency for each task has been assigned and the total contingency is the sum of the individual contingencies.

3.6 Applicable Codes, Standards and Quality Levels

Specific applicable codes have been stated in previous sections. No codes, standards or quality levels beyond standard Fermilab requirements are deemed necessary.

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