8 Accelerator and NuMI Upgrades (ANU)

8.1 Introduction

8.1.1 Executive Summary

Proton Plan is the current campaign of upgrades to maximize delivery of protons to the NuMI beam line as well as to the 8 GeV Booster Neutrino Beam (BNB), which currently serves the MiniBooNE experiment. The goal of Proton Plan is to use a slip stacking technique to load protons into the Main Injector and ultimately deliver 320 kW of beam power to the NuMI beam line while still delivering protons for anti-proton production. The NOνA experiment requires a significant increase in beam power beyond this.

With the conclusion of the Collider program, several machines will become available to be used, in conjunction with the Booster and the Main Injector, to increase the beam power delivered to the NuMI facility. ANU, consisting of upgrades and modifications to existing accelerator and beamline systems, has been developed to increase the proton rate to the NuMI neutrino line. This chapter focuses on the upgrades necessary to reach 700 kW beam power (ANU subproject of NOνA), making use of the Recycler ring (currently an anti-proton storage ring) as a proton pre-injector to the Main Injector. This pre-injection removes the proton injection time from the Main Injector cycle time, and thereby enables the Main Injector to cycle as fast as allowed by magnets, power supplies and the RF system. ANU provides about a factor of 2 increase in beam power, with only 10% increase in total beam intensity in the Recycler and Main Injector, by making full use of the maximum acceleration rate of the Main Injector. Modifications to the proton source and upgrades in the NuMI neutrino line to handle the higher beam power are both addressed in this report.

Table 8.1 compares the present operating scenarios with multi-batch slip-stacking in the Main Injector for NuMI (Proton Plan) and with multi-batch slip-stacking in the Recycler (NOνA).

ANU achieves an 80% increase in proton throughput over Proton Plan by moving the injection and the slipping portion of the slip-stacking process from the Main Injector to the Recycler, and otherwise maintaining the production process of Proton Plan. The various upgrades will now be briefly discussed.

The Recycler will be converted from an anti-proton to a proton storage ring, starting with the decommissioning all anti-proton specific devices, such as stochastic cooling tanks and electron cooling. A new injection line from the MI-8 proton line directly into the Recycler and a transfer line from the Recycler into the Main Injector are needed. The plan is to slip-stack six on six Booster proton batches in the Recycler, for a total intensity of 5×10^{13} protons/cycle, and, at the time they line up, extract them to the Main Injector in a single turn, where they will be recaptured and accelerated. A 53 MHz RF system needs to be added in the Recycler for beam injection and slip-stacking.

The Main Injector will have the slipping process offloaded to the Recycler, but will have to cycle faster and more often. The Main Injector cycle time will be reduced from 2.2 s to 1.333 s. In order to accommodate the faster ramp, two additional RF stations need to be installed.

	Present operating conditions	Proton Plan Multi-batch slip-stacking in MI	NOνA Multi-batch slip-stacking in Recycler
Booster intensity (protons/batch)	4.3-4.5×10^{12}	4.3×10^{12}	4.3×10^{12}
No. Booster batches	7	11	12
MI cycle time (s)	2.4	2.2	1.333
MI intensity (ppp)	3.3×10^{13}	4.5×10^{13}	4.9×10^{13}
To anti-proton source (ppp)	8.8×10^{12}	8.2×10^{12}	0
To NuMI (ppp)	2.45×10^{13}	3.7×10^{13}	4.9×10^{13}
NuMI beam power (kW)	192	320	700
Protons on Target per year to NuMI[1]	2×10^{20}	3×10^{20}	6×10^{20}

Table 8.1: Present and foreseen operating scenarios. The first two columns show NuMI intensities and beam power values for mixed-mode cycles in the Main Injector.

The ability of the NuMI neutrino line to accept a 75% increase in power, over its design value of 400 kW, mainly involves improvements to the primary proton line to handle the faster repetition rate, a new design for the target and upgrades to the cooling systems. The target and focusing horn configuration (neutrino beam optics) is also changed to meet the needs of the NOνA experiment. This means moving the target and the second horn to new locations within the target chase area in order to change the energy spectrum of the neutrinos to a higher energy (the medium energy configuration).

The implementation of the ANU subproject is planned to occur during two separate shutdown periods. The first shutdown period, of about 9 months in the fall of 2010, follows the completion of Collider Run II operations. During this shutdown the modifications to the accelerator complex will be completed and the NuMI beamline will begin preparation for the 700 kW phase, but without changing the neutrino beam focusing optics. This is planned to allow the MINERνA (Main Injector ν-A interactions) experiment [2] to operate for about one year in the low energy neutrino configuration, presently used by the MINOS experiment and to allow work to be completed for the NuMI upgrades. Since MINERνA requires the use of the existing low energy target, the NuMI beamline will be capable of only ~400 kW of beam power, but at the same time it will be possible to commission all the modifications to the accelerator complex. In Spring 2012 a second shorter shutdown is planned to switch from the low energy to the medium energy neutrino configuration. By then the NOνA experiment will have a good fraction of their detector available for data taking. The upgrades for NOνA have been designed for an annual integrated delivery of 6.0×10^{20} protons on target.

[1] See Reference [1]

The NOνA ANU subproject represents a technically feasible plan, which mainly relies on the reconfiguration of existing machines. By itself, these upgrades provide more than a 100% increase in beam power to the NuMI neutrino line over the present Proton Plan.

8.1.2 The Present Accelerator Complex

A sketch of the Fermilab accelerator complex is shown in Fig 8.1.

The Booster is effectively the proton horsepower of the complex. Fed by 400 MeV H^- ions from the Linac, it accelerates protons to 8 GeV of kinetic energy at 15 Hz rate. Booster batches (typically up to $\sim5\times10^{12}$ protons) are transferred through the MI-8 line into the Main Injector (MI) or sent to the MiniBoone neutrino target.

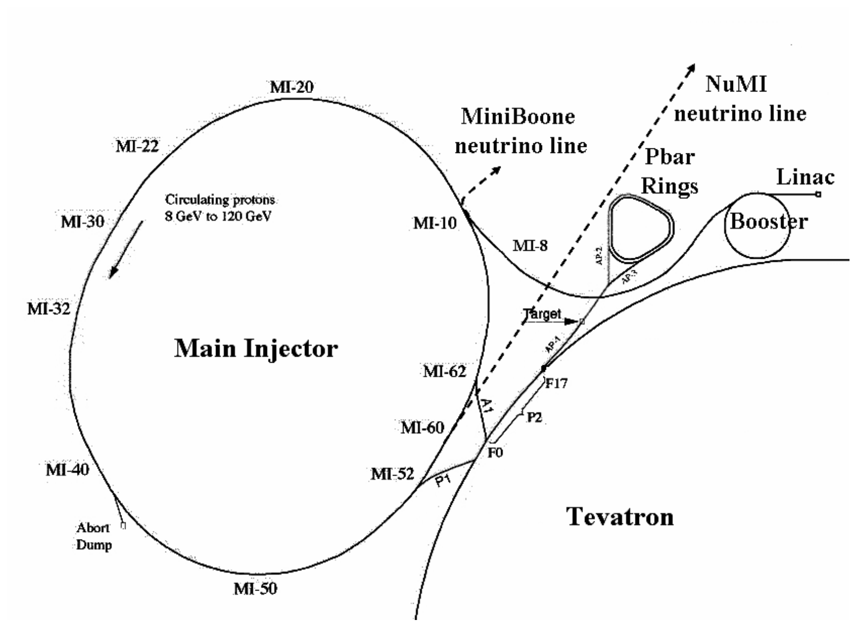


Fig 8.1: The Fermilab accelerator complex.

The Main injector is seven times the circumference of the Booster. Six Booster batches are required to fill up the machine, leaving one seventh of the circumference available for the rise-time of the extraction kicker. Table 8.2 summarizes the MI parameters.

Circumference (km)	3.319	Harmonic number	588
Injection momentum (GeV/c)	8.9	RF frequency at injection (MHz)	52.8
Extraction momentum (GeV/c)	120	RF frequency at extract. (MHz)	53.1
Transition gamma	21.8	Maximum RF voltage (MV)	4.3

Table 8.2: Parameters of the Main Injector.

The Main Injector is the central machine of the complex, equipped with a complex set of injection and extraction lines to connect to the other machines of the complex. It provides protons for anti-proton production, it has a dedicated extraction to the NuMI neutrino line and it is connected to the Tevatron for proton and anti-proton transfers.

An additional machine, the Recycler, is located in the Main Injector tunnel at a distance 57” above the MI ring and with the same basic cell geometry. The Recycler is a fixed 8 GeV kinetic energy antiproton storage ring, which makes use of permanent gradient and quadrupole magnets for the ring lattice. Antiproton transfers in and out of the Recycler Ring take place through two transfer lines connecting the Recycler to the Main Injector. Fig 8.2 shows the Main Injector tunnel in the MI-60 region, where the NuMI extraction is located.

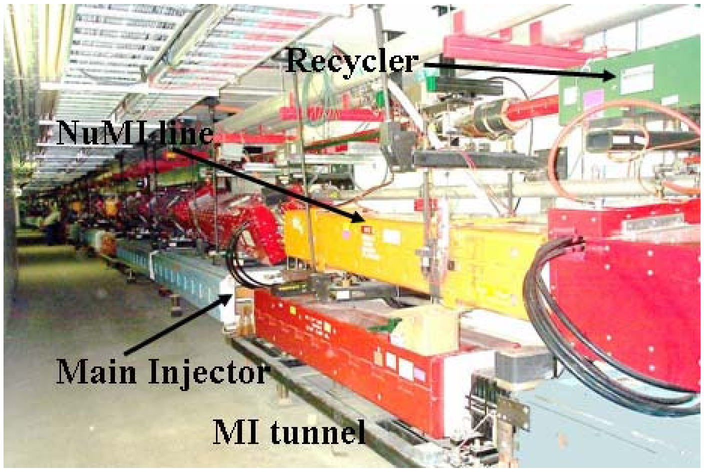


Fig 8.2: A photo of the Main Injector tunnel in the MI-60 region, showing the NuMI extraction line between the Main Injector at the bottom and the Recycler on top.

The NuMI Beamline line points from Fermilab to the MINOS detector installed in the Soudan mine, in Northern Minnesota, at a distance of 735 km from the neutrino target. A schematic of the NuMI line is shown in Fig 8.3.

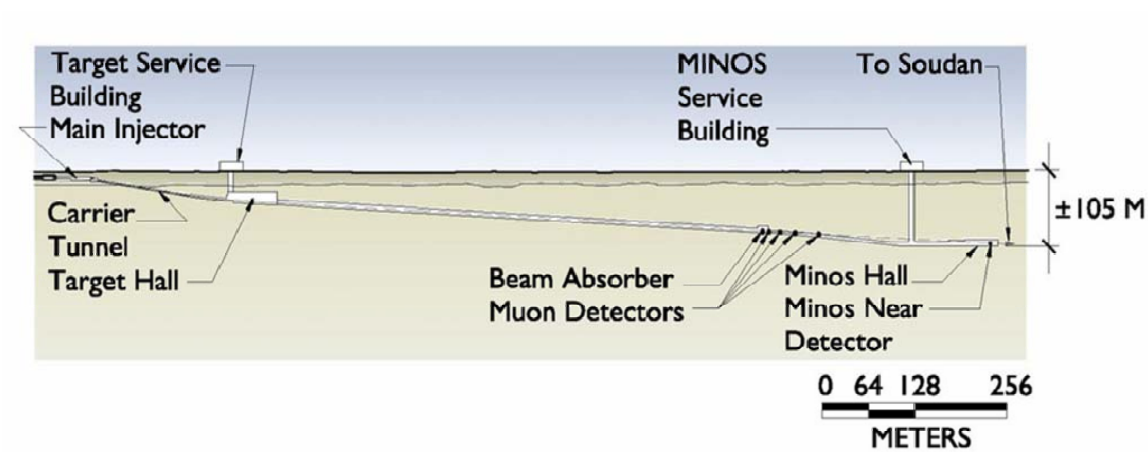


Fig 8.3: Schematic of the NuMI neutrino line. Protons are delivered from the Main Injector via the primary proton beamline through the carrier tunnel. The target and focusing horns are located in the target hall. The long section in the middle contains the decay pipe which is followed by the beam absorber, muon detectors, and near experimental hall.

The 120 GeV/c primary proton beam, single turn extracted from the Main Injector, is transported by a large acceptance primary proton line over a distance of 350 m, brought to a pitch angle of 58 mrad in order to point to the neutrino detector in the far location, and focused onto a water-cooled graphite target. Design values of the NuMI line are 4×10^{13} protons/pulse (ppp) every 1.9 s, corresponding to a power of 0.4 MW.

The graphite target, of two interaction lengths, is followed by two water-cooled, parabolic aluminum horns, pulsed with up to 200 kA, providing a 1/r toroidal field that has a maximum of 30 kG. The focused particles are allowed to decay in a 675 m long decay pipe of 1 m radius, evacuated down to 0.4 Torr. A water-cooled aluminum beam absorber is positioned at the end of the decay pipe.

High rate ionization chambers are used to monitor the beam immediately upstream of the beam absorber (Hadron Monitor) and in three successive alcoves downstream of the absorber (Muon Monitors or detectors).

8.1.3 Proton Plan

The Proton Plan [3] is a campaign of upgrades to maximize delivery of protons to the NuMI beam line, which currently serves the MINOS experiment, as well as the 8 GeV Booster Neutrino Beam (BNB), which currently serves the MiniBooNE experiment. NOνA implicitly assumes that the Proton Plan has been completed and has been reasonably successful in achieving its goals.

The Proton Plan is concurrent with Run II (the second run of the Collider program). The current timeline has the final associated hardware improvements installed in the summer 2008 shutdown, and all benefits realized by mid 2009, at which point, it will be fully superseded by NOνA.

The goal of the Proton Plan is to use a slip stacking technique to load protons into the Main Injector and ultimately deliver approximately 320 kW of beam power to the NuMI beam line while still delivering protons (80kW) for antiproton production. By increasing the total proton output from the Booster, it is planned to continue delivering protons to the 8 GeV beam line (currently the MiniBooNE experiment) at a level of roughly $(1 \sim 2)\times 10^{20}$ per year.

Broadly speaking, the Proton Plan elements fall into four categories:

1. Increasing the maximum Booster repetition rate from the 7.5 Hz to roughly 9 Hz
2. Increasing Booster efficiency so that more beam may be accelerated while keeping the total beam loss in the Booster tunnel at a constant level. Operationally, beam loss has been the limiting factor for Booster throughput, and will likely continue to be for some time.
3. A number of hardware and operational issues to implement slip stacked operation in the Main Injector
4. Some projects aimed at increased reliability and stability, particularly in the Linac.

8.2 Technical Design Criteria

Thermal expansion of the target chase and target hall components will affect the alignment of the target and horns. The NOνA experiment requires that alignment of the beam, target, and horns remain within a 1.5 mm tolerance [4]. Other design parameters for NOνA, together with the Proton Plan parameters, are shown in Table 8.3.

	Proton Plan	NOνA	
Booster			
Extracted Batch Intensity	4.3E+12	4.3E+12	protons
Average Pulse Rate	5.9	10.5	Hz
Average Beam Rate	5.0	9.0	Hz
Norm. Trans. Emittance at Extr.	15	15	π·mm·mrad @ 95%
Long. Emittance per Bunch at Extr.	0.08	0.08	eV·sec @ 95%
δp (After Bunch Rotation)	8	8	(±) MeV/c @ 95%
Recycler Ring			
Number of Injections		12	injections
Total Beam Injected		5.16E+13	protons
Injection Kinetic Energy		8	GeV
Injection RF Frequency		52.809	MHz
RF Frequency Difference		1260	Hz
Extraction RF Frequency		52.809	MHz
δp at Extraction		19	(±) MeV/c @ 95%
Main Injector			
Number of Injections	11	1	injections
Cycle Time	2.2	1.333	s
Beam Momentum at Extraction	120	120	GeV/c
Beam Intensity at Extraction	4.5E+13	4.9E+13	protons
Norm. Trans. Emittance at Extr.	20	18	π·mm·mrad @ 95%
Long. Emittance per Bunch at Extr.	0.4	0.4	eV·s @ 95%
δp/p at Extraction	8.E-04	8.E-04	(±) @ 95%
MI/RR Tunnel Losses			
8 GeV Beam Efficiency	95%	95%	
Controlled 8 GeV Loss to Abort	0.0%	1.9%	
Controlled 8 GeV Loss to Collimators	2.7%	1.8%	
Uncontrolled 8 GeV Losses	2.3%	1.3%	
Transition Losses (Upper Bound)	0.2%	0.2%	
Power Deposited in Abort	0	943	W
Power Deposited in Collimators	744	893	W
Distributed Uncontrolled Loss	0.23	0.27	W/m
NuMI			
Maximum Proportional Loss in Carrier Pipe	1.0E-05	5.7E-06	
Spot Size on Target	1.3	1.3	mm (RMS)
Max. Beam Intens. on NuMI Target	4.5E+13	4.9E+13	protons
Max. Beam Power on NuMI Target	392	705	kW
Protons per Hour	7.3E+16	1.3E+17	protons/hr.

Table 8.3: Summary of Design Parameters for Proton Plan & NOνA.

8.3 Recycler Ring Upgrades

8.3.1 Overview

The Recycler currently serves as the main anti-proton storage ring for the Tevatron Collider program. Through the use of stochastic and electron cooling, greater than 4 x 10^{12} anti-protons have been stored, with lifetime greater than 500 hours. The transverse acceptance is ~65 π mm mr (95% normalized emittance) and the momentum acceptance is ~1.5%. When Tevatron Collider operations cease, the Recycler will be used as a proton pre-injector for the Main Injector (MI) for NOνA. As the Recycler is the same size as the MI, it is possible to do a single turn fill (~11 μsec), minimizing the proton injection time in the MI cycle and maximizing the protons on target. Fig 8.4 shows the layout of the Recycler and the main areas where the work will occur.

To convert from an anti-proton storage ring to a proton pre-injector, filling the Main Injector every 1.3 seconds, it will be necessary to remove anti-proton specific devices in the Recycler, build new injection and extraction lines, build new injection, extraction, and abort kickers, build a new 53 MHz RF system, and upgrade the instrumentation. In the sections that follow, we will present the project components in detail. We plan for all of the conversion activities to take place during a single shutdown period after the Tevatron Collider program ends.

There are several anti-proton specific areas for beam cooling in the Recycler. The stochastic cooling pickup and kicker tanks in the RR10 and RR20 areas will be removed. The electron cooling section in RR30, which consists of the solenoidal cooling channel and electron injection and return lines, will also be removed.

The current R22 line (for pbar injection or proton extraction from the Recycler) and R32 line (for pbar extraction or proton injection into the Recycler) will not be adequate in the NOνA era. The original R22 line was designed to transport 40π pbar beams being recycled from the Tevatron. However, the measured acceptance of the R22 line is smaller than expected and the Lambertson is located in a dispersive region making this line unacceptable for extracting slipped stacked protons from the Recycler. The R32 line allows for proton injection through the MI, while we want direct injection from the Booster. These lines will be decommissioned and replaced with two new transport lines. The new injection line from the MI8 line into the Recycler will start at 848 and end with new injection kickers at RR104. A new extraction line in the RR30 straight section will start with a new extraction kicker at RR232 and end with new MI injection kickers at MI308.

To increase the beam current, we plan on utilizing slip stacking at 53 MHz in the Recycler. The existing Recycler RF system is a broadband 10 MHz system, designed to handle the anti-proton accumulation for the Tevatron Collider program. We will design, build, and install a new 53 MHz RF system for bucket to bucket injection from the Booster, slip stacking in the Recycler, and bucket to bucket extraction to the MI.

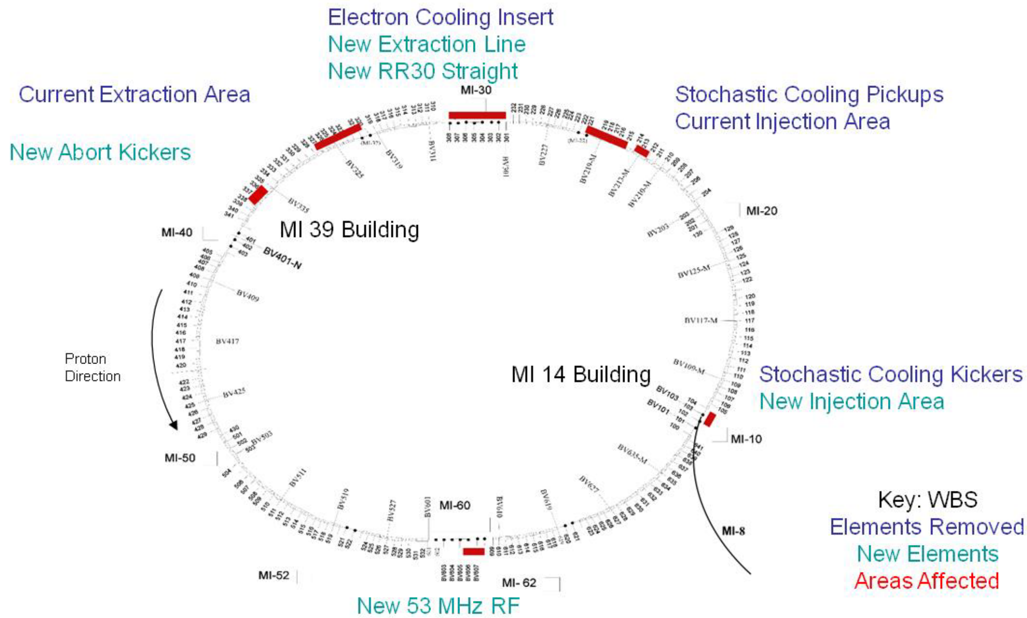


Fig 8.4: Recycler Upgrades Overview

We will upgrade the existing instrumentation to handle the increase in peak intensity (from 6e12 to 6e13) and the change in the RF structure. The Beam Position Monitor (BPM) systems will be upgraded to a 53 MHz system, using the recent MI BPM system upgrade as a model [5]. The damper systems will be upgraded to handle the intensity. We anticipate upgrades to the intensity monitors (a DC current transformer (DCCT) and beamline toroids) as well.

Cooling system modifications to the Recycler will affect three Low Conductivity Water (LCW) cooling systems: the Main Injector global LCW system, the RF (95 degree) LCW system and the Cavity (55 degree) LCW cooling systems located at MI-60. Work affecting these cooling systems is occurring in the Q-100 region (Injection Line), Q-300 region (Extraction Line), Q-400 region (Abort Line), and Q-600 region (RF Cavities). Work on cooling needs for the associated power supplies in the service buildings is occurring in MI-14, 30, 39, and 60 Service Buildings. It is currently assumed that the majority of the Main Injector Cooling Systems will have sufficient capacity for increased loads due to the Recycler modifications. However, there are extensive modifications planned in the Q-100 region, where a new Injection Line will be added.

8.3.2 Ring Modifications

8.3.2.1 Decommission Pbar Devices in the Tunnel

As the Recycler will no longer circulate anti-protons, we need to remove anti-proton specific devices from the ring for possible future use. These fall into two categories: (1) anti-proton cooling devices and (2) anti-proton transfer line devices.

8.3.2.1.1 Removal of Stochastic Cooling Tanks

The Recycler stochastic cooling system consists of pickup tanks in the RR 21 sector and the kicker tanks in the RR 10 sector. The tanks and all the support electronics will be removed from the tunnel and replaced with beam pipe (in the 21 sector) or the injection area devices (in the 10 sector). The removal is a well-understood task, which is anticipated to take 8 technicians 4 weeks to complete. It is one of the first tasks done during the conversion shutdown period.

8.3.2.1.2 Removal of ECool

The Recycler electron cooling system consists of a 6 MV Pelletron in the MI 31 service building, 4.3 MeV electron transfer lines, a 20 m cooling section populated by solenoids, and lattice matching sections for the cooling section. We wish to preserve the system for possible future use (at Fermilab or elsewhere).

In this task, we will remove and package the solenoids for future use, remove the sections of the transfer lines in the MI tunnel enclosure, and remove all Recycler components between 301 and 309 (the cooling insert) including the 38 permanent magnet quadrupoles. These magnets will be sent to Technical Division to be refurbished and used again in the rebuilt MI 30 straight section and the transfer lines (see Sections 8.3.2.2, “New Injection Line”, and 8.3.2.3, “New Extraction Line and RR30 Straight Section”).

As the cooling section solenoids and electron transfer lines were installed in a recent shutdown (Summer 2004), the removal is also a well-understood task. As the magnets will need to be refurbished and installed in other areas of the Recycler during the conversion shutdown, this task is one of the first ones scheduled.

8.3.2.1.3 R22 Line Removal

The R22 line is the anti-proton injection line from the Main Injector to the Recycler. We plan on removing the Lambertson magnets in the Main Injector (at MI Q222) and the Recycler (at Q214) and rebuilding the vacuum sections in both machines. We also anticipate removing instrumentation and trim magnets from the line for use in the new transfer lines. In the conversion shutdown, we do not plan on removing all the components and stands. As the instrumentation will be utilized again, this task is also to be done early in the shutdown.

8.3.2.1.4 R32 Line Removal

The R32 line is the anti-proton extraction line from the Recycler to the Main Injector. We plan on removing the Lambertson magnets in the Main Injector (at MI Q321) and the Recycler (at Q328) and rebuilding the vacuum sections in both machines. We plan on removing instrumentation and trim magnets from the line for use in the new transfer lines. In the conversion shutdown, we do not plan on removing all the components and stands. As the instrumentation will be utilized again, this task is also to be done early in the shutdown.

8.3.2.2 New Injection Line

We are designing a new injection line to take protons directly from the MI 8 line into the Recycler [6,7]. The MI 8 line transfers 8 GeV protons from the Booster to the Main Injector tunnel, where a horizontal switching magnet directs them into the Main Injector or to the MiniBoone target. We want to preserve the ability to inject into the Main Injector and transfer beam to the MiniBoone target, so we plan on installing a vertical switching magnet (upstream of the horizontal switching magnet) to direct protons into the Recycler.

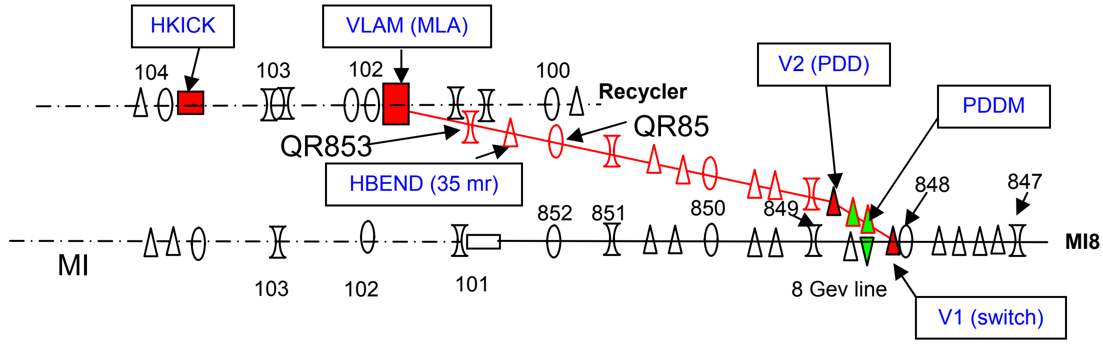


Fig 8.5: Diagram of new Recycler injection line

The solution uses three vertical bending centers and a horizontal kicker. A diagram of the transfer line is shown in Fig 8.5. The first vertical bend (V1 switch) bends up at about a 33 mrad angle to clear the downstream magnets. A vertical dipole (V2, rotated PDD, Fig 8.5) reduces the pitch from 33 mrad to about 14 mrad. These two bends act as a single extended bend center. This pitch is maintained until the third vertical bending center, the MLAW injection Lambertson (located just upstream of Q102A). The Lamberston bends the beam down to place it on the correct vertical closed orbit of the Recycler and cancels the vertical dispersion created by the switch magnet. The injection kicker (HKICK) applies a horizontal kick to put the injected beam onto the Recycler orbit. The injection/abort gap kicker design is discussed in detail later in this document. The required kick implies 5 kicker magnets and 1 tail bumper magnet.

8.3.2.2.1 Powered Elements

The injection line design contains only two large powered elements, the vertical switch magnet and the Lambertson. The vertical switch magnet, V1, is a modified ADC magnet [8]. The magnet aperture is widened from 1.5 to 2.12 inches. The magnet will be labeled ADCW. Preliminary design considerations verify that the required field is attainable.

The Lambertson (MLAW) and kicker geometry and strengths are found in Nova-doc-1495 [6]. In particular, the aperture of the field free region is increased by 5-6 mm which will increase the current requirements by 14%. This does not change the power supply specification. The Lambertson is also rolled by ~5º to generate the correct angle for closure. Additionally, apertures and beam sizes require an MI style beam pipe downstream of the Lambertson and through the Q102 quadrupoles.

There are five quad locations between the switch magnet and injection Lambertson. Powered dipole trims and two powered MQT type quad trims (with enough strength to adjust gradients by +/- 20%) are installed at each quad location.

8.3.2.2.2 Permanent Magnet Elements

The nominal Recycler straight section 20 inch quad RQMF/D was tuned to provide a gradient of 25 to 26 kG/m. Typical gradients in the MI8 matching section to either MI or Recycler are between 50 and 80 kG/m. For matching into the Recycler, each quad location has either two or three permanent magnet quads to keep the gradient within the tunable range of the permanent magnets. These quads will be recycled from the decommissioning of the RR30 straight section.

Utilization of the rolled PDD permanent magnet for V2 constrains the amplitude of the vertical switch magnet to be around 33 mrad. The elevation of the “upper” 8 GeV line at the downstream horizontal dipoles requires the use of mirror magnets. These mirror magnets

(PDDM) will be pure dipoles matching the aperture and field of the PDD. Currently, the separation between the beam centerlines of the upper and lower 8 GeV line at the first mirror magnet in the upper line is 4.324 inches. However, the mirror magnets are offset so that the beam centerline-to-steel dimension on the mirror side should be less than 3.45 inches.

8.3.2.2.3 Lattice and Matching

Retaining the ability to transport beam to the Main Injector, Recycler and MiniBoone will require modifications in the MI-8 line to successfully match the optical lattice functions of both synchrotrons. To get a unique solution, eight parameters must be supplied. To this end, the gradients at the locations 846 thru 853 are adjusted to match into the Recycler. The first electromagnet matching quad in the 8 GeV line is located at 847. This implies the addition of an electromagnet quad at the 846 location where there is currently a pair of gradient magnets. The required integrated gradient is less than 3 kG, which can easily be provided by the MQT trim quad. In addition, a trim quad will be added to the current 8 GeV line at the locations of Q847 and Q848, adjacent to the existing electromagnet quad. These can be utilized at 15 Hz for matching into the MI and or MiniBoone.

Type	Comment	Total	Modify	Construct	Recycle
	Permanent Magnets				
RQMx	Recycler style 20 in. permanent magnet quad	14	14	0	0
PDD_M	PDD mirror magnet, new design	3	0	3	0
PDD	PDD 8 Gev style double dipole, existing style	5	0	3	2*
PDD_R	PDD dipole design, reduced field	2	0	2	0
MGS	Recycler dispersion suppressor mirror magnet	0	0	0	0
	Powered Elements				
ADCW	Modified B1 style to open aperture	1	1	0	0
MLAW	MI style injection Lambertson, new, modified	1	0	1	0
ILA	MI style Lambertson, existing, move	0	0	0	0
	Trim Elements				
MQT	Old MR style quad trim	13	0	0	13
HDC	Old MR style horizontal corrector used in Recycler	2	0	0	2
VDC	Old MR style verticall corrector used in Recycler	2	0	0	2
MCH	LEP Horizontal corrector	2	0	0	2
MCV	LEP vertical corrector	2	0	0	2

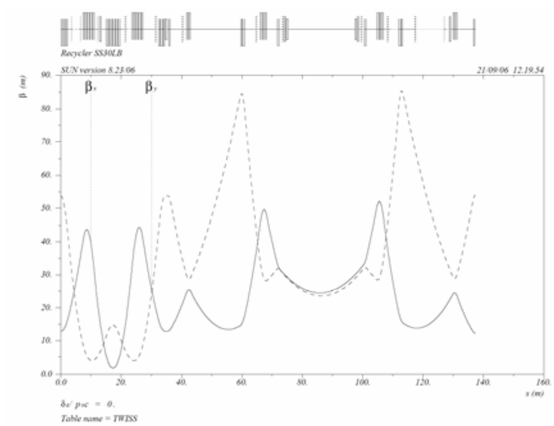
Table 8.4: Magnet information for the injection line.

8.3.2.3 New Extraction Line and RR30 Straight Section

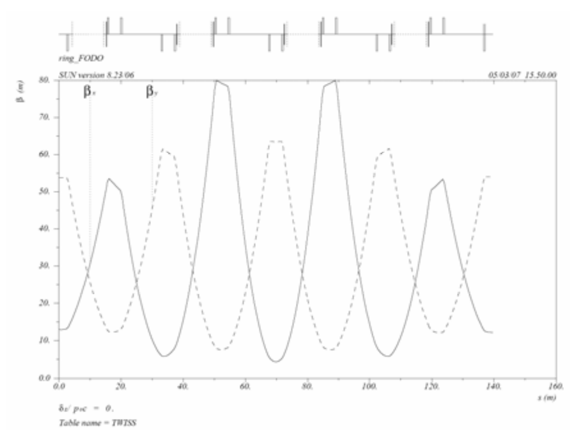
We are designing a new extraction line to take protons from the Recycler to the Main Injector, making use of the MI 30 straight section. The MI-30 straight section is a “D-D 8 half-cell” straight section, which starts at 301 and ends at 309--both horizontally defocusing locations. The MI lattice is a periodic FODO in the region. The Recycler lattice contains the symmetric electron-cooling insert between 305 and 307; the remainder of that Recycler straight section is roughly a FODO section, but is not periodic. The Recycler straight section between Q301 and 309 is replaced with the FODO lattice, as in the initial Recycler design. Fig 8.6(a) and Fig 8.6(b) give the beta functions of the two types of the lattice.

Note that the beta-functions in the SS30-FODO section still reach 80m in the horizontal plane. The beam pipe used in this section is either 3" round or 3.75"x1.75" elliptical and does not represent an aperture restriction. However, the quadrupole strength requirement is ~15% more than the standard permanent magnet quadrupole strength in the Recycler. A solution is to add one more quadrupole per cell, requiring 25 quadruples in the RR-30 straight section.

The extraction line has been redesigned since the CDR to reduce required kicker strength by extending the whole line by a half-cell. The extraction line starts with an extraction kicker at 230 in the Recycler. A rolled, modified MI 8GeV injection Lambertson (MLAW) is located at 232 for the initial vertical bend. The next two vertical bends are located at 302 and 304 with the beamline following the same lattice structure of the Recycler until 306. The MI injection Lambertson is located at upstream of quad 306, which would put the beam on the MI vertical closed orbit. The kicker is now located 12 inches upstream of the Q308 quad coil.



(a) SS30LB



(b) SS30_FODO

Fig 8.6: Lattice functions of the RR-30 Straight Section.

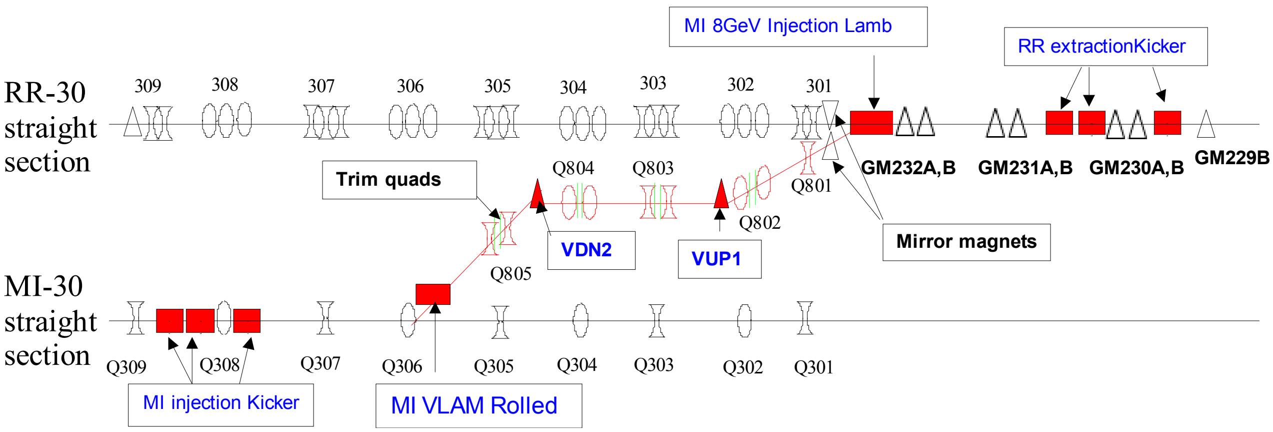


Fig 8.7: Cartoon of the extraction line from RR to MI and the RR 30 straight section.

Type	Comment	Total	Modify	Construct	Recycle
	Permanent Magnets				
RQMx	Recycler style 20 in. permanent magnet quad	9	9	0	0
PDDM	PDD mirror magnet, new design	0	0	0	0
PDD	PDD 8 Gev style double dipole, existing style	0	0	0	0
PDDW	PDD dipole design, reduced field	0	0	0	0
MGS	Recycler dispersion suppressor mirror magnet	1	0	0	1*
	Powered Elements				
ADCW	Modified B1 style to open aperture	2	2	0	0
MLAW	MI style injection Lambertson, new, modified	1	0	1	0
ILA	MI style Lambertson	1	0	0	1
	Trim Elements				
MQT	Old MR style quad trim	10	0	0	10
HDC	Old MR style horizontal corrector used in Recycler	2	0	0	2
VDC	Old MR style verticall corrector used in Recycler	3	0	0	3
MCH	LEP Horizontal corrector	0	0	0	0
MCV	LEP vertical corrector	0	0	0	0

Table 8.5: Extraction line magnetic elements. The columns represent the total number needed for the extraction line, the number that exist but need to be modified, the number to be constructed, and the number to be recycled.

Type	Comment	Total	Modify	Construct	Recycle
	Permanent Magnets				
RQMx	Recycler style 20 in. permanent magnet quad	25	25	0	0
PDDM	PDD mirror magnet, new design	0	0	0	0
PDD	PDD 8 Gev style double dipole, existing style	0	0	0	0
PDDW	PDD dipole design, reduced field	0	0	0	0
MGS	Recycler dispersion suppressor mirror magnet	1	0	0	1
ADCW	Modified B1 style to open aperture	0	0	0	0
MLAW	MI style injection Lambertson, new, modified	0	0	0	0
ILA	MI style Lambertson	0	0	0	0
	Trim Elements				
MQT	Old MR style quad trim	0	0	0	0
HDC	Old MR style horizontal corrector used in Recycler	4	0	0	4
VDC	Old MR style verticall corrector used in Recycler	4	0	0	4
MCH	LEP Horizontal corrector	0	0	0	0
MCV	LEP vertical corrector	0	0	0	0

Table 8.6: RR 30 straight section magnetic elements. The columns represent the total number needed for the extraction line, the number that exist but need to be modified, the number to be constructed, and the number to be recycled.

8.3.2.4 53 MHz RF System

The existing broadband RF system in the Recycler Ring will not be removed. For NOνA operation, a new 53 MHz RF system is required. This system includes RF cavities installed in the Recycler and a new low level RF system. For bucket-to-bucket transfers from the Booster and to the Main Injector, the required frequency is 52.809 MHz. For slip stacking, a tunable frequency range of ± 5 kHz and total voltage of 300 kV is necessary. Fast cavity tuning (for beam loading compensation) and higher mode dampers on the cavities are also required.

We propose to build 2 new RF cavities, to be installed in the 608 region of the Recycler. Controls, power, and other infrastructure support will be installed in the MI 60 service building. We plan on recycling the 53 MHz power amplifiers and modulators from the Tevatron RF systems.

8.3.2.4.1 Specifics of the design

The cavity is a $\lambda/4$ coaxial design with a 25” outer diameter made of OFHC copper with a step-up ratio of 6:1. The central frequency is 52.809 MHz with a Q of ~7000. By using fast garnet phase shifters developed for the Proton Driver [9], the cavity is tunable over a ± 10 kHz range. The shunt capacity is 140 kΩ, leading to 80 kW/cavity at 150 kV. R/Q is 20 Ω. The tetrode anode power dissipation with 1 A of DC beam current and no detuning is 130 kW, while the PA tubes are rated for 150 kW. Higher order mode dampers for the 3^{rd} and 5^{th} harmonic are included in the design. A cross sectional view of the cavity can be seen in Fig 8.8 and a 3D view in Fig 8.9.

To support direct injection from the Booster and proton slip stacking in the Recycler following the decommissioning of the Tevatron, a new Low Level RF system will be required to drive the new 53MHz cavities and provide synchronization for beam transfers. Further details are in Section 8.4, “Main Injector (MI) Upgrades”.

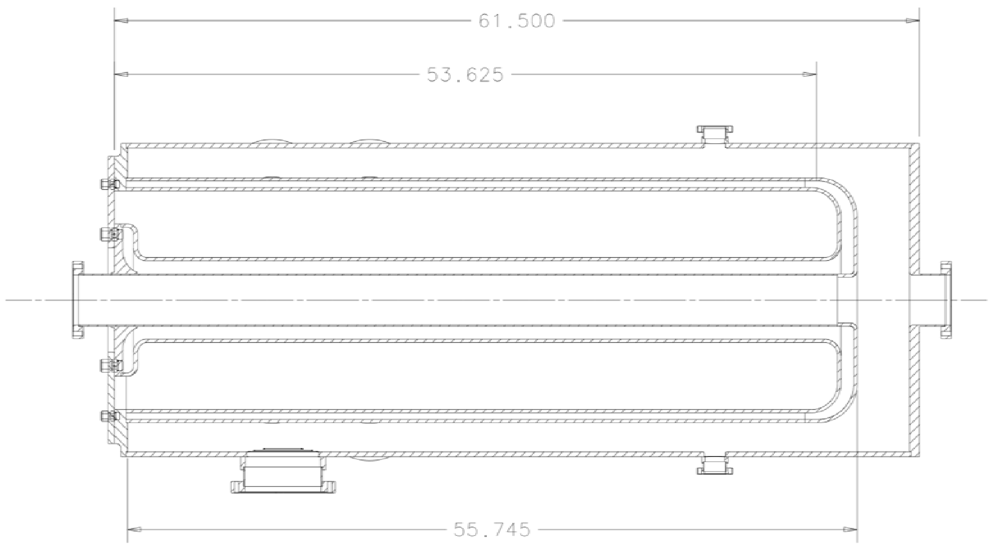


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Fig 8.8: Cross sectional view of RF cavity.

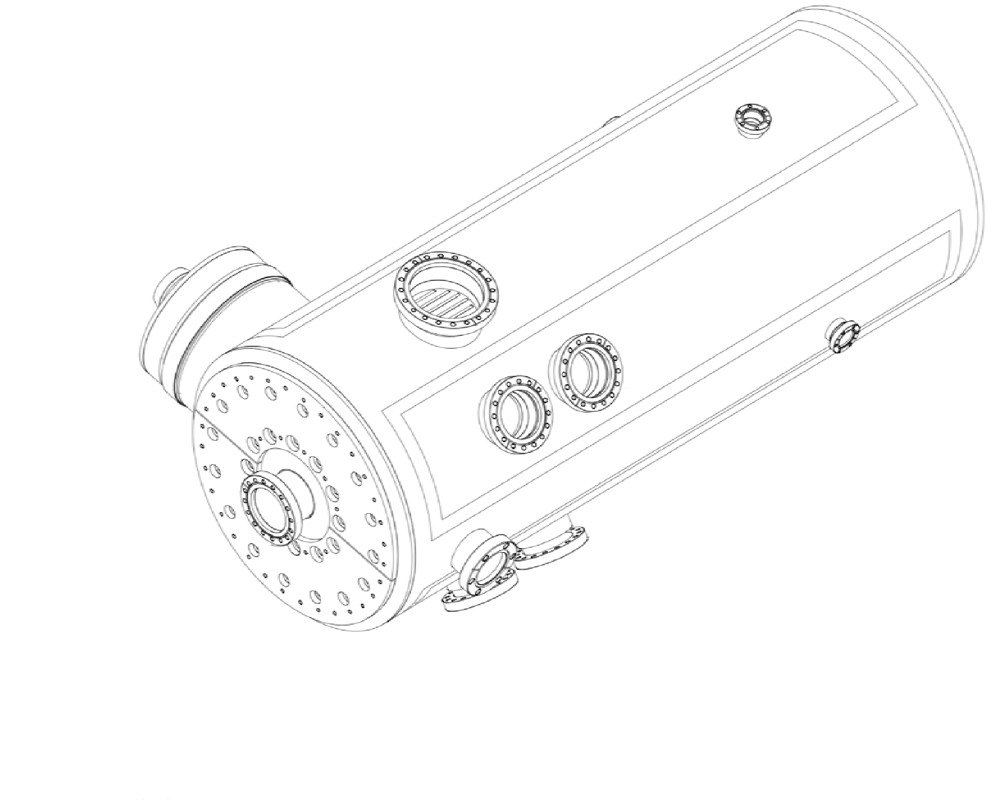


Fig 8.9: 3D view of RF cavity

8.3.2.5 Instrumentation

Instrumentation needs for the Recycler Ring can be broken down into three types of systems:

- Position (orbit) measurements: BPMs and multiwires
- Intensity measurements: DCCT and toroids
- Dampers

All of these systems need significant upgrades for the NOνA era.

8.3.2.5.1 BPMs

The current Recycler Ring BPM system uses resonant pickups and electronics at 2.5 MHz. We will upgrade to a 53 MHz system, modeled on the Main Injector BPM system [5]. A detailed specifications document is available [10]. While the pickups work well at this frequency, the signal cables from the tunnel to the service buildings do not. We need to pull new cables and purchase the associated transition boards for each BPM (216 in total) and reuse the existing EchoTek digitizers.

Signal to noise ratio is an important element of the performance of the system. The new BPM system will have no active elements in the tunnel, so the noise figure of the system will be dominated by the cable going from the BPM pickups to the upstairs electronics. We know from the MI experience that a Heliax type cable performs acceptably, even in the noisy environment of MI 60 (near the MI RF cavities).

We are considering 3 different heliax cables, differing in diameter. They are:

1. Andrew LDF1-50 (1/4 in. foam dielectric)
2. Andrew LDF2-50 (3/8 in. foam dielectric)
3. Andrew LDF4-50A (1/2 in. foam dielectric)

Table 8.7 contains a summary of cable information, including cost, for these three cables.

	Cost ($/foot) (for quantities of 100,000 ft)	Attenuation at 50 MHz (dB/100ft)	Best Case Attenuation	Worst Case Attenuation
LDF1-50	$0.66	0.953	1.43 dB	12.4 dB
LDF2-50		0.736	1.10 dB	9.6 dB
LDF4-50A	$1.29	0.479	0.72 dB	6.25 dB

Table 8.7: Summary of cable information. The best case attenuation is for the shortest cable run (150 ft). The worst case attenuation is for the longest cable run (1304 ft).

The total length required for all the BPM pickups, including transfer lines, is 275,142 ft, with a longest cable run of 1304 ft and a shortest cable run of 104 ft. We have performed the calculation of signal strength for 1e10 protons at 8 GeV in a 19 nanosecond Gaussian bunch. In this situation, a signal attenuation of 12 dB (the worst case in Table 8.7) is acceptable. Considering just signal strength, we believe we can use the LDF1-50 cable throughout the ring.

As stated above, the MI 60 region in the tunnel is the location of the MI RF cavities, so there are significant sources of 53 MHz noise. The larger diameter cable (LDF4-50A ½ in. diameter heliax) does have better noise rejection. The MI BPM system uses a similar ½ in heliax cable in this region of the tunnel. Based on recommendations from the Main Injector BPM project personnel, we will use the larger diameter cable for this region (1/6th of the ring) and the LDF1-50 ¼ in. diameter cable elsewhere.

With this amount of additional cable, we have investigated penetrations and cable tray space. We will need to make use of the service building kicker room penetrations, which are available at each service building.

For position measurements in the transfer lines, we will have both BPMs and multiwires. We will be moving the physical BPMs and multiwires from the current transfer lines to the new transfer lines and pull new cables for both types of instrument.

8.3.2.5.2 Intensity measurements

We will install a new DCCT for the Recycler Ring. We are currently investigating with the Instrumentation Department the choice between a commercial product (the Recycler currently has a Bergoz DCCT) or an in house design (like the Main Injector DCCT). In the RLS, we have costed for the purchase and installation of a commercial DCCT. It is estimated that an in house design will be similar in cost. For the transfer lines, we will move existing Pearson toroids.

8.3.2.5.3 Dampers

We anticipate that we will need both longitudinal and transverse dampers at the intensity of 6e13 protons. For the longitudinal system, we believe that the current pickups, kickers, and power amplifiers are adequate for our needs. For the transverse systems, the pickups and kickers are adequate but we will need to purchase 5 additional power amplifiers. This is what is included in the resource loaded schedule.

8.3.3 Kicker Systems

8.3.3.1 Overview

There are five new kicker systems for this project (see Table 8.8). A new pulser and magnet design are required to inject protons into the Recycler Ring (RR). Another new kicker system is required to remove unwanted beam in the injection gap just before injection. This Gap Clearing System will first be installed in the Main Injector for the remainder of the Collider Run and then moved to the RR as part of the ANU Project. Next, a new pulser and new magnets are required to extract the entire Recycler beam to the Main Injector. Another new pulser and new magnets are required at the other end of that transfer line to inject the beam. Finally, a new pulser and new magnet are required for aborting beam in Recycler. The first two systems are similar and will share the same design. The last three are also similar and will share the same pulser design and an updated magnet design. The two different types of systems will be described in general with a specific table to show differences.

System Name	Location	Total Field (G•m)	Field Rise Time (ns)	Field Flattop (ns)	Flattop Stability	Field Fall Time (ns)	Post Kick Stability
Recycler Injection	RR104	360	57 (3 bkt)	1534 (81 bkt)	±3%	57	±3%
Recycler Gap Clearing	RR400	350	57	1534	±4%	57	±3%
Recycler Abort	RR400	320	1650 (86 bkt)	9510 (502 bkt)	±4%	n/a	n/a
Recycler Extraction	RR232	510	1650	9510	±3%	n/a	n/a
MI Injection	MI309	370	1650	9510	±3%	1650	±3%

Table 8.8: Kicker Specifications from NOvA Document #1596

The first system, Recycler Injection, in Table 8.8 has a fast rise and fall time to cleanly inject an incoming bunch train of protons. The rise time is required to be no more than 3 RF buckets to allow for loading beam from Booster into the Recycler. The flattop has to be no less than 81 RF buckets (1 batch), which is the pulse train length from Booster. The fall time has to be no more than 3 RF buckers so that on the last 6 injections of the slip stacked beam, the existing, circulating beam will not be kicked. This system operates at the Booster repetition rate of 15 Hz, but in a train of 12 injections over a minimum of 1.33 seconds. It must also be thermally stable over time and different Recycler operating modes.

The function of the next system, gap clearing, is to clean beam out of the injection gap which arises from losses in the slip stacking process. This unwanted beam is kicked into the abort line just before the next injection into the Recycler, so it operates in unison with the Recycler Injection kicker. Without this gap clearing kicker, some beam will be kicked into magnets downstream of the Recycler Injection kicker when the next batch is injected. Larger variation on the flattop is allowed because the beam is being dumped, but the tail must remain low to avoid kicking the circulating beam.

The specifications for these two systems require a new kicker magnet design and modification of an existing kicker power supply design. Building prototypes to prove the performance of these systems is mandatory and is planned. This necessary step increases the time before a finished system is ready to install.

The next three systems in Table 8.8 (RR abort, RR extraction, and MI injection) all have a rise time associated with the abort gap in each machine, which is approximately 1/7 of the circumference. The flat top for all has to be long enough to fully extract 6 batches. Only the MI injection kicker has a fall time constraint to avoid kicking the leading bunches of the beam as they come around after injection.

For these three systems, we can make use of an existing kicker magnet design (the current RR extraction kicker). Because of time and personnel constraints during the shutdown, existing magnets will not be removed, refurbished and re-installed, instead new magnets are required to be built. A few modifications to update and improve the design will be done. A prototype magnet with these changes will also be built to verify performance. The shape of the falling edge and post flattop are especially important. A new power supply to meet the specifications for all three of these kicker systems needs to be built. This will be based on an existing power supply so only minor changes will be made. A new charging supply is required to be prototyped for this system however.

Finally, almost all of the existing kicker magnets in the Fermilab complex are built using a ceramic chamber to provide the required level of vacuum. This chamber is installed between the magnetic material and the proton beam, which has several tradeoffs. The magnet itself does not need to be vacuum certified. This greatly simplifies the constraints on materials to 1) provide high voltage insulation, 2) to provide high voltage capacitance and 3) for the magnetic material itself. The ceramic chamber itself can also be used to support beam current return paths to lower the transverse and longitudinal impedance of the magnet. The tradeoff is that a vacuum tight ceramic chamber must be made. Like the development of a new magnet, long lead times are required and prototyping at various stages is required. For this reason, an existing chamber design and end flange design have been chosen. This decision has made the magnet aperture larger than beam physics requirements for the Recycler kickers. Details on all the kicker systems follow.

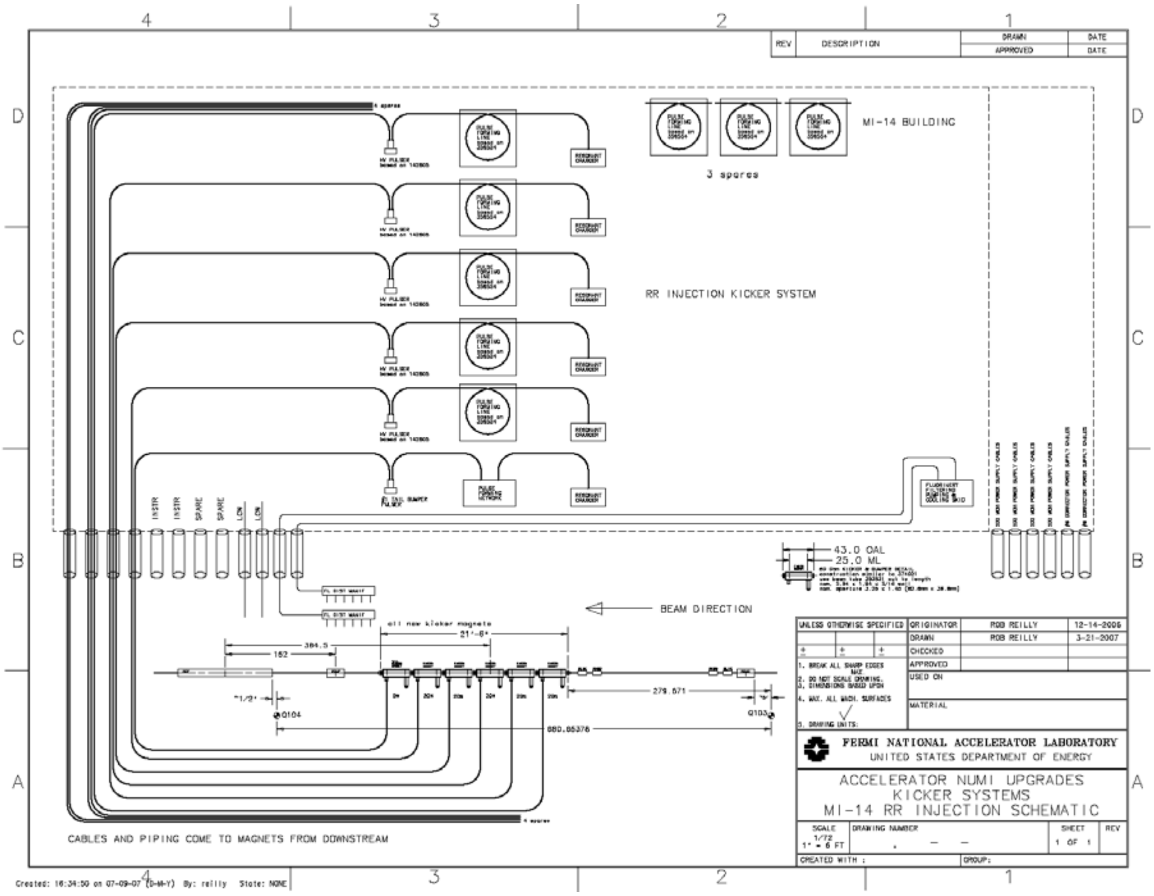


Fig 8.10: Proposed layout of RR injection kicker. Schematic includes location of magnets in the tunnel, cabling, penetrations used, and fluorinert cooling.

8.3.3.1.1 Recycler Injection and Gap Clearing Systems

A new and faster injection kicker system is needed to perform 12 batch slip stacking in the Recycler. The existing Main Injector Injection kicker design is capable of slip stacking 11 batches but studies have shown that several bunches were kicked out of the MI because of the kicker tail. The specifications required to perform the 12 batch injection are shown in Table 8.9 along with the measurements for other existing fast kickers. The new Recycler Injection kicker has approximately the same beam aperture as the existing MI Injection kicker, however the direction of the field is vertical instead of horizontal.

The Recycler injector kicker system will be built on the model of these previous fast kicker magnets. It will have a magnetic aperture of 53 mm x 107 mm (to meet the beam aperture of 33 mm x 81 mm) [11], a fill time of 34 ns, a pulser voltage rise time (1% to 99%) of a little less than 23 ns and a Z_0 of 50 ohms. With these design parameters, the magnetic length is limited to 0.7 meters with a physical length per magnet of 1.1m. This magnet will have a nominal B field of 113 Gauss with a nominal current of 450 and a maximum current of 550 A. In order to get the required 360 G•m, we will need a magnetic length of more than 3.2 m and thus we propose a 5 magnet and pulser system to give substantial tuning range for the main deflection. The additional margin in integrated field may be reduced after the prototype magnet has been built. Reducing the magnetic length may be required to meet the magnetic field rise time specification.

The magnets for the kicker are transmission line style and are terminated with slightly less than the characteristic impedance to give a flat pulse shape. Because the system will be running at a variety of average repetition rates, the affect of average power on the termination resistor value has to be less than ~2%. This has been done successfully on two previous systems including recently the MI Injection kicker. An electrically insulating oil, Fluorinert®, is temperature regulated and pumped through these resistors.

This system is expected to need a “bumper” system to cancel the tail and allow the system to meet the fall time requirement to the 3% level. The bumper system will have a prototyping stage for the power supply. It will use the same magnet as the main kick however the orientation will be reversed so that the kick direction can be made to cancel. The requirements for the bumper power supply are generally known from existing measurements. This power supply is required to reduce the amount of field variation to the 3% level and is especially needed to meet the fall time requirements.

The fall time corrector is necessary to reduce the tail to the ~3% level in the required 57 ns. The same style magnet will be used with these bumper power supplies and installed with the main magnets because the peak current of the tail bumper is roughly the same as the main power supply. The bumper magnets will need to be installed upside down to provide a canceling field for the same polarity of charging and pulser supply. There are subtle polarity issues on the thyratron switch, which is used for the main pulse and bumper pulse, which cause a change in waveform with a different polarity. A proposed layout, including cabling, penetrations from the MI 14 service building, and cooling piping is shown in

Fig 8.10

8.3.3.1.2 Magnet Design

Several fast kicker magnets have been built over the years. Existing designs and their rough capabilities are shown in Table 8.9. The MI injection kicker magnet design is over 10 years old and Booster kicker magnet is over 20 years old. Some improvements can be applied to these to improve response. The Tev injection kicker magnet has most of the improvements incorporated into it.

Magnet Type	Electrical Impedance (Ohm)	Total Inductance (nH)	Propagation Time	Field Rise (ns)	Nominal Field (mT)	Magnetic Height x Width (cm)	Magnetic Length (m)
Booster Kicker	50 Ohm	1250 nH	27 ns	~ 35ns	10	7.3 cm x 7.0 cm	1.08 m
MI Injection	25 Ohm	710 nH	28 ns	~ 50 ns	6.8	11.1 cm x 6.3 cm	0.79 m
Tev Injection	12.5 Ohm	860 nH	70 ns	84 ns	52	4.8 cm x 7.4 cm	0.86 m
NEW RR Injection	50 Ohm	1600 nH	34 ns	57 ns	11.3	5.1 cm x 11.0 cm	0.64 m

Table 8.9: Comparing Existing Kicker Magnet Parameters to New Design. Note that the Tev Injection kicker magnet is driven by a positive and negative power supply to further decrease the field rise time. This should not be necessary for this application.

The Recycler Injection magnet will need distributed capacitance. The same potting material that is required for insulating the high voltage bus will be used for making the high voltage capacitors. This has been done in both the Booster and MI kickers with success, but the capacitance required here is about twice as much per unit length. Simulation of the magnet parameters is being done. A prototype design of the magnet will be built and then the propagation time and impedance will be measured. The prototype will also be pulsed at maximum voltage to determine if there are any major issues.

The magnet design for the gap clearing kicker will be an exact duplicate of the Recycler Injection magnet. The first production magnets will be installed in the Main Injector for gap clearing in the current Collider Run. After the end of the Collider Run, these magnets will be moved from the MI and installed in the Recycler at the same lattice location. The magnetic requirements are exactly the same so no further prototyping will be required and the spares can be shared between systems.

8.3.3.1.3 Main Pulser Design

A fast pulser design was done several years ago for the Tevatron injection kickers (see Fig 8.11)

Originally the pulser was designed to drive a 12.5 Ohm load, but it has been tested with a 25 Ohm and 50 Ohm load. The rise time at higher resistance (lower current) is faster and may be fast enough to meet the requirements for NOνA. Additional work is being done to further reduce the rise time by using saturating magnet materials (ferrite) in order to have a safety margin in the rise time. This shows good promise (Fig 8.12). The ferrite can be seen to reduce the rise time to about 8ns. More work and prototyping are required to determine the source of the overshoot. A little overshoot is in fact helpful in reducing the field rise time, but it must be damped fast enough The mechanical design of the pulser also needs some changes to incorporate the ferrite material in a reliable manner. The pulser has not been able to be pulsed at the 15 Hz repetition rate due to lack of a load cooling system but one is being built for prototype use.

One other design decision to be done is the cable type for the pulse forming line. Two variations are available, both with the required voltage and impedance. The newer style cable has 2/3 the loss factor. This may be critical in meeting the fall time requirement as the dispersive losses in the cable lead to a longer fall time than rise time and even a slightly faster fall time may ease the requirement of the bumper pulser. Testing of the new cable for fall time has begun but the result is difficult to separate from pulser rise time. The cable will need to be tested again when most of the changes to the prototype pulser have been completed.

The pulsers for the Gap Clearing system will also be identical to the Recycler Injection kicker. The slightly higher flattop ripple allowed does not impact the design of the pulser and bumper. The post flattop amplitude remains the same as the Recycler Injection system so the bumper is still required.

8.3.3.1.4 Bumper Pulser Design

The tail correcting bumper will consist of the same pulser and controls as the main pulser, however a pulse forming network (PFN) will be used in place of the pulse forming line (PFL, cable). The tail falls to ~ 20% of the main pulse after 25 ns. Because there are five main magnets and pulsers to get the total kick, the bumper corrector has to supply ~ 100% of the single main pulser current. The tail correcting bumper needs to have the same peak voltage and current as the main pulser and so will have the same switch and controls. The initial fall can be approximated by several RC sections to match the fall time of the pulse forming network for the tail correcting bumper.

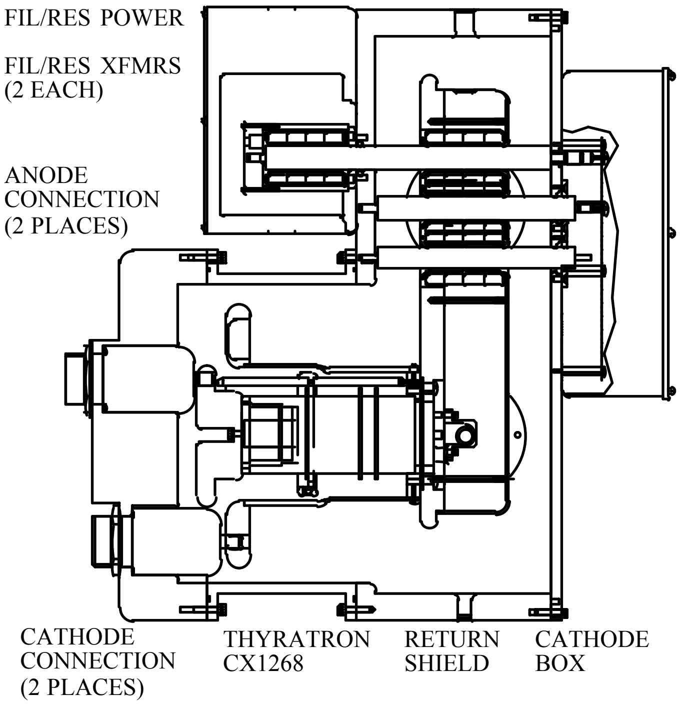


Fig 8.11: Tevatron Injection Kicker Fast Pulser

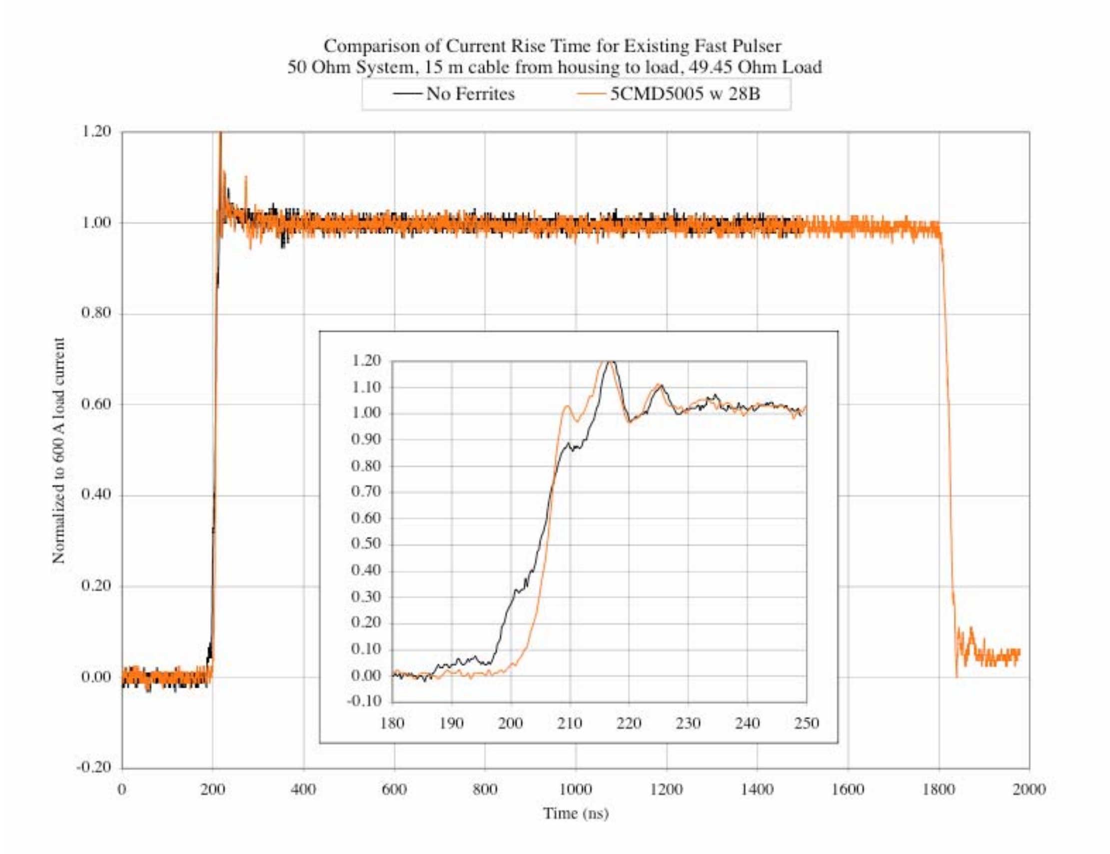


Fig 8.12: Measured Pulse Response of Prototype Pulser. The black trace is a measurement without the ferrite compensation; the orange trace is a measurement with the ferrite compensation. Note the improved rise time in the second case.

8.3.3.1.5 RR Abort, RR Extraction and MI Injection Kicker Systems

These three kicker systems will require a long pulse (~9.5usec) with a fairly long rise time (~1.6usec). We propose updating the design of the existing 25 ohm Recycler transmission line magnets currently in use for the transfer lines with a 1.6 μsec flat top. Each magnet has an insertion length of 1.8 meters (70 inches) and a magnetic length of 1.4 meters (54 inches). The magnet aperture of the new kicker magnets is again 53 mm x 107 mm to meet the beam aperture of 33 mm x 81 mm.

The power supply for these three kickers requires a fairly long pulse and so a pulse forming network is usually used. The existing NuMI kicker uses a PFN to provide a 5000 A pulse into a pair of 10 Ohm magnets in parallel. Because only 1000 A are required for these kickers, it is actually more cost effective to use a long pulse forming line. Six spools of cable will be spliced end to end to provide the required pulse length, and six other spools are required in parallel to provide the correct impedance. An important technical reason for using the cable is that the falling edge for a cable is monotonic and somewhat faster than for a matched PFN. This is important for the MI injection kicker.

The magnets for these kicker systems will not have the load termination installed on them. The termination will be in the same service building as the power supply. This is possible because of the fairly fast field rise time of the magnets used in comparison to the requirement. Because the Recycler extraction has a much larger total field, two magnets will be wired in series.

A tail bumper will be needed for the MI injection kicker and thus is planned and costed in the schedule. The tail bumper will use the same concept as the Recycler Injection system; however the pulser will need to have different component values for the PFN. The system is shown in Fig 8.13.

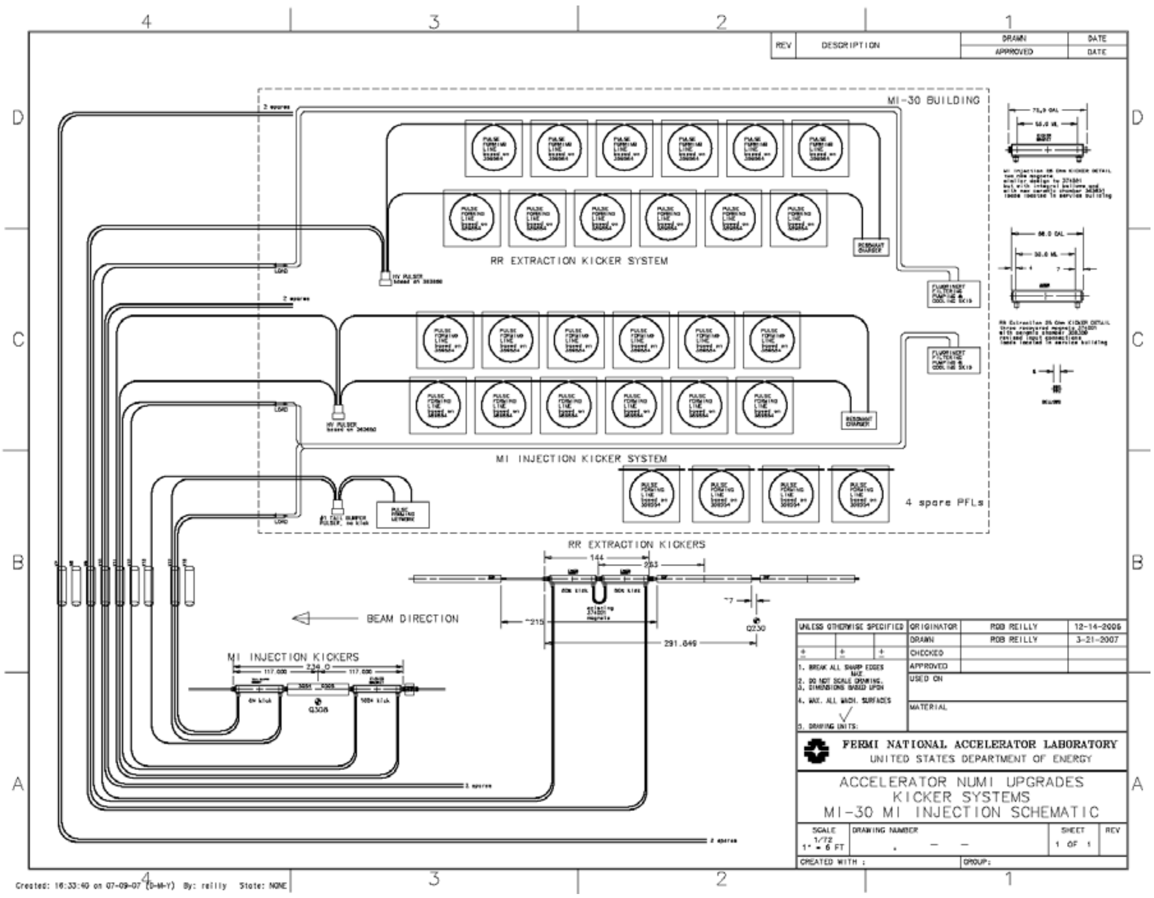


Fig 8.13: Proposed layout of MI 30 injection kicker. Schematic includes location of magnets in the tunnel, cabling, penetrations used, and Fluorinert cooling

All of the kicker systems will need active cooling. Existing Main Injector kickers use an active Fluorinert® cooling for load temperature control. We will make use of these existing designs for the new kicker systems.

8.3.3.1.6 Main Pulser Supply

The main pulser for these systems will consist of controls, a charging supply, a thyratron enclosure and a pulse forming line. The controls will be the same across all kicker systems. A new charging supply will be required. The design has the pulse forming line resonantly charged about 2 msec before the kicker is fired to transfer beam. A new charging system will be prototyped for this application. Resonant charging is used to limit the possibility of the thyratron switch self triggering. It also allows the use of a combination of a readily available commercial charging supply and transformer for improved reliability and overall cost.

The pulse forming line will consist of an improved RG-220 cable made to Fermi specifications. This cable has been used reliably for many years at these voltage levels.

The cable is only available in continuous lengths of up to about 200 m. A total length of approximately 1000 m is required to get the full pulse length. Two of these lengths are then connected in parallel to get the nominal current at the voltage where the cable and switch will operate reliably. The splice required for this is based on existing commercial connector design. Prototypes have been ordered and are being tested.

The switch enclosure will be very similar to the Recycler Injection and Gap Clearing kicker. Minor changes will be done so that a larger voltage and current thyratron can be used. Pulse sharpening will not be needed for this pulser.

8.3.4 Cooling System Modifications

Modifications to the Recycler will affect three Low Conductivity Water (LCW) cooling systems: the Main Injector global LCW system, the RF (95 degree) LCW system and the Cavity (55 degree) LCW cooling systems located at MI-60. Work affecting these cooling systems is occurring in the Q-100 region (Injection Line), Q-300 region (Extraction Line), Q-400 region (Abort Line), and Q-600 region (RF Cavities). Work on cooling needs for the associated power supplies in the service buildings is occurring in MI-14, 30, 39, and 60 Service Buildings.

It is currently assumed that the majority of the Main Injector Cooling Systems will have sufficient capacity for increased loads due to the Recycler modifications. However, there are extensive modifications planned in the Q-100 region, where a new Injection Line will be added. This is an area already running at capacity, both for heat load and pressure & flow capabilities. Additional loads may push the need for the installation of an LCW Pump Room at MI-8 (originally planned for the MI installation, but never installed). This would add about 600 kW of cooling capacity and 450gpm of flow. Therefore, this estimate also covers studying this solution, and the impact of such on the overall operation of the Recycler Cooling Systems.

Additionally, all added heat loads eventually reach the cooling ponds. Studies conducted in the Fall of 2006 [12] suggest that current pond capacities are sufficient for the estimated heat loads. However, the ponds will see an increase in operating temperatures of around 1°F. Further work is required to identify and verify all additional heat load changes with the expected 700 kW operation conditions, compare with current operational conditions, and repeat modeling of the resulting pond water temperatures.

Details on all these system upgrades follow.

8.3.4.1 Injection Line

This work consists of the relocation and reconnection of pipe and bus for magnets in the Q-100 area. In addition, lines are installed from the Q100 tunnel area into the MI-14 service building, where the connections to new Fluorinert® skids and power supplies will be made.

8.3.4.2 Extraction Line

This work consists of the relocation and reconnection of pipe and bus for magnets in the Q-300 area. Additional lines are installed in the MI-30 service building, where connections to new Fluorinert® skids and power supplies are made.

8.3.4.3 Abort Line

This work consists of the relocation and reconnection of pipe and bus for magnets in the Q-400 area. In addition, lines are installed from the Q-400 tunnel area into the MI-39 service building, where connections to new Fluorinert® skids and power supplies are made.

8.3.4.4 RF Cavities

This work consists of the relocation and reconnection of LCW lines to magnets and cavities in the Q600 through Q609 region, as well as the installation of additional pipe drops for the new cavities. Likewise, there will be additional pipe drops installed in the MI-60 gallery to supply LCW to new power supplies. This work will be performed on both the RF (95°F) and Cavity (55°F) LCW Systems, which have the main components located in the MI-60 Pump Room.

Both the Main Injector and Recycler lines are adding RF cavities in the region. At this time it is thought that the capacity of both the 95°F and 55°F systems is adequate for all additional RF cavities. This will be verified as part of the engineering design process.

8.3.4.5 MI-8 Pump Room

Such a pump room was initially planned with the construction of the Main Injector. Because of this, the building floor space already exists for the installation of this pumping facility, as does the piping to the MI-8 beam line LCW headers, pond water lines to PV-9 and Pond H, and substantial basic electrical service to the room. Also, 100 Hp LCW pumps were procured as part of the MI build package, and are sitting as spares, ready for use.

It must be emphasized that at this time, it is not known whether or not the addition of this pump room is fully justified and required. Such determination will be made in the design reviews for the Recycler and Main Injector upgrades.

For the installation of the MI-8 Pump Room, the majority of component costs and installation efforts are fairly well known, hence the use of low contingencies on many tasks. The very notable exception to this is the Pond Water system to and from the MI-8 heat exchanger. Pond Pump Vault PV-9 was originally planned for this use, but has since been redirected and outfitted for supplying pond water to MI-62. It appears these lines may be already functioning at full capacity. The extent of the ability to adapt or upgrade PV-9 to also feed Pond Water to MI-8 is not known at this time, and will require engineering work, covered in the OPC BOE. This leads to 3 distinct scenarios:

1) we have to add larger pumps,
2) we need larger pumps plus either larger or new pond-to-vault lines, or
3) we need an entirely new vault, with new lines and pumps.

Further engineering is required to determine correct needs. To address this task with a reasonable accuracy, we have costed Scenario 2 and 100% contingency is used for both M&S and labor for PV-9 modifications.

8.3.5 Changes in the Recycler Upgrades Design since the CDR

We have made changes since the CDR in the following areas:

- Transfer lines
- Kicker specs
- BPM cable choice

The design changes have been driven by the desire to simplify the construction, installation, and operation of the Recycler Ring, thus applying value engineering and risk management.

8.3.5.1 Changes in transfer line design

We have made changes to both the injection and extraction line design. The main design change in the injection line is to move from a design with a series of 4 vertical bends to a design with 2 vertical bends. The change was driven by two considerations, (1) to simplify installation and (2) to minimize the number of powered elements near the Recycler Ring. The design presented in the CDR had 4 large powered dipoles (the ADCW listed in Table 8.4), one as the switcher magnet in MI8, two in the mid point of the line, and one near the injection area of the Recycler. By changing to two vertical bends, one being the switcher magnet and the second a permanent magnet dipole, we no longer have to support these multi-ton magnets between the floor and the ceiling (for the two in the mid point) or near the ceiling (for the one near the injection area), thus making the installation of the line simpler. In addition, we do not have the possible field effects of having a large ramped dipole magnet near the Recycler.

The main design change in the Extraction line is to move the injection point in the MI one half cell from the 309 location to the 308 location (with a corresponding move in the extraction point in the Recycler). This location is better for both aperture and phase advance reasons. With the MI injection kicker at 308, we can use the same ceramic beam tube and magnet for this kicker as we are using for the Recycler extraction and abort kickers, thus eliminating a separate design for both the ceramic beam tube and the magnet.

8.3.5.2 Changes in Kicker specifications

We have decided to accept 81 Booster bunches per Booster batch instead of 82. This change loosens the kicker rise/fall time specifications from 38 nsec to 57 nsec with ~1% loss of protons to the NuMI target. The change the MI injection location (discussed in Section 8.3.2.3 and Section 8.3.5.1) results in a change to the required aperture and integrated gradient.

Based on measurements on the MI 10 Injection Kicker, the kicker specifications were relaxed to 3% (from 1%) for flattop stability and post kick stability for the systems with the tighter requirements. Due to this change, the coarse bumper (flattop bumper) system can be removed from the project and still meet the ± 3% specs. This thus means that the RR Extraction system has no bumpers and the MI Injection, RR Injection and the Gap Clearing Systems all only have tail bumper systems.

The kicker systems will be able to meet ± 3%, and the damper system will simply improve upon this. However, this will mean that the tail bumper will not be able to be a hot spare, as it will be installed “upside down”. However, with a several hour shutdown, it could be reconfigured and used as a spare if necessary.

8.3.5.3 Changes in BPM cable choice

We have completed the Recycler BPM specification, which allowed a detailed cable specification to be written. We have narrowed down the cable choice based on these specifications and received new pricing information.

8.3.6 Remaining Design Work for the Recycler Upgrades

There is significant design work to do on the Recycler Ring modifications and kicker systems tasks. Most of what has been presented in previous sections represents the physics and preliminary designs for the different aspects of the project.

For the Recycler Ring modifications, we need to continue and complete the detailed engineering design work for the injection line, extraction line, and RR30 straight installations. The work spans the range from individual stand designs for magnets to the installation plan for each beamline. These design tasks are included in the project schedule, e.g., the installation planning tasks are a series of tasks in WBS 2.0.1.1.1.14, including resources and M&S costs. There is a similar set of work for the 53 MHz RF system.

The kicker systems have an extensive R&D and prototyping program that has already begun. The R&D work includes the magnet design, the primary and bumper power supply design, and the Fluorinert® cooling system design. In addition, there is detailed installation design in the accelerator enclosures.

Changes to the water cooling systems are still at the conceptual level. Further work is required to verify and identify the total heat loads with the 700 kW operating conditions, to compare with current operating conditions, and to model the cooling pond water temperatures.

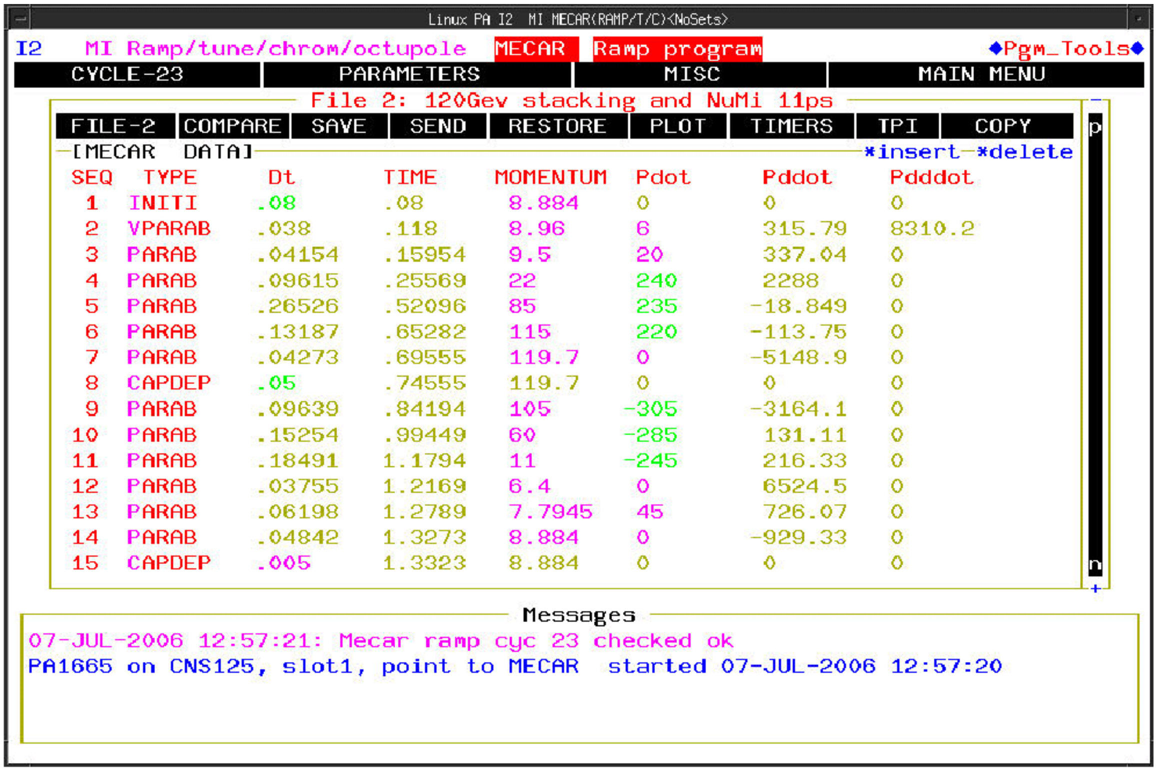
8.4 Main Injector (MI) Upgrades

8.4.1 Overview

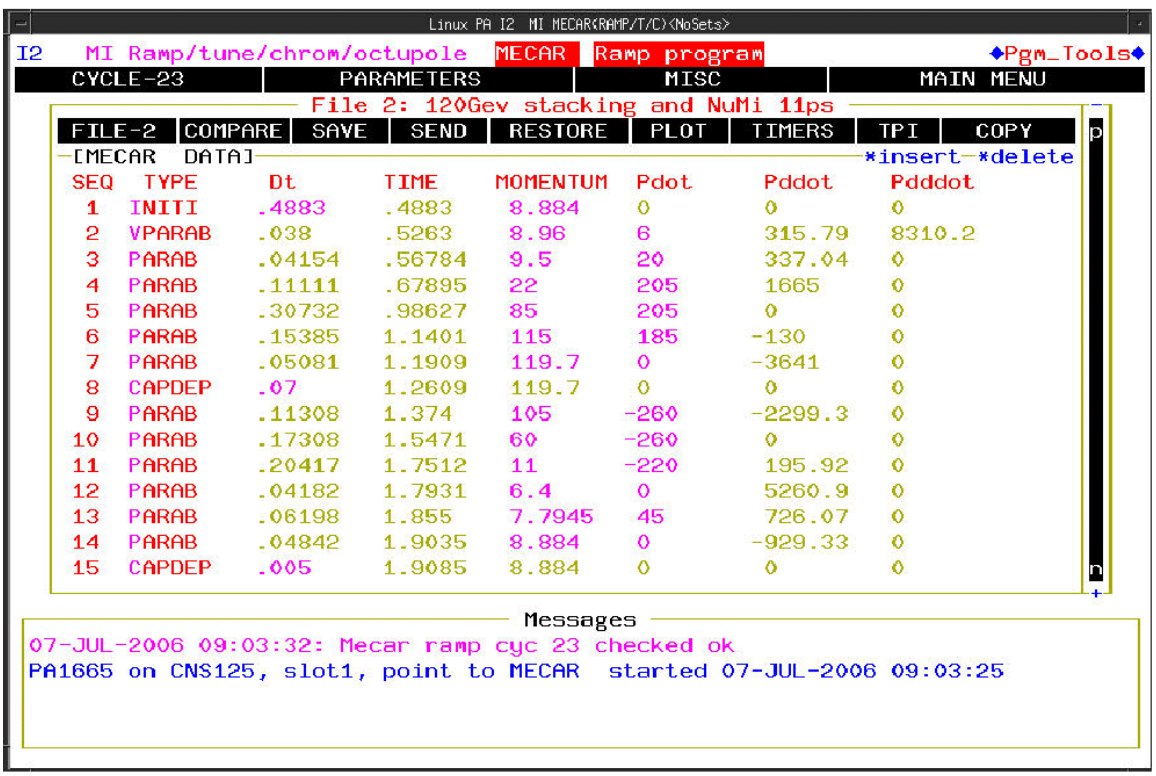
For NOvA the Main Injector will be accelerating only 10% more proton intensity as in the Proton Plan (4.9E13 ppp instead of 4.5E13 ppp). The beam power out of Main Injector is much larger (705 KW instead of 392 KW) mainly because the cycle time is reduced from 2.2 sec to 1.33 sec. By using the Recycler Ring for stacking, the Main Injector cycle time is reduced to 1.5 sec increasing the beam power from 392 KW to 628 KW (a factor of 1.47 because of the cycle reduction and a factor of 1.09 because of the intensity increase). To further decrease the Main Injector to 1.33 sec and thus increasing the power to 705 KW we will need to increase the maximum acceleration rate from 204 GeV/sec to 240 GeV/sec. In order to accommodate the faster ramp, one of the quad power supplies needs to be upgraded and two extra RF stations need to be added.

8.4.2 Modifications

In order to reduce the Main Injector 120 GeV cycle time to 1.33 sec, the maximum acceleration rate has to be increased from 205 GeV/sec to 240 GeV/sec. The current 120 GeV ramp used for the mixed mode Slip stacking and NuMI along with the NOvA era proposed ramp is shown in Fig 8.14. The current Main Injector 120 GeV ramp has a 488 msec dwell at injection in order to accommodate the slip stacking for pbar stacking and five injections for NuMI. This dwell time is reduced to 80 msec for NOvA since we only have one injection per cycle from Recycler.



SEQ	TYPE	Dt	TIME	MOMENTUM	Pdot	Pddot	Pdddot
1	INITI	.08	.08	8.884	0	0	0
2	VPARAB	.038	.118	8.96	6	315.79	8310.2
3	PARAB	.04154	.15954	9.5	20	337.04	0
4	PARAB	.09615	.25569	22	240	2288	0
5	PARAB	.26526	.52096	85	235	-18.849	0
6	PARAB	.13187	.65282	115	220	-113.75	0
7	PARAB	.04273	.69555	119.7	0	-5148.9	0
8	CAPDEP	.05	.74555	119.7	0	0	0
9	PARAB	.09639	.84194	105	-305	-3164.1	0
10	PARAB	.15254	.99449	60	-285	131.11	0
11	PARAB	.18491	1.1794	11	-245	216.33	0
12	PARAB	.03755	1.2169	6.4	0	6524.5	0
13	PARAB	.06198	1.2789	7.7945	45	726.07	0
14	PARAB	.04842	1.3273	8.884	0	-929.33	0
15	CAPDEP	.005	1.3323	8.884	0	0	0



SEQ	TYPE	Dt	TIME	MOMENTUM	Pdot	Pddot	Pdddot
1	INITI	.4883	.4883	8.884	0	0	0
2	VPARAB	.038	.5263	8.96	6	315.79	8310.2
3	PARAB	.04154	.56784	9.5	20	337.04	0
4	PARAB	.11111	.67895	22	205	1665	0
5	PARAB	.30732	.98627	85	205	0	0
6	PARAB	.15385	1.1401	115	185	-130	0
7	PARAB	.05081	1.1909	119.7	0	-3641	0
8	CAPDEP	.07	1.2609	119.7	0	0	0
9	PARAB	.11308	1.374	105	-260	-2299.3	0
10	PARAB	.17308	1.5471	60	-260	0	0
11	PARAB	.20417	1.7512	11	-220	195.92	0
12	PARAB	.04182	1.7931	6.4	0	5260.9	0
13	PARAB	.06198	1.855	7.7945	45	726.07	0
14	PARAB	.04842	1.9035	8.884	0	-929.33	0
15	CAPDEP	.005	1.9085	8.884	0	0	0

Fig 8.14: Current 120 GeV Main Injector ramp (bottom) and NOvA ramp (top).

The voltages and currents for the Main Injector Bend and the two Quad Buses during the NOνA ramp are shown in Fig 8.15. The max voltage available in the main bending bus is 11.8 KV, while the voltage available for the horizontal and vertical quad busses is 3.2 and 2.8 KV respectively.

As can be seen from Fig 8.15, during the NOνA ramp we are going to exceed the maximum available voltage of the defocusing (vertical) bus. For this we propose to increase the available voltage at the defocusing bus by replacing one of the transformers with a higher voltage one and modifying the corresponding supply. These changes will make the available voltage from the defocusing bus equal to the focusing one.

The RMS current for the Main Injector dipoles and quads for the NOνA ramp has been calculated to be 4000 A and 1600 A respectively. These numbers are lower than the values of 5000 A and 2000 A that the Main Injector water-cooling system was designed to handle. For comparison the RMS current values for the present Main Injector $23 ramp are 3550 A and 1425 A.

The Low level RF (LLRF) is responsible for controlling the frequency(s) and phase of the RF that is applied to the beam. It accomplishes this control through physics models and feedback loops using phase and radial position detectors. The LLRF systems are also responsible for controlling beam transfers between accelerators and providing beam markers to the beam sync clock system which can be used to identify a specific bucket in the machine. Some of the services that the LLRF system provides are: paraphrase control, counter phasing, cogging, injection phase and bucket alignment, transition phase jump, and bunch rotation.

In comparison to the LLRF system, the high level RF system (HLRF) receives the RF signal from the LLRF system and is also responsible for applying the requested RF voltage to the beam. To accomplish this control, the HLRF system has a collection of curves that include: anode program for voltage, bias program for cavity tuning, and several gain curves to keep the stations linear. There are also feedback compensation that works on beam loading and anode program variations.

To slip stack protons in the Recycler Ring, a two RF group controller is needed that will interface with Booster for transfers into the machine and the Main Injector for extraction. Automated frequency and phase control are needed for each RF group. Transfer enable and revolution markers must be provided to the control system to synchronize kickers and instrumentation. In addition, beam and system diagnostics need to be available to the operators and studiers. The present Main Injector Low Level RF (LLRF) system provides all the same required functionality and we propose that a duplicate MI system be modified for the RR. The present Main Injector system can be modified to interface with the new RR system with minor modifications.

While the custom hardware for the new LLRF would be quite expensive to build from scratch, we plan to decommission the present RR and TeV LLRF system before proton stacking in the RR begins. Then the plan is to salvage the bulk of the required hardware to build both new operational and development crates. New custom cables and cable pulls will be needed. While a great deal of software will be reused, there will be a fair amount of software modification, testing and commissioning work to be done. The RR LLRF system is included in the MI Modifications WBS since it will be managed by this team. The Recycler HLRF will be managed by the recycler team and is described in Section 8.3.2.4.

Two new service buildings will be needed to house the kicker and beamline supplies named MI-14 and MI-39. Before those buildings can be used operationally the communications infrastructure needs to be build. This includes racks, controls hardware and communications cable. This work is included in this WBS.

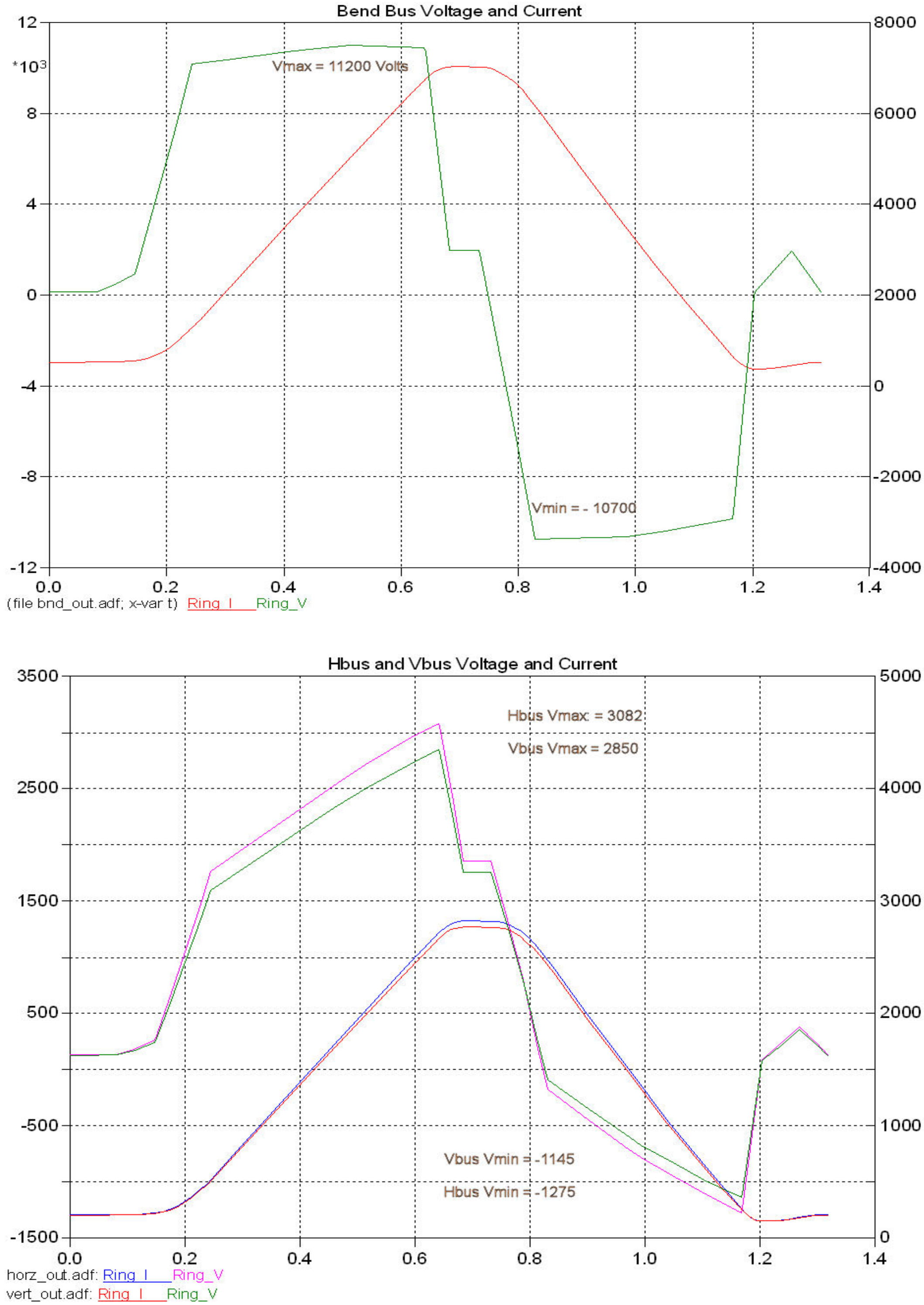


Fig 8.15: Voltages and currents for the bend bus (top) and the two quad busses (bottom) during the NOνA ramp.

The A1 line used for Pbar transfers from Main Injector to the Tevatron will not be used and needs to be decommissioned. In addition the three Lambertson magnets and the kicker used for the Pbar extraction in the Main Injector ring need to be removed since they represent aperture restrictions and are large sources of impedance. This work is included in this WBS.

8.4.3 RF Cavities

The current Main Injector RF system consists of 18 stations (RF cavities, power amplifiers, power supplies and ancillary systems) providing a maximum acceleration voltage of 235 KV and 175 KW per station. It has enough power to accelerate up to 5.5E13 protons with 240 GeV/sec.

The moving bucket area available after transition is a function of the acceleration rate and the maximum RF voltage available. For a fixed RF voltage and acceleration rate, the bucket area has a minimum at $\sqrt{3}$ times the transition energy. In the Main Injector we have found that we need a moving bucket area after transition of at least 1.8 eV-sec with slipped stacked beam in order to avoid beam losses. From Fig 8.16 we can see that with 18 RF stations we cannot produce a sufficiently large enough bucket area to efficiently accelerate slipped stacked beam faster than 240 GeV/sec. Since we have a total of three spare cavities we propose to install two extra cavities in Main Injector in order to have enough extra voltage for running with 240 GeV/sec reliably (even with a station down). A picture of an MI RF cavity is shown in Fig 8.17. The two cavities are going to be installed at the “phantom” locations 4A and 14A. Most of the utilities that we need are available and the penetrations exist in these locations. In the location 4A two barrier cavities are currently installed that will need to be removed, while in the location 14A we have the second harmonic (h=1176) cavity used for proton coalescing which will no longer be needed after the end of the collider program (Fig 8.18). In installing cavities at 4A and 14A, the cavities at 4 and 15 will need to be moved slightly to allow for this installation.

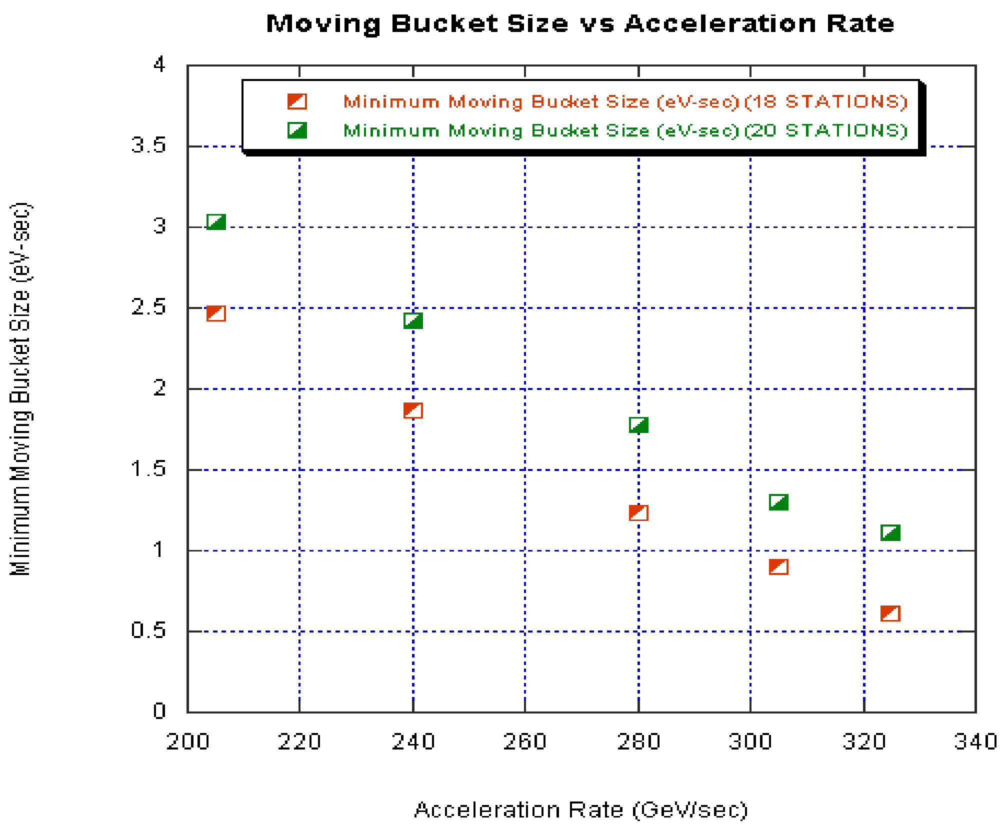


Fig 8.16: Minimum moving bucket area as a function of acceleration rate for 18, 20 RF stations.

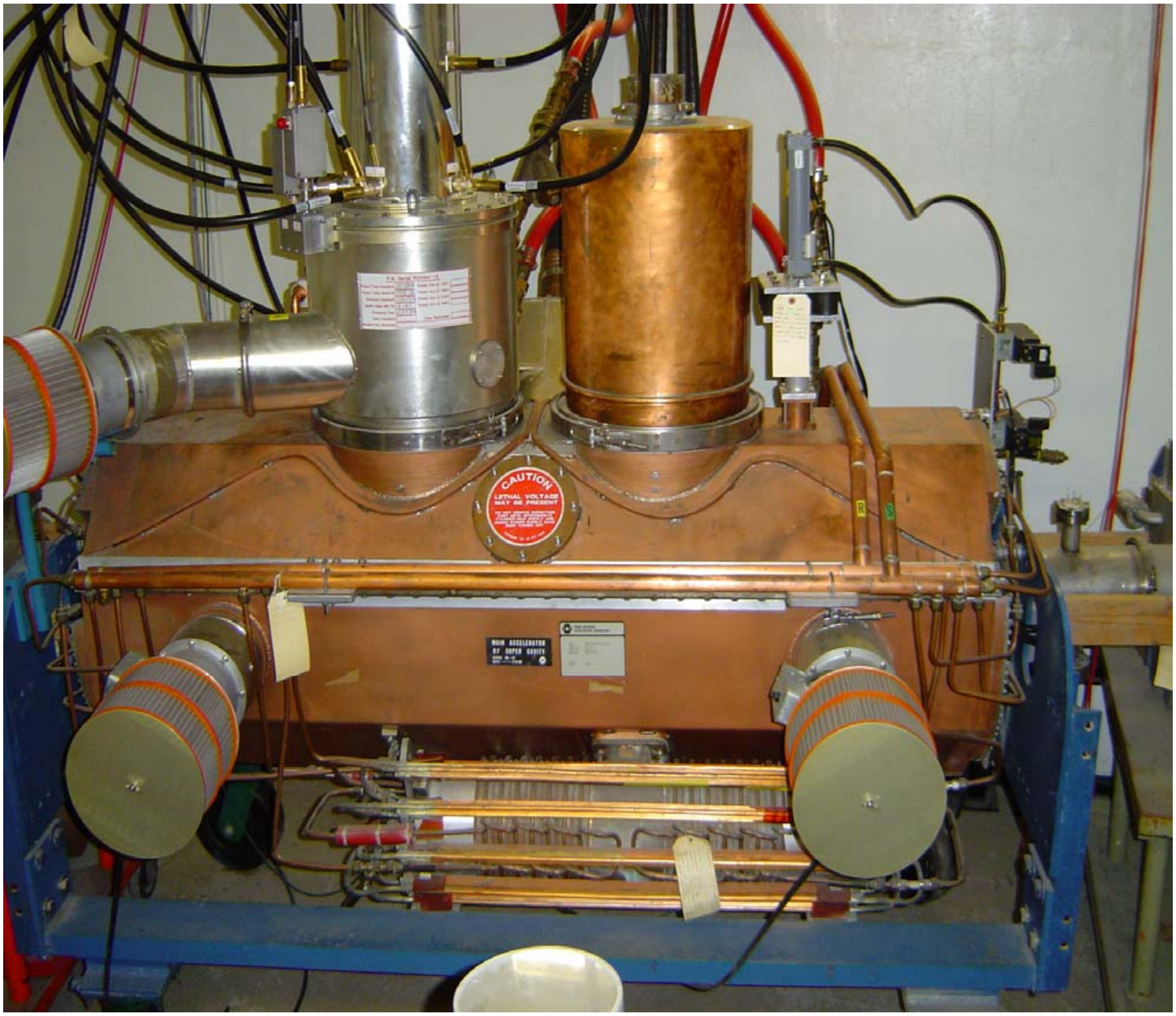


Fig 8.17: Picture of a MI RF Cavity. In front and under the cavity one of the cavity tuners can be seen. On the top of the cavity one can see the places of the two possible power tubes. Currently only one power tube is installed in each cavity (top left).

Fig 8.18: Pictures of the phantom locations where the two extra RF cavities will be installed. The location 4A is shown on top while the location 14A is shown in the bottom.

Two new modulators and two bias supplies will need to be fabricated. Those modulators and bias supplies are the same as the existing MI supplies. A picture of those supplies is shown in Fig 8.19.

Fig 8.19: Pictures of the series tube modulator supply (left) and the bias supply (right).

The spare cavities do not include the power amplifier tubes which need to be purchased and the whole assembly that houses the tube and attaches to the cavity needs to be manufactured. A picture of the power tube assembly is shown in Fig 8.20. The power amplifiers are driven by 8KW solid state drivers that are located upstairs in the gallery. Two extra solid state drivers will be needed for the two extra RF stations. The solid state amplifiers needed (eight 1KW modules for each station) will be recycled from the Tevatron but we will need to purchase the DC power supplies and the racks. A picture of a solid driver amplifier rack is shown in Fig 8.21.

Fig 8.20: Picture of the power tube assembly. We can see the matching section on top and the copper cooling lines. The power tube is located at the bottom of the assembly.

Fig 8.21: Pictures of a rack housing the solid state driver for an MI rf station.

The most challenging part of this job is the manufacturing and installation of the bus bars for the cavity tuners. Those bus bars are used to connect the bias supplies from the equipment gallery to the cavity tuners which are located next to the RF cavities in the tunnel. .The total length of the existing bus bars is 502" and, originally, they were comprised of two pieces welded together. The bus bars of the existing 18 RF stations were installed by using a support and installation fixture at the early stages of the MI-60 RF service building construction when there was no roof (Fig 8.22). In the present plan we will clamp together three 14' (168") pieces. This way we can install the whole bus bar through the penetrations without having to take part of the building's roof off. A picture of the proposed clamp assembly for the bus bars is shown in Fig 8.23.

Fig 8.22: Pictures of the original bus bar installation during the construction of the MI-60 building. In the top picture the whole bus bar can be seen hanging from the crane with a support, while in the bottom picture we can see the bus bar inside its fixture for installation.

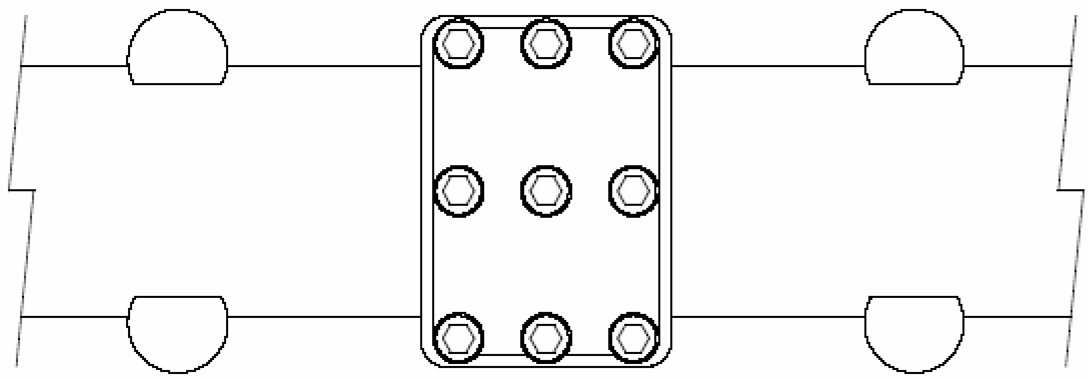


Fig 8.23: Drawing of the proposed clamp assembly for the MI bus bars.

8.4.4 Cooling system modifications

Cooling system modifications are required by the MI, RR, and NuMI. While modifications to RR and NuMI cooling systems are quite extensive, they are rather small in scope for the MI.

Cooling system modification considerations resulting from MI upgrades are primarily limited to two areas. The first is the increased heat load to the entire MI LCW system in general, due to changes in the MI cycling specifications. The second is the addition of kickers in the Q-600 region.

In general, the MI LCW system will see a global increase in heat load of around 25%. Hydraulically, the current systems can supply the required flows and pressures, since little of the MI equipment changes. Thermodynamically, this poses questions for the capacities of the Cooling Ponds. Pond Water Modeling already performed suggests that, when normalized for our operational conditions, a global heat load increase of 25% will result in a pond water rise of approximately 1°F [12].

The additional Kickers will require cooling water. The current RF (95°F) and Cavity (55°F) LCW Systems housed in the MI-60 Pump Room were initially built with sufficient capacity that they should easily accommodate these additional Kickers, both hydraulically and thermodynamically.

MI, RR, and NuMI cooling systems are all interrelated. Therefore, all Cooling Systems will go through Conceptual Design Reviews to assure good engineering practices are maintained, and any conflicting needs are addressed. Furthermore, capabilities for heat removal the Cooling Ponds will be further verified.

8.4.5 Changes in the MI Upgrades Design since the CDR.

The main change since the CDR is the optimization in the position of the MI collimators needed for the Proton Plan and NOvA. The final positions of those collimators that are scheduled to be installed the summer of 07 for Proton Plan are such that they do not interfere with the NOvA injection line from the Recycler to Main Injector. As a result no collimator moves need to be included in the MI Upgrades required for NOvA.

We have also a design for the manufacturing of the bus bars for the cavity tuners that greatly simplifies the installation and does not require the use of an external crane and removal of parts of the roof from the MI-60 building.

8.4.6 Remaining Design work for the MI Upgrades

The design of the bus bars for the two extra RF stations is expected to be finalized the summer of 07. The design of the RR low level RF system remains to be finalized. To the first order this design is expected to be very similar to the existing MI low level RF system since the expected functionality is the same. Even if the MI water cooling system was designed to handle the increase in heat load the realistic capacities of the cooling ponds need to be re-evaluated.

8.5 Radiation Safety for the Recycler and Main Injector

8.5.1 Overview

In this chapter, the radiological considerations for operation of the Recycler and Main Injector for NOvA are considered. The scope of the review includes the 8 GeV Transfer Line, the Recycler Ring, and the Main Injector. (The radiological concerns for the NuMI beamline are addressed separately in Section 8.6.6.) The analysis contained in this section is based on current requirements of the Fermilab Radiological Controls Manual. This section is considered preliminary; analysis and proposed solutions have not yet been fully reviewed or approved by laboratory safety professionals.

The radiological considerations for all of the above accelerators and beam lines have been considered extensively and are documented in shielding assessments conducted by the Accelerator Division and reviewed and approved by the ES&H Section. In all cases, the shielding assessment for each accelerator and each beam transfer line is used as a starting point in the evaluation which is to follow. Other measurements and verification data available are used where applicable.

The posting and entry control requirements for access to areas outside of beam enclosures where prompt radiation exposure may exist for normal and accident conditions are given in the Fermilab Radiological Controls Manual and are repeated here in Table 8.10 and Table 8.11, respectively. In some instances such as at a beam absorber or target hall, the normal condition may dominate or be equivalent to the worst case condition.

Dose Rate (DR) Under Normal Operating Conditions	Controls
DR < 0.05 mrem/hr	No precautions needed.
0.05 ≤ DR < 0.25 mrem/hr	Signs (CAUTION -- Controlled Area). No occupancy limits imposed.
0.25 ≤ DR < 5 mrem/hr	Signs (CAUTION -- Controlled Area) and minimal occupancy.
5 ≤ DR < 100 mrem/hr	Signs (CAUTION -- Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel.
100 ≤ DR < 500 mrem/hr	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no gates or doors are a permitted alternate. No beam-on access permitted.
DR≥ 500 mrem/hr	Prior approval of SRSO required with control measures specified on a case-by-case basis.

Table 8.10: Control of Accelerator/Beamline Areas for Prompt Radiation Under Normal Operating Conditions

Maximum Dose Equivalent (D) Expected in 1 hour	Controls
D < 1 mrem	No precautions needed.
1 ≤ D < 5 mrem	Signs (CAUTION -- Controlled Area). No occupancy limits imposed.
5 ≤ D < 100 mrem	Signs (CAUTION -- Radiation Area) and minimal occupancy. The Area RSO has the option of imposing additional controls in accordance with the guidance of Article 231 to ensure personnel entry control is maintained.
100 ≤ D < 500 mrem	Signs (DANGER -- High Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel.
500 ≤ D < 1000 mrem	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no gates or doors are a permitted alternate. No beam-on access permitted.
D ≥ 1000 mrem	Prior approval of SRSO required with control measures specified on a case-by-case basis.

Table 8.11: Control of Accelerator/Beamline Areas for Prompt Radiation Under Accident Conditions

The NOνA goal is to operate the NuMI target hall at 700 KW beam power or about 1.3E17 protons per hour. To accommodate such operation, the Accelerator Division Beam Permit must be considered. For the RR and the MI, the Beam Permit used by the Operations Department is set equal to the DOE approved Beam Safety Envelope. Additionally the AD ES&H Department has established an Operating Intensity Limit which is approximately 90% of the Beam Permit. The AD Operations Department imposes a Warning limit on the Operating Intensity Limit. The Warning Limit is the de facto upper level of beam intensity at which beam is operated. In the most conservative of cases, the net effect on the Beam Permit is that operations are conducted at about 80% of the Beam Permit. In evaluating the Accelerator complex then, it is necessary to consider the radiological implications of operating 120 GeV accelerators and beam transfer lines at 700KW/0.8 or 875 KW.

The beam intensity necessary to be evaluated for all accelerators and beam transfer lines for NOνA operation is thus 1.64E17 protons per hour. There is no consideration of additional beam power for other programs in this review. However, excess capacity is identified where it exists.

Note that there are a fair number of Radiation Safety Systems used in the present configuration of the Accelerator complex. The arrangement of these systems is designed to meet present operational requirements. The Radiation Safety Systems will need to be reviewed and may need to be reconfigured for NOνA. The configuration of the Radiation Safety Systems will require reevaluation, based upon the new programmatic goals and anticipated operating scenarios. Only minor changes are envisioned relating to radiation safety as sufficient earth shielding should be present over the MI 8 Line, Recycler and Main Injector. The MI shielding assessment will need to be updated for NOνA operation and labyrinths, penetrations, etc. will need to be revisited.

8.5.2 Machine Shielding Assessments

8.5.2.1 MI 8 Line

The MI 8 line shielding was evaluated as part of the 1998 MI shielding assessment [13]. The present Beam Permit limit for the MI8 line is 1.35E17 protons per hour. The limit for the MI8 line was set to meet programmatic goals of the time. The MI8 line was assessed beginning at cell body 803 through the injection region at MI 10. The MI 8 line shielding is equivalent to at least 24.5 feet throughout the entire length. The magnet to ceiling height in the MI 8 line is about 3 feet through the sections 803 to 810 and about 6 feet for the remainder of the line.

Table 8.12 shows the required amount of shielding considering the line for unlimited occupancy. Thus the MI 8 line is adequately shielded for 700 KW (NOνA).

energy	intensity	cycle time (sec)	component to ceiling distance
8	1.64E+17	3600	3
		Required shielding	23.3

Table 8.12: Shielding requirement for MI 8 line for 700 KW NOνA operations.

The Main Injector shielding assessment will need to be revised to allow sufficient 8 GeV beam intensity to support 700 KW NOνA operations. The nature of the revision work would be to apply the present shielding scaling methodology for analysis of 8 GeV shielding. It should be possible to establish a Beam Permit of up to 1.64×10^{17} protons per hour based upon the existing 24.5 feet of shielding over the MI8 line. Exit stairwells, labyrinths, drop hatches, and penetrations would also need to be re-examined to determine the whether any of them are more limiting than the earth berm shielding. The actual upper limit of the Beam Permit could be set based upon the most limiting feature of the MI8 line.

8.5.2.2 Recycler Ring

The Recycler Ring shielding assessment was originally conducted within the MI shielding assessment in 1998 [13]. The present intensity limit for the Recycler Ring is 1.2E16 protons per hour, so shielding assessment updates are required before NOνA operation can take place.

Table 8.13 shows the required shielding for a minimally-occupied, controlled area, the category under which the MI shielding was re-evaluated during an October 2004 shielding assessment [14].

energy	intensity	cycle time (sec)	component to ceiling distance
8	1.64E+17	3600	1
		Required shielding	23.9

Table 8.13: MI shielding requirement for Recycler Ring operation to support 700 KW NOνA operations for a minimally-occupied, controlled area

The shielding design requirement for the Main Injector was 24.5 feet; however, the as-built condition achieved was typically 26 feet. The Recycler Ring shielding should be sufficient if the MI shielding is evaluated as minimally-occupied, controlled area. Exit stairwells, labyrinths, drop hatches, and penetrations would also need to be re-examined to determine the whether any of them are more limiting than the earth berm shielding.

8.5.2.3 Main Injector

The Main Injector shielding assessment was reviewed and appended in October 2004 [14] in order to provide the incremental increase in beam power to support the NuMI project. In the October 2004 assessment, the MI shielding berm was evaluated primarily as a minimally-occupied, controlled area. A Safety Assessment of the MI berm included with the latest assessment concludes that Controlled Area posting is not required for minimally-occupied, controlled areas in accordance with the requirements of Article 236 of the FRCM [15]. Some regions of the MI have been posted as Controlled Areas as delineated in Article 236 of the FRCM.

There was some built-in conservatism identified in the 1998 Shielding Assessment, which has, to date, not been considered for the Main Injector. While the magnet to tunnel ceiling distance in the MI beam enclosure is typically 5.5 feet, the shielding was evaluated for a magnet to tunnel ceiling distance of 3 feet. The shielding requirement for 120 GeV operations at 700 KW (NOνA) considering the actual magnet to tunnel ceiling distance and unlimited occupancy requirements, is shown in Table 8.14.

energy	intensity	cycle time (sec)	component to ceiling distance
120	1.64E+17	3600	5.5
		Required shielding	24.4

Table 8.14: MI shielding requirement for 700 KW operations (NOνA)

The Main Injector shielding design was for a minimum of 24.5 feet. The typical as built shielding thickness achieved was 26 feet. From the forgoing, one may conclude that the shielding is sufficient for 700 KW operation of the Main Injector for NOνA.

The existing Main Injector shielding assessment (October 2004) will need to be revised for NOνA operation. Exit stairwells, labyrinths, drop hatches, and penetrations would also need to be re-examined, although no issues are foreseen.

8.5.3 *Surface Water, Ground Water, Air Activation, and Residual Activation*

The activation of surface water, ground water, and air are considered in this section. In general, the activation of air and water associated with the Accelerator complex is well understood. The levels of activation of air and water under present conditions, while measurable, do not approach any State or Federal limits. The levels of water and air activation can be expected to increase by the ratio of the beam power increase required for NOνA. The anticipated levels of water and air activation for NOνA should not pose any restrictions on operation of the Accelerator complex. The specific conditions are discussed below.

Residual activation of beam line components is an important consideration for a number of reasons. In general, as beam power increases the radiation dose to workers can be expected to increase. In addition, higher levels of activation can lead to reduced lifetime of accelerator components. The efforts to reduce residual activation are discussed in the following sections.

8.5.3.1 MI 8 Line

Groundwater was extensively reviewed for the MI project. Residual activation routinely found in the MI8 line is historically quite low. Ground water activation does not pose a limitation on NOνA operation.

Surface Water is routinely monitored in MI 8 Line sumps. Periodic sump sample results from MI8 line routinely show less than detectable radioactivity. Surface water resulting from operation of the MI 8 Line does not pose a limitation on NOνA operation

MI8 Line air activation in the MI8 Line has been monitored by the AD ES&H department. No significant activity has been detected. Air activation in the MI8 Line should not pose a limitation on NOνA operation.

Residual activity in the MI 8 Line has historically been quite low, residual activity levels in the MI 8 line (except at Booster extraction and MI injection) are quite low

Residual activation due to MI 8 line operation does not pose a limitation on NOνA operation.

A new beam collimation system has been designed and built for the MI8 line [16]. Radiological concerns for the collimation system have been addressed. Operation of the new collimation system in the MI 8 Line will not pose a limitation on NOνA operations.

8.5.3.2 Main Injector and Recycler Ring

Ground water was extensively reviewed during the Main Injector shielding assessment. Ground water activation does not pose a limitation on NOνA

Surface water is routinely monitored at 17 sump locations around the Main Injector. Tritium levels found in the sump water are typically less than the detection limit of 1 pCi/ml. Recently, a small number of samples have been found with 1 to 3 pCi/ml. Beginning in 2005, Main Injector sump discharges are being directed to controlled retention ponds and routinely monitored and managed. Main Injector surface water activation does not pose a limitation on NOνA operation.

Air activation has been monitored in the Main Injector by the AD ES&H Department. Beam losses are distributed around the Main Injector and no significant sources of air activation have been identified. Control of beam losses in the Recycler Ring and the Main Injector is the primary method available to control air activation. Air activation due to operation of the Recycler Ring and the Main Injector should not pose a limitation on NOνA operation.

Residual activation in the Main Injector is actively managed by Main Injector Department personnel. Loss points are determined in radiation surveys by department personnel. Orbit corrections or optics corrections are applied. Follow up radiation surveys are made and improvements in Main Injector residual activation levels have lead to dramatic reductions in residual activation in spite of increasing Main Injector beam power. Nevertheless radiation levels in those parts of the tunnel where work is scheduled, remain a concern. In order to effectively manage this issue the project will monitor the activation levels at these areas and will take measures to mitigate the problem. The measures chosen will depend on the anticipated activation levels and will include the following; designing the construction work flow and methodology so as to minimize the time required inside the tunnel, using lead blankets to protect workers from activated beamline elements, and if necessary removing activated elements from the tunnel during the construction work.

8.6 NuMI Upgrades

8.6.1 Overview

To meet its physics goals the NOνA experiment requires 6×10^{20} protons on target per year from the NuMI facility. As explained earlier, this proton delivery rate is accomplished with modifications to the Recycler Ring and upgrades to the Fermilab accelerator complex. For the NuMI facility this implies a faster cycle time of 1.33 seconds and modest increase in the protons per pulse on the target. The beam parameters for the original NuMI beamline design and for the NOνA/ANU upgrades are summarized in Table 8.15 which also includes beam parameters for the highest beam power and intensity achieved operationally as of August 2007. To handle the increase in beam power, up to 700 kW, the existing NuMI beamline requires upgrades beyond the original design capability of 400 kW

	Highest Power Operations*	Highest Intensity Operations†	NuMI Design	NOνA/ANU
Beam power to NuMI (kW)	315		400	700
MI intensity (ppp)	3.3×10^{13}	4.1×10^{13}	4.0×10^{13}	4.9×10^{13}
MI cycle time (seconds)	2		1.9	1.33
Spot size on target (mm RMS)	1.0	1.2	1.0 – 1.2	1.3
Protons/hr	5.9×10^{16}		7.3×10^{16}	13×10^{16}

Table 8.15: Comparison of the NuMI beam parameters during operations, for the original NuMI design and for the NOνA/ANU upgrades. (*The highest power was achieved on December 27, 2006 during an operations period without pbar stacking. †The highest intensity was achieved on February 22, 2007 during 11-batch slip stacking studies.)

The essential nature of the neutrino production process (see [17] for instance) is unchanged for the NuMI upgrades. The first step in the production of neutrinos is directing a beam of protons from Fermilab's Main Injector onto a production target. Interactions of the proton beam in the target produce mesons (mainly pions and kaons), which are focused toward the beam axis by two magnetic horns. The mesons then decay into muons and neutrinos during their flight through a long decay tunnel. A hadron absorber downstream of the decay tunnel removes the remaining protons and mesons from the beam. The muons are absorbed by the subsequent earth shield, while the neutrinos continue through to an experimental hall at Fermilab and onwards toward “far” detectors. A view of the NuMI tunnel is shown in Fig 8.24 and a schematic of the neutrino production process is shown Fig 8.25. More detail can be found in the NuMI Technical Design Handbook [19].

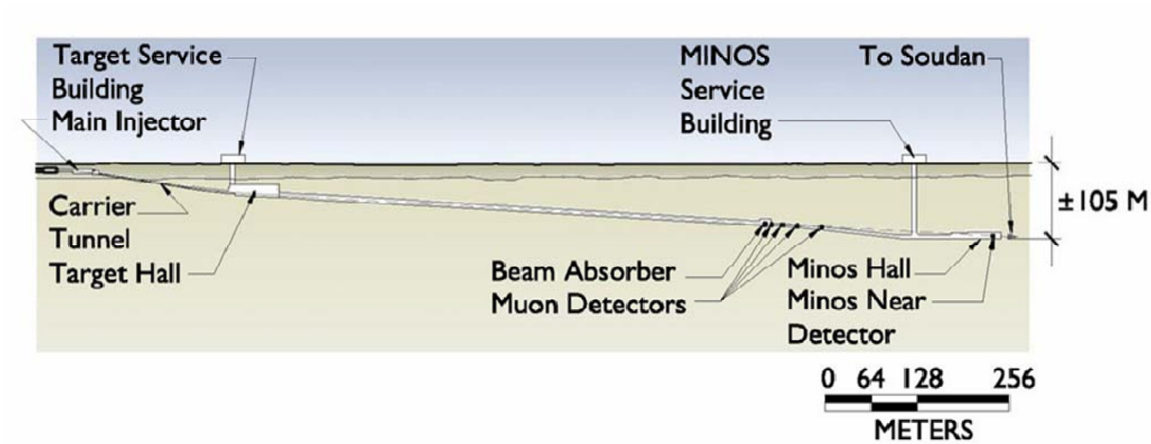


Fig 8.24: The NuMI beamline tunnel. Protons are delivered to the target hall from the Main Injector via the primary beamline and through the carrier tunnel. The target and focusing horns are located in the target hall. The long section in the middle contains the decay pipe which is followed by the beam absorber, muon detectors, and experimental hall.

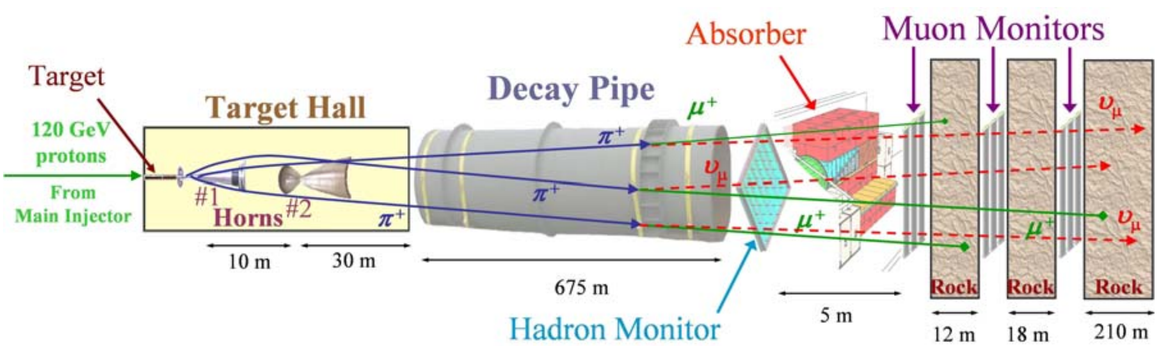


Fig 8.25: A schematic of the neutrino production process in the NuMI beamline.

NuMI uses pulsed magnetic horns with parabolic shaped inner conductors to focus the pions. The horns produce magnetic fields that act to first order as lenses, where the focal length is proportional to the pion momentum. Thus the relative position of the target and the first horn determines the momentum selection of the pions. Pions that were well focused by the first horn pass unaffected through a central aperture in the second horn. Pions that were not well focused by the first horn move to a larger radius and are focused by the second horn, extending the momentum range of the system.

To fully optimize the neutrino beam energy spectrum it is necessary to optimize the locations of the target and the horns. In the original NuMI design three different target and horn placements were chosen to give low (LE), medium (ME), and high energy (HE) neutrino beams. The resulting neutrino energy spectra in these three cases are shown in Fig 8.26. Plotted are the spectra of the neutrino energy at a location along the axis of the neutrino beam. One such location is the MINOS far detector. For the NOνA experiment the neutrino energy spectrum is different because the NOνA far detector is located off-axis. In this case the energy spectrum depends on the off-axis angle as shown in Fig 8.27. The NOνA experiment is located 14 mrad off-axis and will operate with the NuMI beamline in the ME configuration. The narrowness of the energy spectrum at the far detector is important for the NOνA experiment because it improves the background rejection.

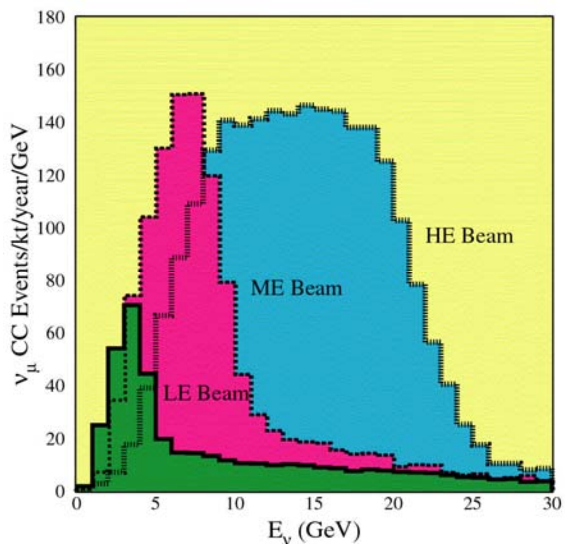


Fig 8.26: Expected energy spectra of charged-current (CC) events at the MINOS far detector (located on the axis of the neutrino beam) for low (LE), medium (ME) and high (HE) energy beam configurations.

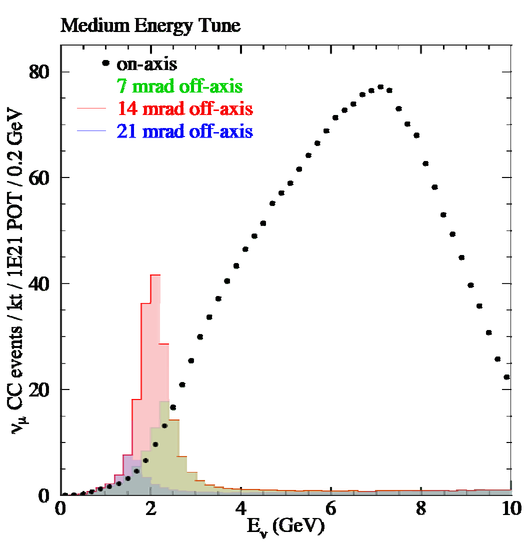


Fig 8.27: The expected energy spectra of charged-current (CC) events at the NOνA far detector with NuMI in the medium energy configuration. Shown are the spectra for different off-axis angles of the NOνA far detector.

As part of the NuMI upgrades, the target and focusing horn locations will be changed to meet the needs of the NOνA experiment. This means moving the target and the second horn to new locations within the target chase area in order to change the energy spectrum of the neutrinos. Simulations have been performed to confirm that the location of the target in the ME configurations is optimal for the NOνA experiment [18]. A description of the different configurations is given in [19].

Other parts of the NuMI upgrade are modifications to handle the increase in beam power from 400 kW to 700 kW and to allow operations at the faster cycle time.

In the following sections the designs are presented for each of the NuMI beamline systems requiring upgrades for the NOνA ANU subproject. Here we summarize the scope of the upgrade by listing the major changes needed:

- Replace five of the primary beamline quadrupole magnets with magnets from the A1 transfer line which are designed to handle the higher heat load of a faster cycle time.
- Replace the existing target and baffle with a new design capable of handling the higher beam power.
- Reconfigure the target chase from the low energy to the medium energy neutrino configuration. This involves repositioning Horn 2, reconfiguring the shielding, and extending the Horn 2 stripline.
- Add capacity to the target chase cooling system to maintain a reasonable temperature of the target pile.
- Upgrade the cooling water systems including the RadioActive Water (RAW) systems for the target, horns, decay pipe, and hadron absorber.
- Update the beam permit system inputs to help prevent accident conditions which can damage beamline components.

Two separate shutdown periods are planned for the installation of the upgrades. The first shutdown period follows the completion of Collier Run II operations. During this shutdown the NuMI beamline begins preparation for the 700 kW operations and accomplishes the following tasks:

- Upgrade the target chase cooling system
- Upgrade the capacity of the RAW systems
- Replace the quadrupole magnets in the primary beamline
- Extend the Horn 2 stripline
- Modify the target chase shielding in preparation for the future Horn 2 relocation.

It is expected that the MINERνA experiment will operate for about 2 years with NuMI in the low energy configuration. Because this requires the use of the existing target, the NuMI beamline will be limited to a maximum beam power of 400 kW during this time. Upon completion of the MINERνA operations a second shutdown is planned to switch from the low energy to the medium energy configuration and to replace the target with a higher power design. After the second shutdown, the NuMI facility will be capable of operating at a beam power of 700 kW.

The second shutdown involves the following tasks:

- Replace the target with the medium energy target design
- Replace the Horn 1 with the new design
- Relocating Horn 2 from the low to the medium energy position

8.6.2 Primary Proton Beam

The current 400 kW design NuMI beam has the capability to extract up to 6 Booster batches from the Main Injector at a cycle time of 1.87 sec. Both the extraction system and the primary beam transport are conservative designs, with robust operation for NuMI demonstrated and operational beam loss levels consistently 1-2 orders of magnitude below the relatively severe NuMI design criteria of 1×10^{-5} fractional beam loss. If the next level upgrades for beam intensity capability, involving slip-stacking of multiple batches to NuMI, can maintain the level of beam control achieved for NuMI, a significant window for higher per pulse beam intensity is available. The most significant modification of the NuMI primary beam-line for ANU involves acquiring the capability for faster cycle repetition rates. More detail can be found in [20].

8.6.2.1 Extraction Kicker

Only limited modifications to the NuMI extraction kicker system are needed. No modification of the kicker magnet is needed since the bunch spacing and beam energy do not change for the NuMI upgrade. The existing NuMI extraction kicker is designed for a 9.6 μs flattop and operates at 50 kV. The shorter Main Injector cycle time reduces the available time for power supply charging from 1.1 to 0.7 sec and this leads to the requirement for a new extraction kicker charging power supply.

An upgraded fluorinert pump is also required for the existing kicker system water heat exchanger to handle the additional heat load caused by the increased repetition rate.

8.6.2.2 QQM 3Q120 Quadrupole Magnets

The most significant upgrade to the NuMI primary beamline is the replacement of the highest current 3Q120 quadrupole magnets. For NuMI these quadrupole magnets were refurbished from existing fixed target beam system inventories, but a number of internal cooling leaks were found during this process in some of the tested magnets. The available laboratory supply of 3Q120 magnets was exhausted to successfully refurbish the 19 ones needed for NuMI, along with two spares.

For these 25 to 30 year old magnets, a concern is that the water-cooling of the coil packs is inefficient since there is no direct cooling for the coils themselves. To provide some safety margin, cooling for the highest current NuMI quadrupoles was augmented with external cooling plates as shown in Fig 8.28.

Fig 8.28: NuMI 3Q120 with External Cooling Plates

Although there have been no failures of installed NuMI quadrupoles to date, the Technical Division [21] recommends replacing the NuMI quadrupoles with the highest operating currents (those operating at greater than 70 amps) for cycle times below 1.87 seconds. The newer design QQB magnets have direct water cooled coils and are more suitable for use after the NuMI upgrades. Since the A1 line, which transfers pbars from the Main Injector to the Tevatron, will not be used after the finish of collider operations, the existing QQB magnets in this line will be removed and used for the NuMI upgrades. The QQB design has internal coil cooling, fewer turns and higher current for the same field. The QQB magnets are projected to be much more robust. Specification differences between QQM and QQB quadrupole magnets are shown in Table 8.16.

	QQM	QQB	Units
Turns per pole	118	28	
Resistance	1.6	0.16	Ohm
Inductance @ 100 Hz	1.4	0.082	H
Water flow @ 100 psi (not including supplemental plates)	17	5.7	GPM
Core width	17	17	Inches
Core height	15	15	Inches
Steel length	120	120	Inches
Flange-to-flange length	132.0	132.0	Inches
Core to lead end flange	5.0	6.5	Inches
Core to bellows end flange	7.0	5.5	Inches
Assembly drawing	ME-388120 Link to TIF	ME-331805 Link to TIF	

Table 8.16: QQM quadrupole magnet versus QQB quadrupole magnet specifications.

Hence, the plan is:

- Remove six of the QQB design 3Q120 magnets from the A1 line at the conclusion of collider operations. (The 3Q120 nomenclature refers to the 3 inch aperture of the quadrupole and the 120 inch length of the magnet.)

- Replace the five quadrupole magnets in the NuMI beam-line with the highest operating current with the QQB design magnets. The five quads and their currents are:
    - Q111 (78 Amps)
    - Q112 (83 Amps)
    - Q113 (83 Amps)
    - Q114 (78 Amps)
    - Q120 (71 Amps)

The QQB design magnets can be installed in the primary beamline using the existing magnet stands since the QQB magnets have the same external dimensions as the existing QQM magnets.

New 75 kW, higher current power supplies are required to utilize the more robust QQB quadrupoles for NuMI, as well as higher current capability cables between power supplies and magnets. These supplies will be vendor built to Fermilab design specifications. Several identical units are currently in operation in the accelerator complex.

8.6.2.3 Large Power Supply Modifications

Relatively minor changes are needed to the existing large dipole power supply setup to enable the faster cycle time for NOνA. These are summarized in Table 8.17.

I:LAM60	**Tap change** from 50 to 100 volts. RMS current from 474 A to 434A
I:LAM61	**No change.** Increase RMS current from 931A to 1073A
E:V100	**Tap change** from 50 to 100 volts. RMS current from 1426A to 1226A
E:HV101	**No change.** Increase RMS current from 814A to 932A
E:V118	**Use full voltage.** Increase RMS current from 2270A to 2292 A

Table 8.17: Large power supply changes for 1.33 second cycle time.

With the increase in beam power for NOνA, there also is increased danger to beam system components from large accidental beam loss, even with a single bad pulse. Currently the Beam Permit System robustly precludes a 2nd bad beam pulse, but only monitors power supply currents at a level of 0.5 to 1.0%. This leaves a significant window where a power supply regulation problem could be missed at a level which could produce component damage from miss-steered beam.

The planned solution for this is to implement new BμLB regulation systems for the six major dipole power supplies. This upgrade will provide a precision power supply readout capability of accuracy 0.01% to the permit system, as well as additional feedback control for enhanced power supply regulation.

8.6.2.4 Upgraded Primary Transport Profile Monitors

An operational requirement [22] for the NuMI primary beam is to maintain fractional beam loss at a level of less than 1×10^{-5}. The existing primary transport profile monitors are built with extremely thin 5 μm Ti foils spaced at 1 mm pitch, to have a minimum amount of material (~ 4×10^{-6} interaction lengths) exposed to the beam. These are generally not used during NuMI operations due to a 10-20 second required insertion time during which beam loss is an order of magnitude greater and generates beam permit trips. This is not a problem for the pre-target profile monitor at the downstream end of the primary beam, which can and does remain in the beam at all times since it is just upstream of the target pile.

For the other beam transport monitors, the plan is to implement the thin Ti foils with an existing design fast acting (< 1 sec) mechanical drive and vacuum system. These systems will also be built such that excess material is not exposed to the beam during monitor insertion. Of the ten units needed, a total of five of the mechanical systems already exist for NuMI. Five new mechanical systems will be constructed, as well as new Ti foil packages for the ten units.

As this is an upgrade which should provide a considerable improvement for profile monitor use in Fermilab high intensity beams, the foil package prototype development is not part of the NOνA project.

8.6.3 Target Hall Technical Components

A layout of the NuMI Target Hall including the technical components is shown in Fig 8.29 and Fig 8.30. The technical components are used to produce and focus pions and kaons, and to monitor the proton and pion/kaon beam. Specifically, the components needing modifications for the NuMI upgrade are the:

- Baffle
- Target
- Carrier for the Target and Baffle
- Hadron Monitor
- Beam Abort Input for Hadron Monitor

Only minor modifications are needed to the magnetic focusing horns in order to handle the increased energy deposition in the horns at the higher beam power. The horns have a finite lifetime of about 1-2 years before they need replacement. Therefore the modifications to the horn design can be accomplished during the usual production cycle for fabricating replacement and spare horns.

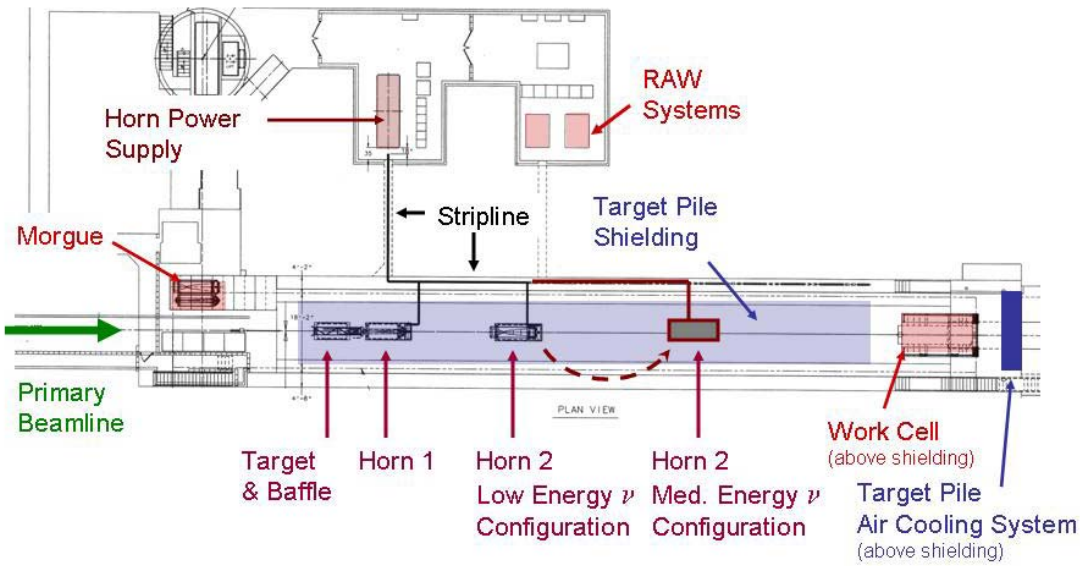


Fig 8.29: Plan view of the NuMI Target Hall. Note that the Horn 2 location depends on the neutrino energy configuration.

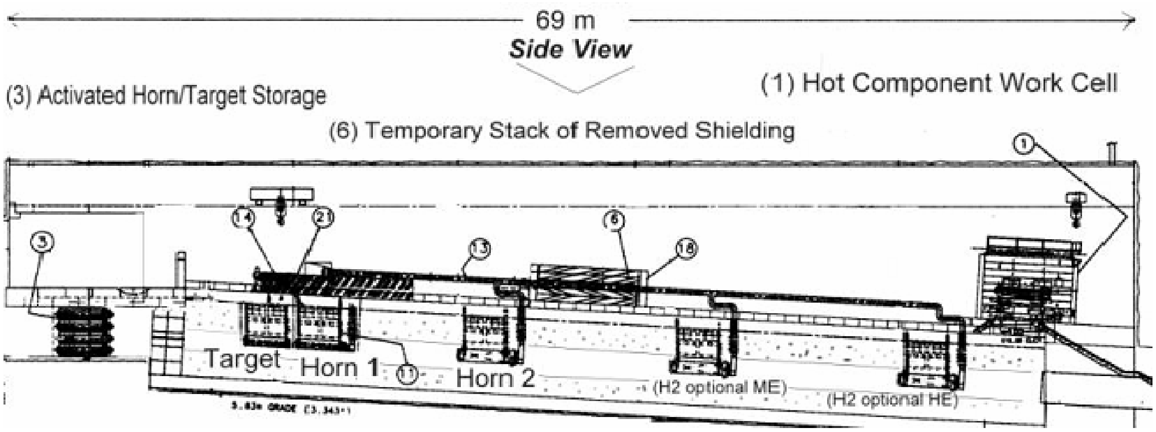


Fig 8.30: Elevation view of the NuMI target hall. Note the three possible locations for Horn 2 corresponding to the Low, Medium, and High Energy neutrino spectrums shown in Fig 8.26.

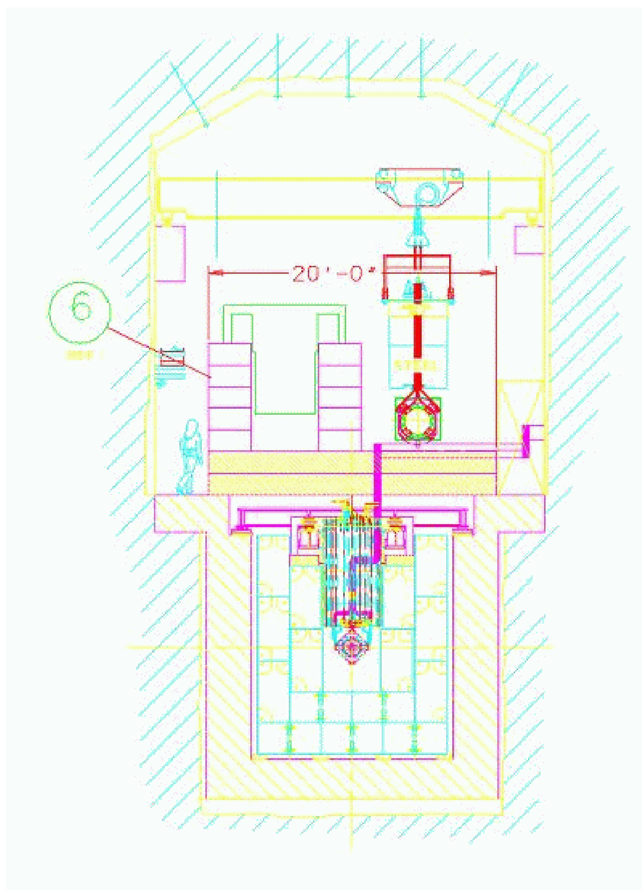


Fig 8.31: Cross sectional view of the NuMI target hall, showing a temporary stack of removed shielding, and a module plus horn being transported.

8.6.3.1 Target Baffle

In the NuMI baseline design a 1.5 m long baffle 68 cm upstream of the target fin protects the neck of the horn and the target cooling hardware from miss-steered beam pulses. The baffle moves along with the target from Low Energy (LE) to High Energy (HE) locations.

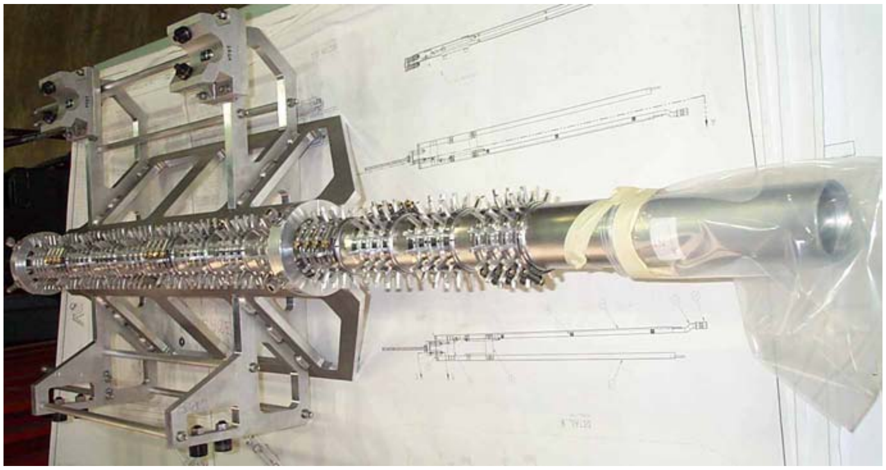


Fig 8.32: NuMI target pile baffle

The NOνA beam intensity of 4.9×10^{13} protons/spill is 22% higher than the NuMI baseline design. In the base design, excluding high-cycle fatigue (which the baffle should not be subject to) the stress safety factor of the baffle in accident conditions is 4.5 [23]. With this margin on the safety factor the baffle design is well inside the safety factor and the baffle will survive the shock of accident conditions in NOνA running.

The baffle serves to protect the horn neck and the target cooling system. The heating (and thus induced stress) of various components is shown in [19] as a function of the baffle location; moving the baffle upstream reduces the stress. For the NOνA project, the move of the target to the ME location naturally moves the baffle further from the horn neck, compensating for the higher intensity per spill. The protection of components of the new target will have to be evaluated, but based on the safety factors for the old components, is likely to be OK without modification of the baffle. If desirable, the baffle can be moved another 1 m upstream of the target (to its current location for the HE beam), increasing the stress safety factor.

The D.C. beam power in the upgrade is 75% higher than the NuMI baseline design. The baffle is air-cooled with pin radiators, and the temperature rise is used to monitor the amount of beam scraping. Calibration with real beam shows the original safety factor would cover the increased temperature but there is room for more pin radiators on the baffle which will be added.

SLG grade R7650 graphite was used in the baffle rather than the POCO ZXF-5Q used in the calculations in [23], but R7650 has a better combination of yield strength, heat capacity, coefficient of thermal expansion and Young's modulus.

8.6.3.2 Medium Energy Target

The NOνA experiment requires a medium energy neutrino configuration as discussed in Section 8.5.1. In this configuration the optimal location for the target begins 135 cm upstream of Horn 1 and extends to 15 cm upstream of Horn 1. As part of the NuMI project, the Institute for High Energy Physics (IHEP), Protvino, Russia had already completed a preliminary design of a target for use in this configuration. A general view of the target design is shown in Fig 8.33. The medium energy (ME) target design is described in IHEP reports and drawings [24, 25].

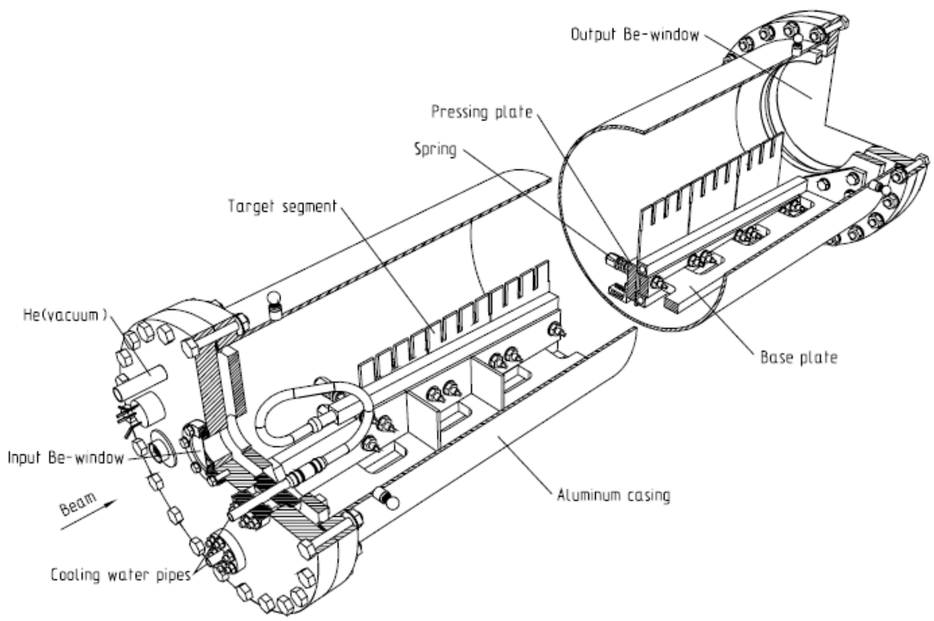


Fig 8.33: General view of the Medium Energy Target

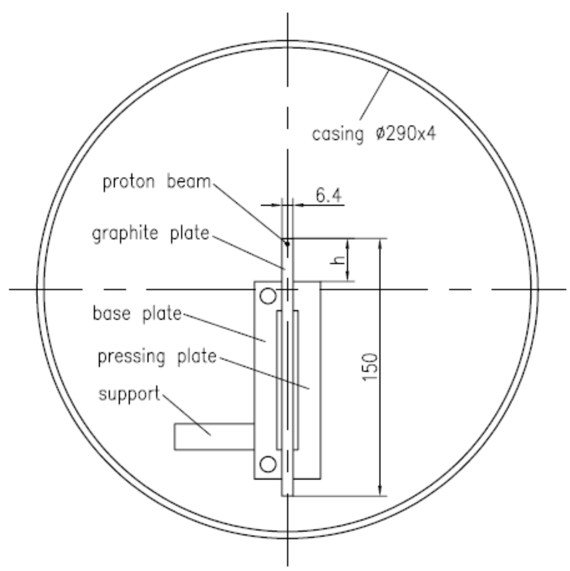


Fig 8.34: Cross section of the Medium Energy Target

Views of the ME target design are shown in Fig 8.33 and Fig 8.34. The incident protons travel through the upper portion of twelve 6.4 mm thick and 100 mm long graphite plates. The bottoms of the graphite fins are clamped by a base plate that contains water-cooling channels. Two springs per target plate provide ~2 atmospheres of pressure. The distance from the fin tip to the cooling channel is minimized at the upstream end where beam heating is maximal. To prevent absorption of secondaries contributing to the neutrino flux, the fin extension increases continuously along the target length. The base and pressing plates are made of an aluminum alloy and anodized with 30 μm thick alumina. To decrease quasi-static thermal stresses, cuts are machined in the upper part of each graphite plate forming four 22 mm long, 30 mm high segments (or teeth). Note that the casing diameter for the medium energy target is wider than the inner conductor of Horn 1 and therefore operations in the low energy configuration are precluded with the ME target design.

The longitudinal position of the ME target will remain fixed and will not be remotely moveable. Remote motion capability in the transverse plane is still provided by the target module in order to perform target and horn scans. To perform these horn scans the design of the target carrier and motion apparatus must provide enough travel to completely remove the target and aluminum casing from the beam path.

IHEP has performed preliminary calculations of stress and temperature in the ME target with a 6.4 mm wide graphite target. The calculations were made as a function of beam spot size from 1.0 to 1.5 mm rms for up to 5.5×10^{13} protons per pulse every 1.3 seconds corresponding to a primary beam power of 780 kW. The preliminary results show that the target design is capable of withstanding the higher beam power provided that the transverse size of the proton beam is 1.3 mm rms or larger in both transverse planes [26].

Further analysis and design of the IHEP medium energy target is required to add water cooling to the outer casing and to understand the cooling of the windows at the entrance and exit of the target.

8.6.3.3 Target Carrier

The target carrier hangs below the target module and is used to support the target and baffle. A picture of the target carrier used for MINOS operations is shown in Fig 8.35. In the present design the target carrier also provides remote longitudinal motion capability of the target and baffle within the target carrier. For the ME target needed for the NOvA experiment, longitudinal motion is not required and will not be provided with the new target carrier design. Since the ME target casing has a larger diameter than the low energy target some modifications to the target carrier will be necessary.

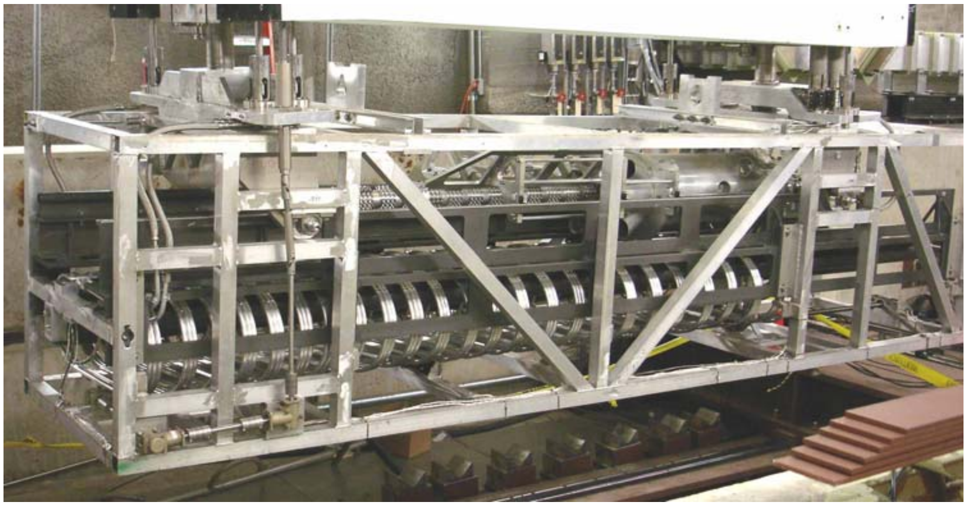


Fig 8.35: Photo of the target carrier used during operations for the MINOS experiment.

8.6.3.4 Hadron Monitor

The purpose of the hadron monitor is to measure the intensity and transverse widths of the remnant hadron beam at the end of the decay pipe just upstream of the hadron absorber. The location of the hadron monitor with respect to the NuMI beamline is shown in Fig 8.36. A photograph of the present Hadron Monitor is shown in Fig 8.37.

The present Hadron Monitor [27] will not be able to handle the increased beam intensity during operations for the NOvA experiment. The University of Texas – Austin designed and built the first hadron monitor and will design and build a new hadron monitor to handle the increased beam power.

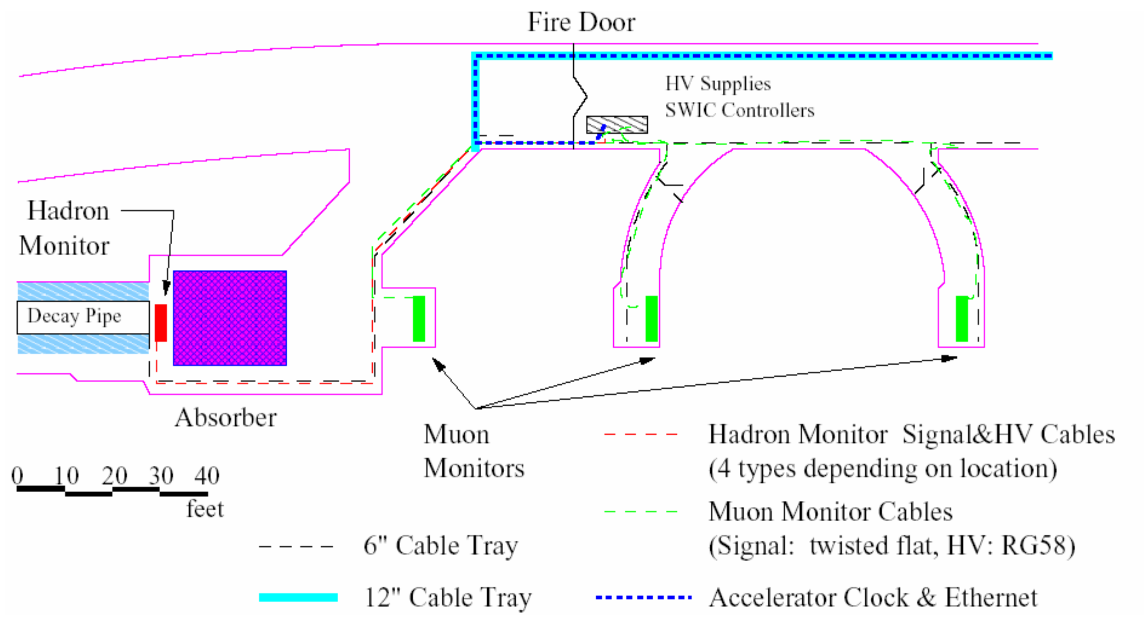


Fig 8.36: Plan view of the downstream end of the NuMI beam line, indicating the decay pipe, beam absorber, and the Hadron Monitor upstream of the absorber.

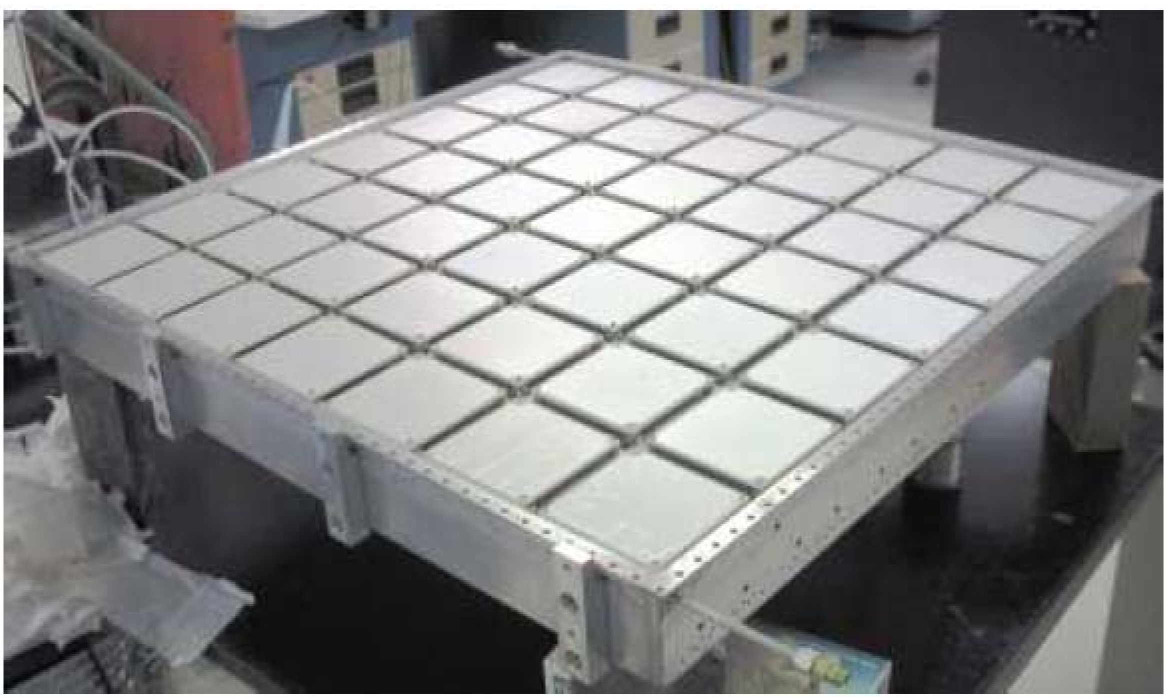


Fig 8.37: Photograph of the first Hadron Monitor prior to installation in the NuMI beam line. A total of 49 ionization chambers reside inside the thin aluminium gas vessel. Each ionization chamber consists of parallel ceramic plates with silver electrodes.

8.6.3.5 Hadron Monitor Beam Abort

Protection of the NuMI Target Hall equipment from errant beam pulses is necessary in operations for the MINOS and NOvA experiments. Equipment monitoring and beam diagnostics are already used as part of a beam permit system for NuMI. The increased beam intensity for the NOvA experiment increases the possibility of equipment damage. To mitigate this risk, the Hadron Monitor will be incorporated into the beam permit system. Intensity and beam size thresholds on the Hadron Monitor can be used to not permit beam operations on the next pulse in the event of an errant beam pulse. Tasks looking into using the Hadron Monitor in the beam permit system are in the resource loaded schedule.

8.6.4 Target Hall Infrastructure

The Target Hall Infrastructure covers the support systems for the technical components (target and horns), shielding of the target hall from radiation, and cooling of the target pile and support systems within the target chase. Also included are space issues in the target hall for the different shutdown activities planned, with particular emphasis on the Horn 2 move to the medium energy position which will require significant shielding reconfiguration. Available space is very limited for moving and staging various shielding/technical components so early planning is crucial. The cooling of the target pile and support systems covers upgrades to the chase air cooling system and enhancements to the Horn 1 stripline block cooling.

8.6.4.1 Target Hall Operations Space Planning

Several shutdown activities are planned in the target hall, but space is very limited and careful planning is needed ahead of time to effectively carry out these tasks. A list of the major target hall activities is given below. Some of the activities are not part of ANU and will be done as part of NuMI operations and upgrades. These activities are marked as off-project. Since the off-project activities will occur in conjunction with ANU, an overall plan must be developed.

- Horn 2 move to the medium energy position (includes evaluating R-Block, T-block and blue block staging options, stripline extension, etc.).
- Target & Horn change outs, upgrades and repairs. (Off-project)
- Radioactive component repair/removal (work cell activities, remote tooling & manipulators setup, additional shielding, etc.). (Off-project)

Fig 8.38 and Fig 8.39 show a longitudinal cross section of the target hall shielding together with the proposed new Horn 2 location. Fig 8.40 shows a picture of the NuMI Target Hall looking downstream during a recent target repair job. In Fig 8.40 concrete R-blocks have been removed and staged at the downstream end near the work cell (red shield door), T-block are staged just upstream of that. It can be seen that space is very limited especially when it will come to staging several more shielding blocks which will be required during the Horn 2 relocation. Some creative stacking arrangements will have to be developed for effective and safe staging of these blocks.

Concrete “R” blocks placed on top of the target vault (to seal the target pile and provide shielding) are also used for shielding and storage of the T-blocks and blue blocks as shown. Since the new horn location falls beneath the existing T-block and Blue-block storage space, a completely new shielding storage scheme will have to be developed. This will also have to take into account the addition of a new (temporary) work area just upstream of the work cell to be used for conducting radioactive component repairs using remote tooling (The radioactive component repairs using remote tooling is an off project activity). A preliminary layout of this proposed new shielding configuration is shown in Fig 8.41. This will require more shielding blocks, and more concrete blocks will also be required to extend the existing battlement (vertical R-blocks that run parallel to the length of stripline) further downstream. Therefore, it is important that a detailed study of the available space be conducted that aims to develop a comprehensive new layout plan for the various target hall activities. As a result, new equipment (mostly in the form of structural supports) might be designed to help with the transport and staging of shielding blocks during shutdown activities, in a way that optimizes use of the target hall space. The cost of this equipment is included in the resource loaded schedule.

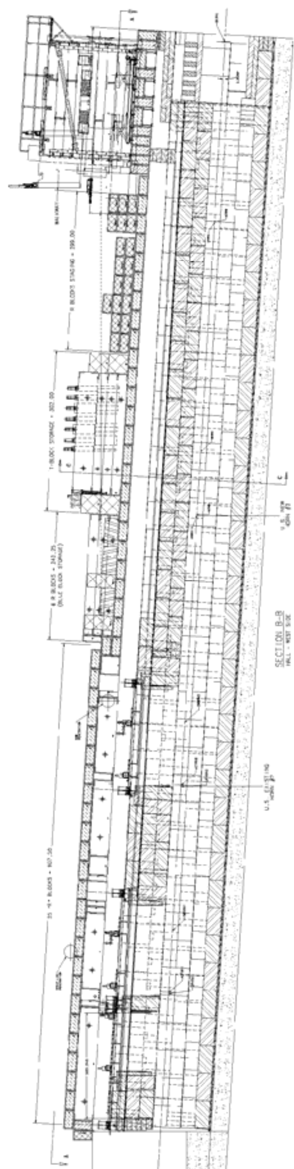


Fig 8.38: A Longitudinal cross section of the NuMI Target Hall showing shielding layout.

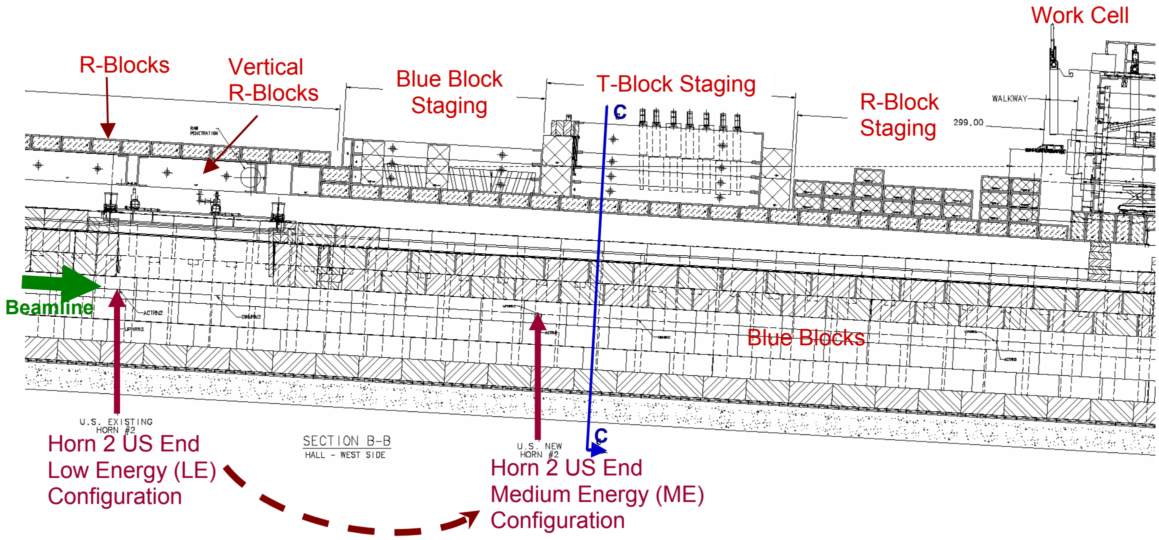


Fig 8.39: Close up of NuMI Target Hall longitudinal cross section showing existing Horn 2 location and proposed new medium energy position approximately 13 meters further downstream. As can be seen, the shielding block staging areas will have to be re-located to accommodate Horn 2.

Fig 8.40: NuMI Target Hall looking downstream during a recent target repair job.

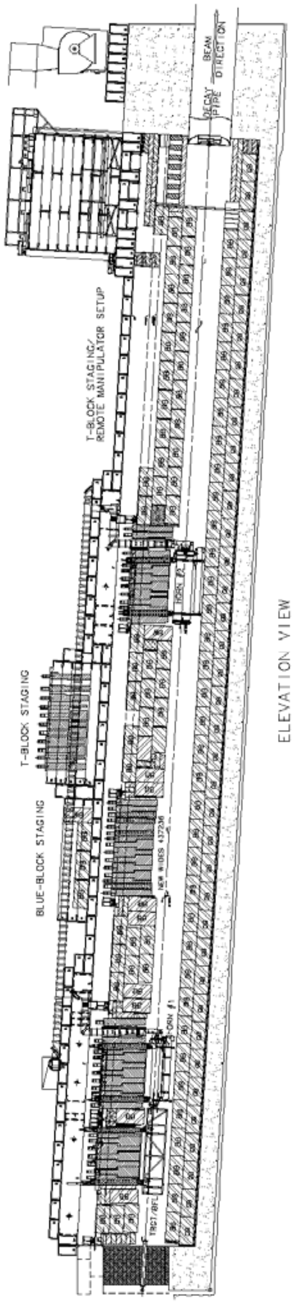


Fig 8.41: A Longitudinal cross section of the NuMI Target Hall showing proposed shielding layout for NOvA (i.e. after Horn 2 relocation).

8.6.4.2 Horn 2 Relocation to Medium Energy Position

To switch from the low energy to the medium energy neutrino spectrum, Horn 2 will need to be relocated approximately 13m further downstream [28] from its current position in the target chase, as shown in Fig 8.38 and Fig 8.39. This will require extension of the existing stripline and significant reconfiguration of the existing shielding layout.

8.6.4.2.1 Stripline Extension

The stripline is the electrical connection between the 240 kA pulse power supply and the horns. The original NuMI design concept was to have Horn 2 capable of being moved into three discrete locations and provisions were made to extend the existing stripline in the future for the new horn locations. However, no stripline extensions were built so new ones are needed for the NOνA Project. Fig 8.30 shows the stripline running along the wall and the connections needed for the various horn 2 locations. Fig 8.40 shows the existing stripline along the left wall, enclosed in plastic, and the connection to horn 2 (about ½ way down on the left in the photo), under the R-blocks, but now visible due to the R-Blocks being removed.

The stripline consists of 8 layers of high conductivity 6101-T61 aluminum bus bars which are 12 inches wide by 0.375 inches thick. The bus bars are held together by aluminum clamps with fiberglass insulators in low radiation areas. The walkway stripline assembly is mounted to steel C-channels supported by steel stands. The walkway stripline extension will be pre-assembled in a building and then installed in the target hall. On the downstream end of the existing walkway stripline in the target hall there are silver plated contacts that currently have four shunts plugged into them. The shunts will be moved to the end of the new extension (10 meters downstream) and the new stripline extension will plug into the end of the existing stripline. The two existing stripline assemblies (chase and module stripline sections connecting to Horn 2), under the R-blocks will be reused at the new Horn 2 location.

The horn power supply is a 0.225 F capacitor bank that operates up to about 1 kV and the power supply output is presently set to 200 kA at 680 V. The two focusing horns, each a single turn air core magnet, are constructed in a co-axial configuration. The addition of 10 meters of stripline will increase the inductance of the system by 160 nH. The power supply voltage will have to be increased to 787 V to maintain the 200 kA output. Even though there is an increase in power supply output, the electrical heating of the stripline will increase only slightly due to 10 extra meters of stripline.

8.6.4.2.2 Shielding Reconfiguration

The target hall shielding is made up almost entirely of steel "blue blocks" stacked as shown in Fig 8.42. At the horn locations, the center three rows of blue blocks are replaced with the horn modules together with associated shielding blocks (T-blocks, end blocks and stripline block.) A drawing of the Horn 2 module is shown in Fig 8.43. A photograph of the Horn 2 module assembled on a test stand at MI-65 is shown in Fig 8.44.

At the new location for Horn 2 in the shielding pile, the center set (of approximately 12) blue blocks will need to be removed to make space for the Horn 2 module. Also needed are 6 additional vertical R-blocks to extend the existing battlement (vertical R-blocks that run parallel to the length of stripline) for the Horn 2 relocation. These additional R-blocks are used to raise the level of the R-block shielding covering the chase and thereby create a vertical space for the stripline extension when Horn 2 is relocated downstream. (The vertical R-blocks can be seen in Fig 8.39.)

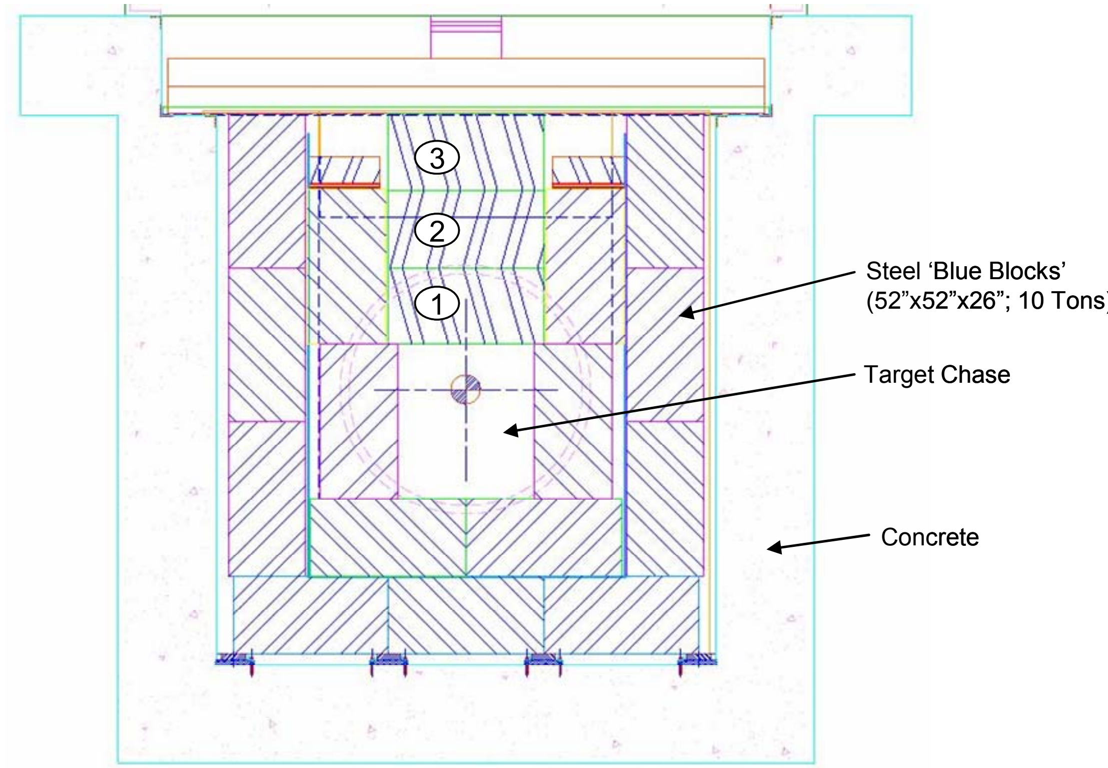


Fig 8.42: Typical NuMI Target Hall shielding cross section. At the new Horn 2 position, only the center row of blue blocks (marked 1, 2, & 3) will have to be removed.

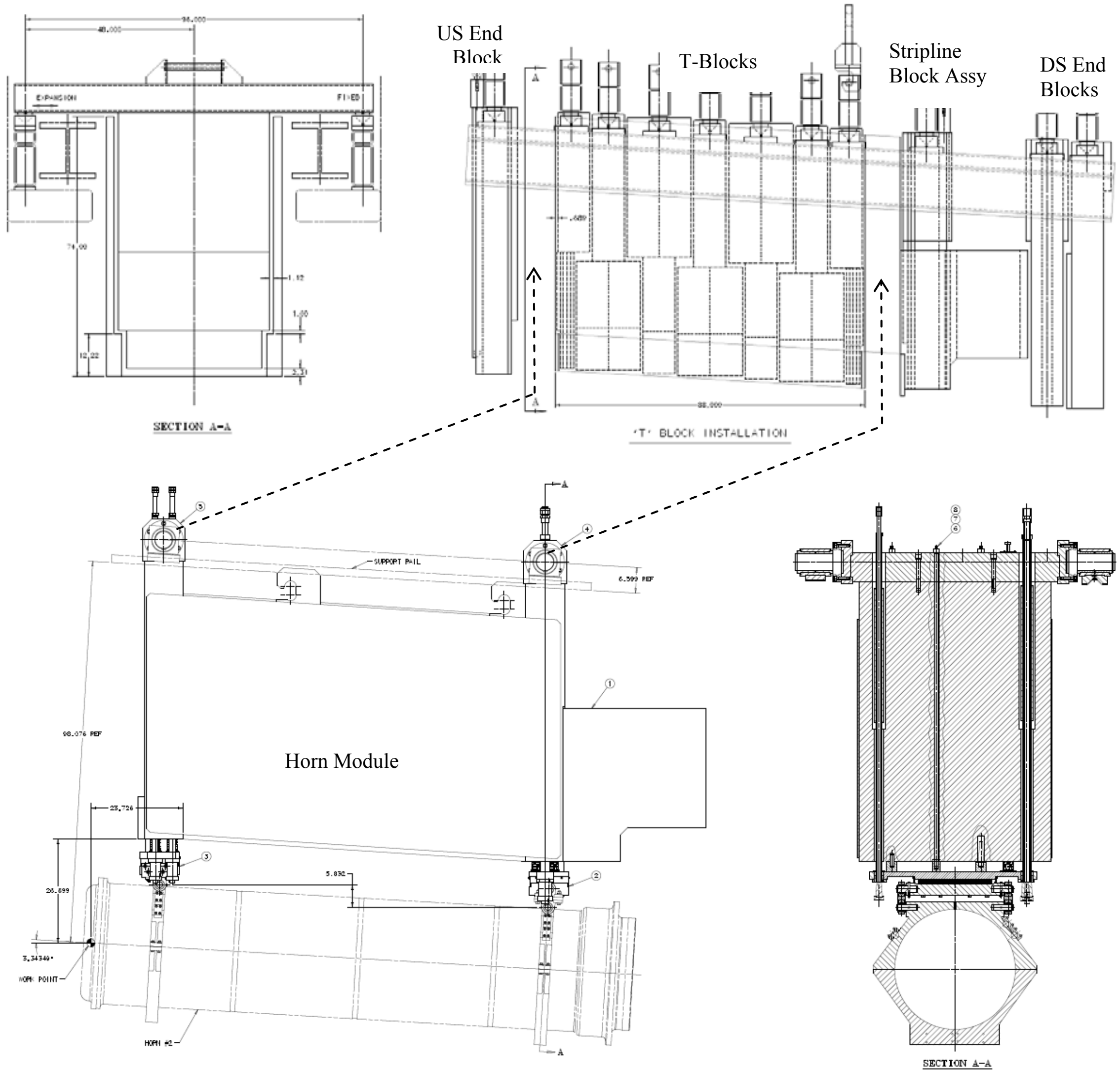


Fig 8.43: NuMI Horn module and shielding blocks (T-blocks, end blocks, & stripline block) that will be moved to the ME position together with Horn 2.

Fig 8.44: Horn 2 attached to module in the MI-65 service building.

To greatly simplify moving Horn 2 to its new location, a new set of shielding T-blocks and support tube will be built as shown in the drawings in Fig 8.45. This shielding scheme will be installed in the vacant LE location after Horn 2 is moved. (Re-using the extracted blue blocks from ME is not a viable option due to the difficulty in remote stacking radioactive blue blocks). The new shielding blocks are similar to the existing T-block design (Fig 8.43), with the major difference being wider (and heavier) T-blocks at the center to fill the space left by the module walls. Due to this increased weight, the concrete R-blocks were re-analyzed [32] and found to be structurally adequate to support the additional load of the T-blocks during staging as shown in Fig 8.41.

This new shielding scheme will eliminate the need for the module assembly altogether and can be installed in either the low energy or medium energy location and essentially acts as a shielding “plug”. Therefore, work could begin on its installation during the first shutdown in the schedule after the completion of Collider Run II operations. During this shutdown, the ME blue blocks can be extracted and the new shielding T-blocks installed in their place. Finally, it is anticipated that some additional custom filler blocks will be needed to match the new interface condition after removal of blue blocks and installation of the new T-blocks.

Once Horn 2 is ready to be moved, it will simply require swapping of the assemblies, Fig 8.43 and Fig 8.45, at the LE and ME locations. It should also be noted that a new Horn 2 carriage and T-Block support tube weldment will have to be built and surveyed into position. Another advantage of having two interchangeable assemblies is that it will allow Horn 2 to be easily moved back to the low energy position if the need arises in the future.

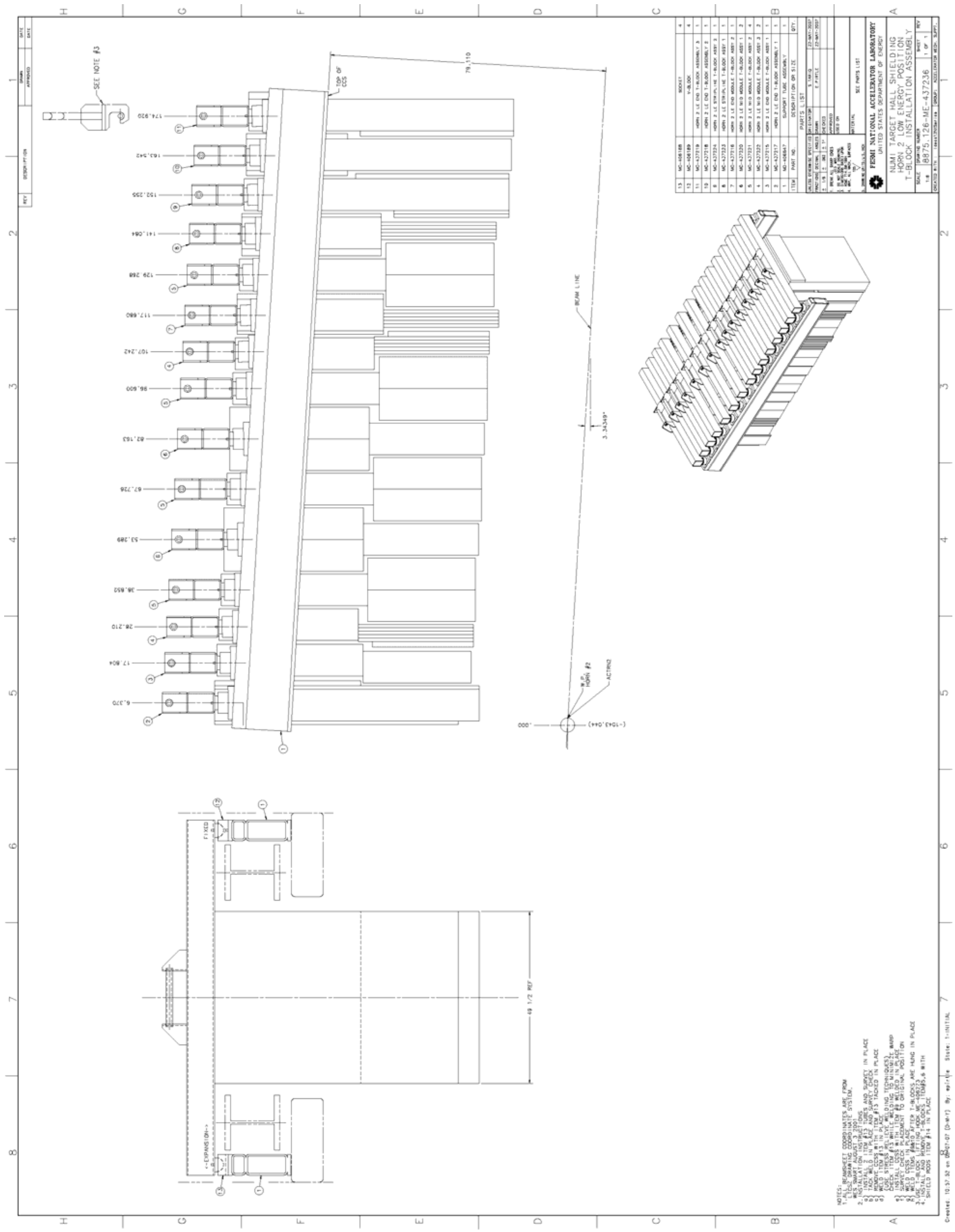


Fig 8.45: Revised shielding T-block design pattern and support tube assembly to be installed at the LE location.

Fig 8.46: Horn 1 connected to transmission line in the MI8 service building.

The resource loaded schedule assumes the use of new shielding T-blocks as described above, with most of the steel being purchased from the outside which is the most expensive option. A cost saving alternative also being studied is to utilize steel available onsite at minimal cost (mostly radioactive shielding steel left over from previous experiments) plus maximizing the use of continuous cast salvage steel which is significantly cheaper than regular HR plate. Recycling radioactive steel from onsite prevents creating any new future radioactive waste. This latter option, if viable, could lead to significant cost savings in both the short and long term.

During the Horn 2 move, a number of surplus blue-blocks will be taken out from the new location. These could then either be completely removed from the target hall (the ideal scenario) or stored in some fashion within the available target hall space. A detail radiation survey needs to be first conducted to measure the residual dose rates. If dose rates are reasonable, a coffin can be designed to safely remove and transfer some of the blue blocks to an external storage site (weight and size of the coffin being the limiting factor), and this is covered by the Radioactive Component Repair/Removal off project task. The morgue could also be used as a temporary storage for hot blocks but this should only be considered a short-term solution. As shown in Fig 8.41, some of the blocks could be stacked on top of the existing two layers of blue blocks assuming there is no interference with equipment. These options will all be part of the detail study on available space issues in the target hall. The resource loaded schedule assumes we will remove and re-use/store most of the blue blocks within the available target hall space, with the possibility of loading some of the blocks on a coffin/hearse assembly ready for transport up-shaft.

If residual dose rates are high on some of the blocks, which will most likely be the case with the target chase blocks, then remote handling will be required. The existing remote handling lifting fixture and camera system are not adequate to do this task effectively. An assessment of the remote lifting system will have to be made resulting in upgrades to the fixture and camera system. These upgrades are included in the resource loaded schedule.

8.6.4.3 Target Chase

Additional cooling of the target chase is needed due to the large amount of beam energy deposited. With the 700 kW of beam power anticipated for NOνA, approximately 280 kW is deposited in the target pile. Maintaining a reasonable temperature in the target chase is important for several reasons:

- Thermal expansion of the target chase and target hall components will affect the alignment of the target and horns. The NOνA experiment requires that alignment of the beam, target, and horns remain within a 1.5 mm tolerance [28].
- The target pile consists of stacked steel blocks (referred to as "Blue Blocks"), which are painted to reduce corrosion. Burning and smoldering of the paint can be a problem if the target pile becomes too hot.
- Higher temperatures and radiant heating from the target pile can add to the heat load of target, horns, and striplines (see section on Radiant Heat Loads). This can lead to unacceptable temperatures of the target hall components.

Testing of the paint samples is planned to determine the maximum allowable temperature requirements in the target chase. Further analysis is also planned to determine the maximum acceptable operating temperatures for the target hall components.

8.6.4.3.1 Target Chase Cooling

A preliminary estimation of the expected target chase temperatures has been performed. The beam energy deposition values used in this analysis are scaled up from the NuMI values by multiplying them by 1.75 (the ratio of 700 kW to 400 kW). The preliminary estimate for NOνA target pile shielding temperatures is shown in Fig 8.47. The highest shielding temperature is 115 °C at the peak beam heating location just downstream of the Horn 1 location. The estimate has been made using the refined 2-D NuMI target pile finite element model (FEM).

The original NuMI target pile FEM was refined by incorporating the actual average heat transfer rate from two Duratek shielding blocks in the inner chase wall. The average rate was experimentally determined by monitoring the temperature of the two Duratek blocks as they cooled down with no beam heating and with the target pile fan on. Both of the Duratek blocks are at the location of the theoretical peak of beam heating. The blocks are on opposite sides of the chase directly across from each other and just downstream of Horn 1. Each of these blocks has a thermocouple welded to it that was used to monitor block temperature during the test. The light blue colored block in Fig 8.47 has the one with the thermocouple welded to it on that same side of the chase.

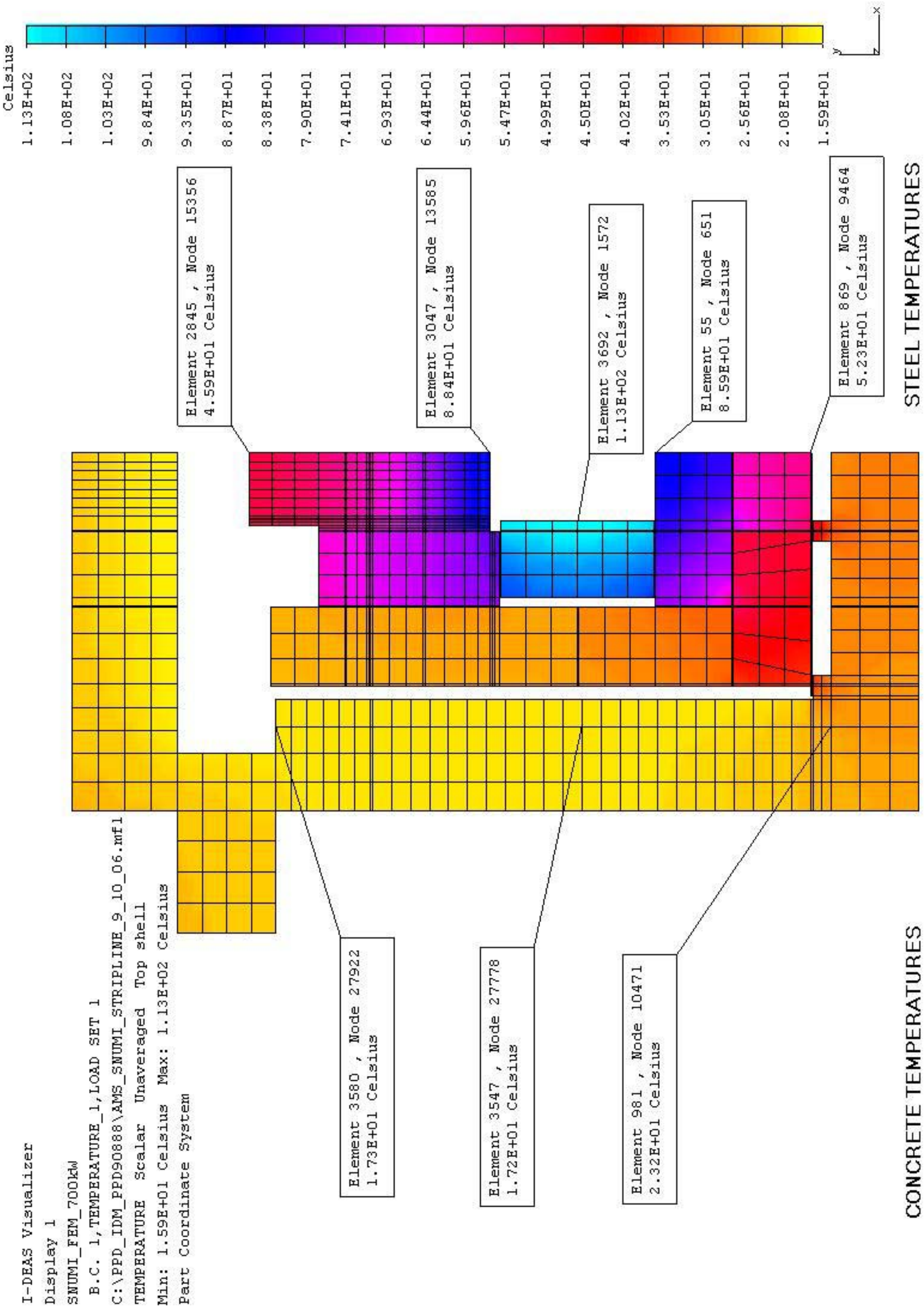


Fig 8.47: Estimated target pile peak temperatures at 700 kW of beam power.

Concrete temperatures estimated using the 2-D NuMI FEM are slightly higher than expected because the model assumes that the concrete liner is insulated at its outermost boundary where it contacts water-bearing rock instead of being modeled as a semi-infinite solid. A MARS simulation of the complete target chase region (including technical components) at 700 kW beam power has been performed to obtain updated energy deposition numbers shown in Table 8.18. This data will then be used in a new comprehensive 3-D FEM of the target chase region and will provide more accurate temperature data. Preliminary results from this FEM study can be found in [30].

Table 8.18 gives a breakdown of the NOvA heat loads in the target chase [31]. The target pile heat load of 260 kW was based on MARS and includes an 18% safety factor. The total heat load for the target chase is thus estimated at 458 kW. The NuMI operational upgrade during the 2007 summer shutdown (as part of the tritium mitigation plan) will install 4 new surface chiller units (and a new dehumidification system) with a capacity of 160 kW each to replace the existing chiller unit downstairs. This upgrade will meet NOvA requirements by running three of the four chiller units for a combined total capacity of 480 kW to cover the 458 kW NOvA heat load. The fourth unit can then be kept as an on-line spare and made quickly operational if one of the other three were to fail. This adequately addresses the operational and reliability concerns for NOvA. The remaining scope for the chase cooling upgrade is to evaluate the existing chiller cooling coil design and address the option of adding more heat exchanger coils to increase capacity of the air cooling system. This heat exchanger upgrade will involve modifying the existing coil box to accommodate the new coils and laying out piping to connect the new coils to the existing coolant loop. This upgrade will include specifying valves and instrumentation, making control wiring diagrams, and updating the existing controls (PLC and ACNET). This heat exchanger upgrade is included in the resource loaded schedule.

Description	Load (kW)	Comments
Target Pile (710kW beam)	260	from MARS + 18% SF
Stripline	7	
Fan	50	
Chilled water pump	20	
Dehumidify 14kg/hr water*	11	
Dehumidifiers	110	2 units, 55kW ea
Total load to chiller:	**458**	

*Air leak ~600cfm

Table 8.18: NuMI Target Hall Chiller Heat Loads for 710kW beam power.

In summary, from this preliminary estimate we should be able to meet the alignment tolerance [28] of Horn 1 based on the latest estimates of the motion of Horn 1 due to thermal effects [32, 33]. A detailed analysis of the target chase region (using 3-D FEM) is currently underway to calculate more accurate temperature and alignment data. The NuMI chiller/dehumidification upgrade this summer will accommodate NOvA's increased heat load, and the only upgrade required for the existing cooling system will be the addition of new heat exchanger cooling coils. Finally, a further study of the paint characteristics and target hall components will be conducted to determine if the temperatures will be acceptable.

8.6.4.3.2 Radiant Heat Loads

As discussed in the previous section, the Duratek shielding blocks at the inner chase wall are predicted to reach very high temperatures due to the increased beam power, especially downstream of Horn 1 (113ºC). Thermal radiation between the hot wall surfaces and sensitive chase components (such as horns, target, and stripline) is of concern. The comprehensive 3-D finite element analysis (FEA) model will be used to compute the amount of heat transfer (primarily radiation heat transfer) from the shielding blocks to the chase components. This additional heat input will be included in the thermal analyses for these components to determine whether radiation heat shields will be needed. The cost for these heat shields will be covered under the Horn 1 off-project task. Additional chase temperature monitoring equipment will also be installed at critical locations, such as on chase walls and module bottoms, to better monitor temperatures of these areas during operation. The cost of this monitoring equipment is included in the resource loaded schedule.

8.6.4.3.3 Horn 1 Stripline Block

The section of NuMI Horn 1 stripline (aluminum 6101-T61) which delivers pulsed current from the top of the Horn 1 module to the downstream end of the Horn conductors is heated from two sources: joule heating from the current pulse and beam heating from the interaction with secondaries from the upstream target. One upper portion of this stripline is encased in steel shielding called the stripline block (basically part of the Horn 1 shielding module). The path of the stripline through the block is actually a dog-leg to reduce straight line holes through the shielding and is called a labyrinth (see Fig 8.48). The lower portion of this stripline flares out to attach (through bolted connections) to the conductors of Horn 1 and is part of the Horn 1 assembly (see Fig 8.49). The two portions, upper and lower, are connected via a remotely operated clamp mounted on the bottom of the stripline block.

Cooling to the stripline is achieved via 4 heat transfer paths, depending upon location: 1) forced air convection through the stripline block labyrinth channel (about 14 scfm from "short-circuit" in the chase air circuit), 2) forced air conduction of the Horn stripline that is exposed to chase airflow, 3) natural air convection of the Horn stripline that is "hidden" downstream of the Horn and not exposed to chase airflow, and 4) conduction along the stripline (in the same "hidden" area as 3) to the Horn 1 body (water cooled).

Future operations with 700 kW beam on target increases the beam heating source by a factor of roughly 1.75. Concerns that the increased heating will raise the temperature of the stripline above acceptable limits need to be addressed. This will require upgrades and enhancements to the chase stripline assembly cooling.

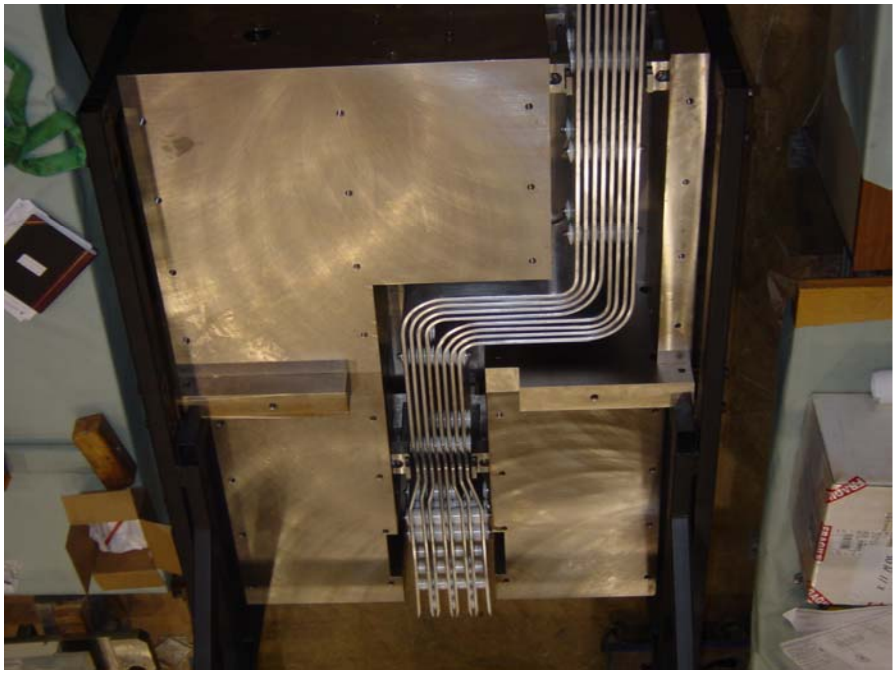


Fig 8.48: Stripline Block Assembly showing labyrinth with the cover removed.

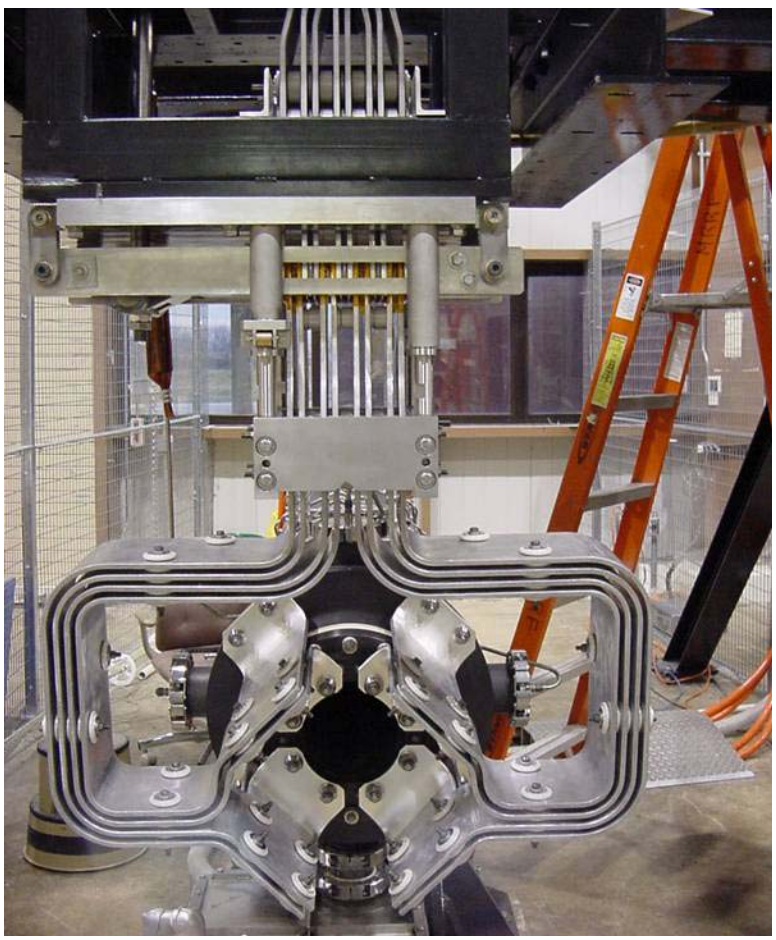


Fig 8.49: Photo of Horn 1 Stripline going up into the remote clamp on the test stand

An FEA of the stripline with the original NuMI design conditions (400 kW beam power) predicted a peak temperature of 100 ˚C in the stripline flag area (stripline segment that is bolted onto the Horn 1 nearest the beam centerline). This FEA was repeated for the ANU beam conditions (700 kW) and the peak temperature in the stripline flag rose to 166 ˚C (Fig 8.50). However, the joule heating estimate used in this FEA was overly conservative and high by a factor of 2, so further analysis is needed. Fig 8.51 shows structural FEA results for 400 kW NuMI conditions. The highest stresses are about 13 ksi in the region near the bolted connections to the horn conductors and are estimated to be 16.25ksi for the 700kW condition. Further details on stripline cooling concerns can be found in reference [34].

For ANU beam conditions, a more detailed and comprehensive thermal and structural FEA will be performed using the latest estimations of heat loads and cooling capacities to more accurately predict temperatures and stresses. This will be in conjunction with R&D to measure air velocities and convection heat transfer coefficients around a mock-up of the Horn 1 downstream chase area (using spare stripline components), which will help determine the level of forced air cooling required (if any). This work is currently underway and Fig 8.52 shows the test set-up at MI-8. The cost for this testing is included in the resource loaded schedule. The schedule also assumes that forced air cooling will be required, and the cost for the design, procurement, and assembly of a new cooling system on the stripline block has been included.

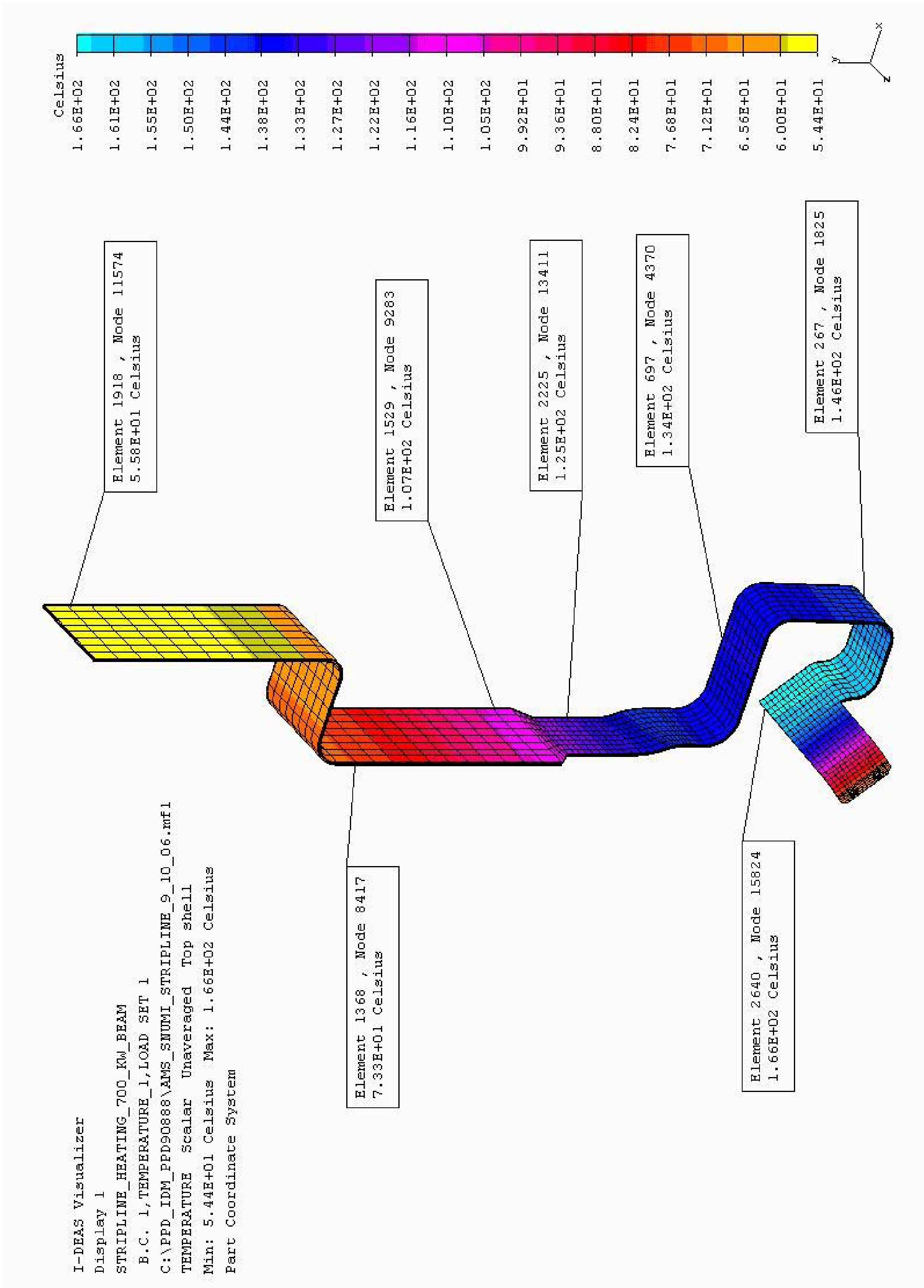


Fig 8.50 : Preliminary estimate for ANU Horn 1 stripline temperatures using NuMI FEM.
Note: Temperature distribution is over-predicted in figure (see text).

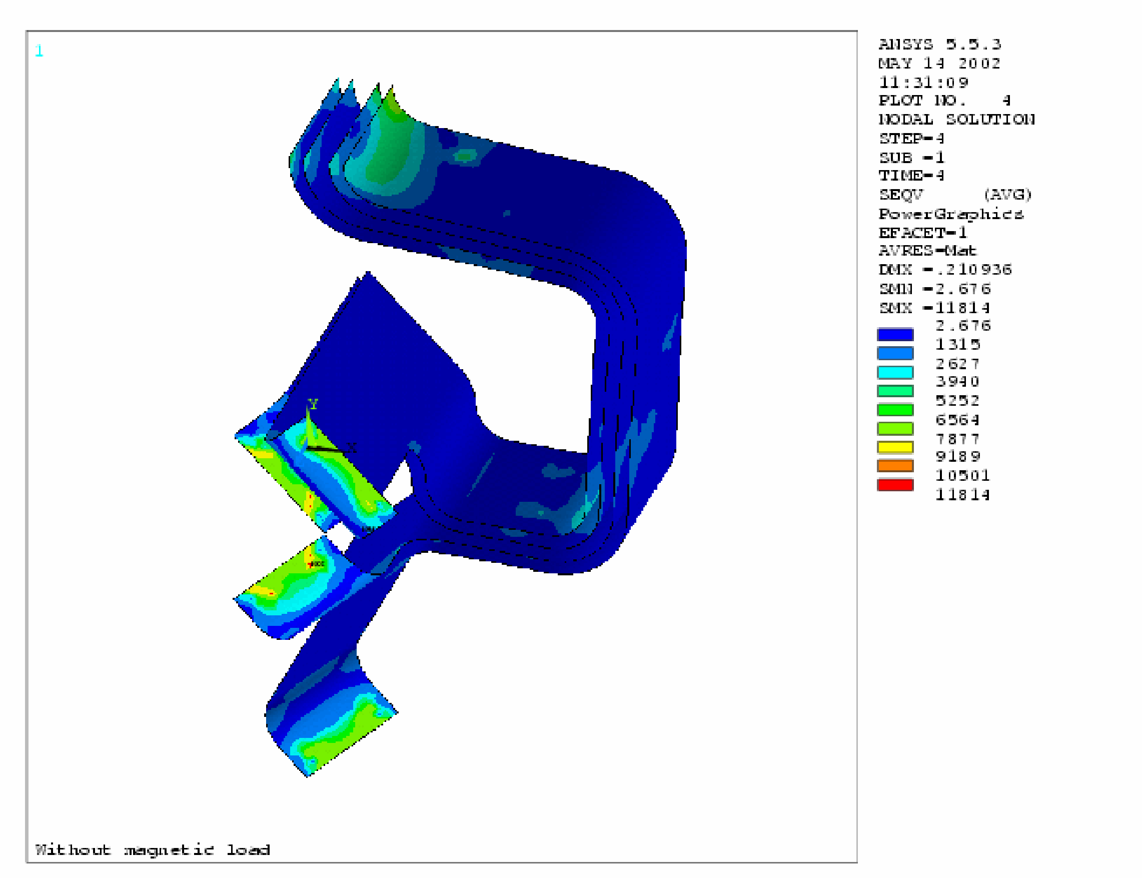


Fig 8.51: Equivalent stress (psi) in Horn 1 stripline for NuMI (400 kW beam) case without magnetic loading (includes alignment offset and thermal expansion).

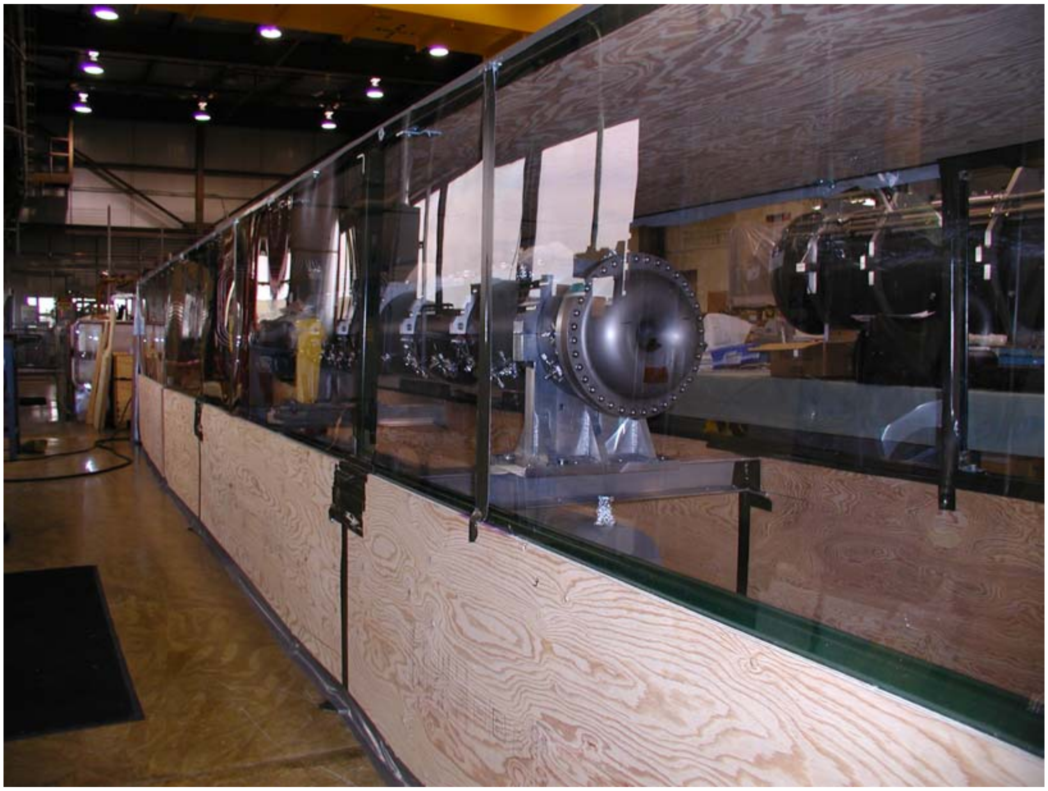


Fig 8.52: Wind tunnel mock-up at MI-8 of the Horn 1 chase area (using spare horn and stripline components) to study air velocities and cooling characteristics of stripline components.

8.6.5 Decay Pipe, Hadron Absorber, and Utilities

8.6.5.1 Decay Pipe and Hadron Absorber

The NuMI decay pipe consists of a 2 m diameter A36 steel pipe, 0.375 inches thick, 670 m long, encased in a cylindrical shell of concrete varying in diameter from 4.6 to 6.3 meters. In use, the steel pipe is evacuated. The decay pipe is cooled by twelve tubes, evenly spaced azimuthally, and running parallel to the steel pipe, but attached directly to the pipe only at the stiffening rings, which are spaced ten feet apart. The tubes comprise six distinct circuits. Six tubes bring chilled water from the downstream to the upstream end, where it is re-chilled and returned (see Fig 8.53 and Fig 8.54). The design flow rate of each circuit is 4.5 gallons per minute, for a total system flow of 28 gallons per minute. The water temperature leaving the chiller is 25 °C. The decay pipe and cooling has been analyzed at the higher heat loads expected during NOνA operations. Sufficient cooling can be supplied with a doubling of the flow rate in the decay pipe cooling pipes [35].

The upstream NuMI decay pipe window is a 72 inch diameter closure consisting of a 1 m diameter, 1/16 inch thick aluminum central portion, transitioning to a 3/8 inch thick steel head at the larger diameters (Fig 8.53). This transition is achieved with an explosion-welded aluminum-to-steel flange. This structure is not actively cooled. The heating and stresses in the central portion were investigated using an axisymmetric finite element model with approximately 800 four-node elements. A thermal version of the model was used to calculate the temperature profile in the head; a structural version of the model then read the temperature profile to calculate stresses. The rules for the allowable stresses were taken from the ASME Boiler and Pressure Vessel Code, Section VIII, Div. 2, Appendix 4. The loading to the thin window is due to vacuum and the cyclic thermal stresses resulting from beam energy deposition. The NuMI decay pipe window is capable of withstanding the higher beam power operations for the NOνA experiment as documented in [35].

The NuMI hadron beam absorber core consists of nine water-cooled aluminum modules, 1.32 x 1.32 x 0.31 meters in size. The (present) NuMI design criteria require that the absorber operate for one hour (approximately 1800 pulses) under the fault condition. The fault condition is defined as an improperly steered primary beam that misses the target and clears the protection baffle and thus is a much focused beam. Under normal operating conditions only about 18% of the 120 GeV primary protons strike the absorber, and the rms radial size of the beam is 20 cm compared to 5 cm in the fault condition. The fault condition is the critical operating condition for the absorber system [35]. To prevent multiple fault condition pulses, the hadron monitor will be used to monitor the NuMI beam. The hadron monitor will also be incorporated into the Beam Permit System and automatically stop beam operations should an errant beam pulse be detected.

Analyses of the mechanical integrity of the decay pipe, decay pipe window, and hadron absorber have been completed under NOνA/ANU operating conditions. In summary, these systems are capable of handling operations of the NuMI beamline with 700 kW of beam power and no modification to these NuMI beamline elements are required. A description of the analyses can be found in [36].

Fig 8.53: Decay Pipe Upstream Window (with decay pipe cooling pipes shown).

Fig 8.54: Decay Pipe Downstream Window (with decay pipe cooling pipes shown) and Absorber Hall (Hadron Absorber not installed) – emergency egress passageway on left.

Fig 8.55: Hadron Absorber Installed

8.6.5.2 Basic NuMI Cooling Systems Layout

The NuMI cooling systems consist of numerous Radioactive Water (RAW) and Non RAW skids in several locations. The following three diagrams are maps showing the general location and layout of the various systems. Beginning upstream, where the NuMI beamline originates, a Low Conductivity Water (LCW) system is housed at MI-62 (Fig 8.56). This feeds cooling water to the NuMI Extraction Line from the Main Injector Enclosure through to the Target Hall, where it cools the Target RAW skid. It also supplies some cooling for power supplies upstairs at MI-65.

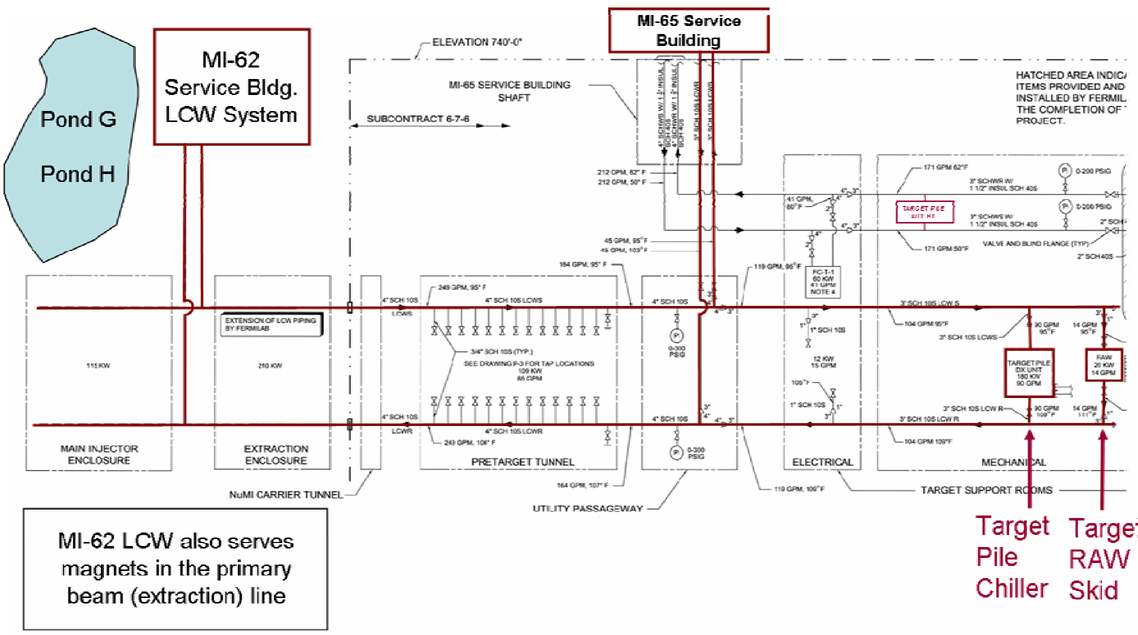


Fig 8.56: LCW System from MI-62 to the NuMI Extraction Line

In the Target Hall, there are also several RAW Systems to cool the Target, as well as both Horn 1 and Horn 2 (Fig 8.57). Also, there is a RAW System which cools the Decay Pipe, and which has a heat exchanger and expansion tank located on the Upstream (US) end at the Target Hall, and a second heat exchanger and circulation pumps located at the Downstream (DS) end at the Absorber Hall (Fig 8.57 and Fig 8.58). Lastly, in the Absorber Hall are the RAW and Intermediate Systems for the Absorber (Fig 8.58).

Outside of the local systems mentioned above, two systems bring water from external sources. The first is Industrial Chilled Water, ICW, which is 55 degree unpolished cold water from CUB, which supplied additional cooling capacity at MI-65. Second is the ground water, which is reclaimed from the MINOS sump, and used to cool the systems in the Absorber Hall and MINOS Hall before being pumped on to CUB for use there.

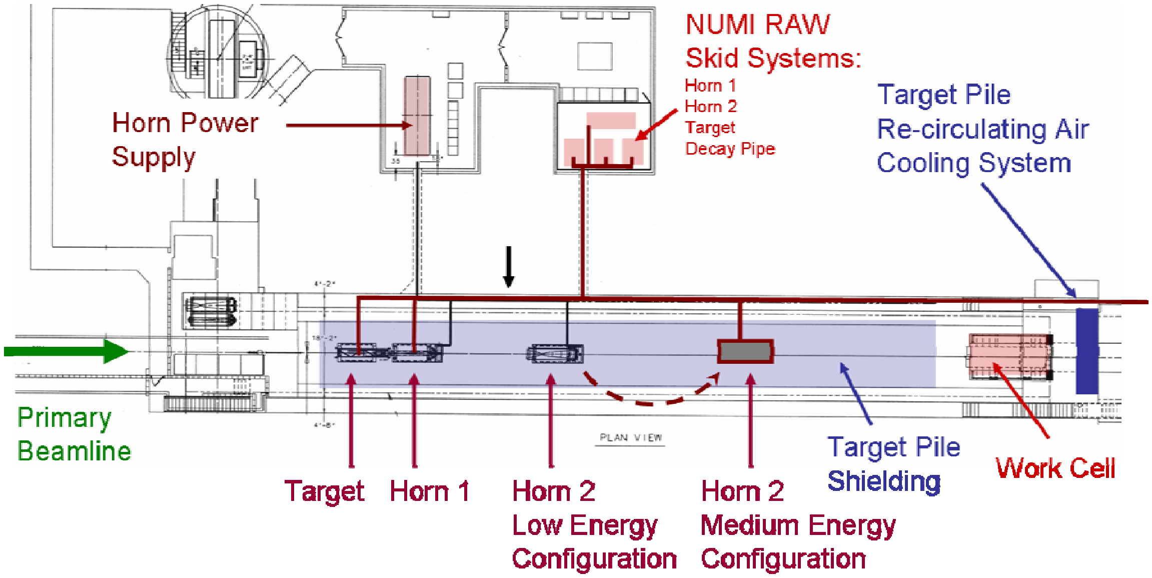


Fig 8.57: Horn, Target, and US Decay Pipe RAW Systems in the Target Hall

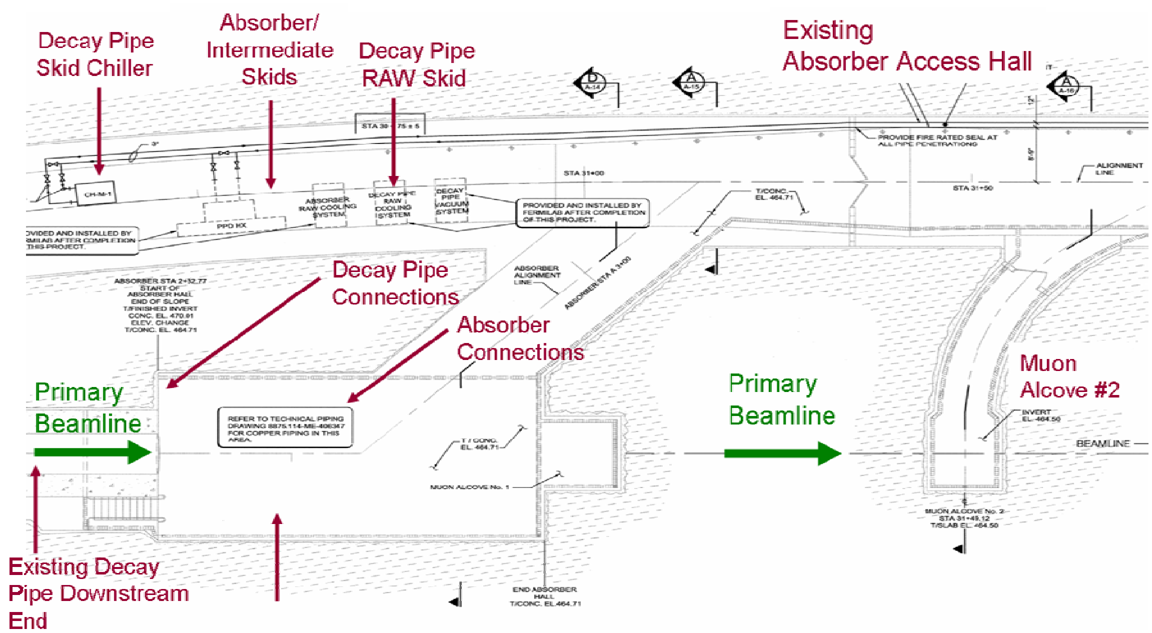


Fig 8.58: Downstream Decay Pipe and Absorber Cooling Systems in the Absorber Hall

8.6.5.3 NuMI RAW Systems

NuMI uses 6 RAW skids and 1 intermediate RAW skid to cool the target, horns, decay pipe, and hadron absorber. At this time, the skids appearing to require upgrades for capacity or performance are the Horn 1 and 2 skids, and the Hadron Absorber RAW and Intermediate skids. In any case there are plans to upgrade the instrumentation of the RAW skids to include remote readback of the temperature and flow measurements. Preliminary estimates of the necessary upgrades follow.

8.6.5.3.1 Target Raw System

Initial calculations suggest that the target RAW skid will be sufficient for NOνA, but final determination awaits a report from IHEP on the heat load of the medium energy target design. The need for upgrading the pumps and heat exchanger is not likely at this time, and such costs are not included in the project. The skid will be upgraded with modern instrumentation and controls.

8.6.5.3.2 Horn 1 and 2 RAW System

It is likely that the Horn 1 skid will need an upgrade to handle the higher heat load for NOνA. In addition to circulating the cooling water, the pump on the RAW skid also powers the ejector pump which removes water from the collection tank below Horn 1. Presently the ejector pump is barely adequate for the purpose of removing water from the holding tank. Therefore, the Horn 1 RAW system will be equipped with a larger water pump and the ejector pump for Horn 1 may be redesigned as well. This may be due to either pump capacities or piping sizes which restrict the pump capacities.

Initial calculations suggest that the Horn 2 RAW skid will be sufficient for NOνA. However, ejector pump performance will be reviewed to ensure similar issues do not exist with Horn 2. Project costs include both pumps and heat exchangers for both Horn 1 and 2 RAW systems. Both Horn 1 and 2 skids will be upgraded with modern instrumentation and controls.

8.6.5.3.3 Horn 1 and 2 RAW Piping

Horn 1 RAW system modifications that may require changes to the ejector piping are included in the Horn 1 estimate. Similarly, possible piping changes for the Horn 2 ejector pump are included in the Horn 2 estimate. Although it is not precisely known at this time which components need addressed, or to what extent, it is thought that the estimate is sufficiently conservative to address the performance issues suitably.

At this time, there are no plans to shift the location of Horn 1. Therefore, there are no associated piping costs.

During the shutdown for installing Horn 2 into the Medium Energy position, Horn 2 piping will need modifications. The piping for the RAW system will need to be extended from the Horn 2 low energy location to the Horn 2 medium energy location.

8.6.5.3.4 Decay Pipe RAW

At this time, the need for upgrading the pumps and heat exchangers for the Decay Pipe Systems is not clear. It appears that the current Decay Pipe RAW Systems are performing more than adequately. This may be due largely to the inability to model the system correctly. Originally, a worst-case scenario was used, one in which no heat loss to the surrounding rockbed was assumed. In reality, this transfer does occur, and apparently accounts for a significant level of cooling. At this time, Decay Pipe Upstream RAW Skid does not need to operate near capacity, and the chiller installed for the Decay Pipe Downstream RAW Skid is not even used. Therefore, sufficient capacity should be already available.

Decay Pipe RAW (Upstream Skid): An upgrade is planned for the Decay Pipe RAW skid that is located in the RAW room in order to handle the higher heat load for NOνA. The skid will be upgraded with modern instrumentation and controls.

Decay Pipe RAW (Downstream Skid): The skid will be upgraded with modern instrumentation and controls.

8.6.5.3.5 Hadron Absorber RAW and Intermediate

The absorber raw system will need upgrading to handle the higher heat load. In addition, there is an **Intermediate RAW System** inserted between the Absorber RAW system and the NuMI sump water cooling. This provides an extra measure of protection by isolating the absorber RAW water from the sump water. This system will also be upgraded with new pumps and heat exchangers for both, plus planned upgrades in instrumentation.

8.6.5.4 NuMI Cooling Water (Non-RAW)

There are three primary water-cooling systems used for NuMI. These cooling systems serve power supplies in the Main Injector and Primary Beamline areas, the RAW water systems in the target hall, the target hall air-cooling system, and decay pipe and absorber RAW systems.

Of the three water-cooling systems, only the heat exchanger on the MI-65 Secondary Chilled Water (SCHW) system needs upgrading before running NuMI at 700 kW. This was addressed during the Summer 2007 Shutdown, at which time an entirely new Target Pile air-handling system was installed.

8.6.5.4.1 MI-62 Low Conductivity Water (LCW) System

Currently this system serves heat loads in the Main Injector, extraction enclosure, pre-target area, power supplies in the below grade power supply room and in MI65, and the target area RAW skid. Refer to Table 8.19 for a summary of these heat loads. Some heat loads do increase, but these are offset by the removal of the Target Pile heat loads, which will be supplied by a separate chiller. Net heat loads will be slightly less than current demands. Therefore, modifications to this system for the NOνA 700 kW upgrade are considered to be minimal, consisting of additional instrumentation.

Systems Served by MI-62 LCW (Pond-H)	**Estimated Heat Loads (kW) NuMI (400 kW beam power)**	**Estimated Heat Loads (kW) NOνA (700 kW beam power)**
MI-62 LCW Pump	51	51
MI-62 Power Supplies	13	13
MI-NuMI Extraction Stub	453	471
Pre-Target Enclosure	189	196
MI-65 Target Service Bldg	33	40
Horn Power Supplies	12	18
Target Pile Chiller Coil	180	0
Target RAW	20	20
Total	**951**	**809**

Table 8.19: Systems served by the MI-62 LCW system. The capacity of the LCW system is 1.2 MW.

The existing Main Injector cooling pond that provides heat rejection for the LCW system is Pond H. It is approximately 1.1 acres and was initially designed to serve a 550 kW heat load through pump vault PV9. PV9 was modified during the NuMI construction project and has flow characteristics of 820 gpm with 90 ºF Cooling Pond Water Supply (CPWS) and 100 ºF Cooling Pond Water Return (CPWR). PV9 flow is routed to buildings MI62, MI65 and MI8. There currently are no connected loads in MI65 or MI8.

It is noted that the extra load will increase the temperature of Pond-H by about 1 degree. Pond-H is already somewhat problematic during summer months and can reach temperatures above the desired 95 degrees of the LCW system. Further analysis of Pond-H heating is continuing and more results can be found in [37, 12]. As a summary, cooling pond thermodynamics were modeled by a method that first benchmarked them to the actual performance we operate at and witness, and then modeled with a global heat load increase of 25%.

8.6.5.4.2 NuMI Sump Water Cooling System

In the MINOS Hall (underground cavern), heat is rejected to the sump water collected from tunnel inflow. The current inflow, measured in Oct 2006, is 165 gpm which is less than the initial flow of 235 gpm at occupancy in March 2004. Electronics equipment in the MINOS detector hall rejects heat to the 165-gpm sump water system through an LCW system and to air through fan coil units located in the hall. A portion of this flow, approximately 75 gpm, is then pumped to the Absorber area where the sump water is routed through an intermediate RAW skid for the hadron absorber and the decay pipe chiller in series. Refer to Table 8.20 for a summary of these heat loads. The intermediate Absorber RAW system was designed with a capacity of 210 kW and will not need to be upgraded. However, costs for pump and piping upgrades are included as a precautionary measure. Upgrades to the Absorber and Decay Pipe heat exchangers, which transfer heat to the Sump Water system, are covered in their respective sections.

This water is available for use by the NuMI facility after the NOνA upgrades and (if necessary) additional cooling for the MINERνA detector, the MINOS near detector, or the NOνA near detector will be supplied by an additional cooling system that is not included in the scope of the NuMI upgrades.

Systems Served by MI-62 LCW (Pond-H)	**Estimated Heat Loads NuMI (kW) (400 kW beam power)**	**Estimated Heat Loads NOνA/ANU (kW) (700kW beam power)**
Decay Pipe RAW	82	116
Intermediate Absorber RAW	60	105
Total	**145**	**220**

Table 8.20: Heat Loads for systems served by NuMI tunnel sump water.

8.6.5.4.3 MI-65 Secondary Chilled Water (SCHW) System

The current configuration of the secondary chilled water (SCHW) system consists of primary and standby 7-1/2HP pumps, a heat exchanger (HX) located on the mechanical mezzanine of the MI65 service building, and 4" piping that traverses down the shaft and to the below grade service rooms. Heat loads rejected to this system include the power supply room fan coil unit, the decay pipe cooling RAW skid, Horn 1 RAW skid, and Horn 2 RAW skid. Refer to Table 8.21 for a summary of these heat loads.

Currently, the Target Pile Chiller and Fan Coil Unit are being upgraded off project to be supplied with their own chiller at MI-65, so these loads will be removed. Therefore, included are costs for instrumentation upgrades only.

Heat from the heat exchanger is rejected to the Industrial Chilled Water, ICW, supplied from the Central Utility Building (CUB). The current SCHW pump has a flow and head capacity of 212 gpm at 60 fthd. The heat exchanger was designed with the following parameters: CUB chilled water ewt 45 ºF/lwt 55 ºF at 215 gpm; SCHW ewt 60 ºF/lwt 50 ºF at 212 gpm with a 310 kw capacity. At this time, no additional capacity requirements are expected for the CUB ICW. However, upgrades to the instrumentation are planned, and costs are listed as such.

Systems Served by MI-65 SCHW	**System Design Capacity (kW)**	**NOνA/ANU (700 kW) Heat Load (Estimated kW)**	**Comments**
Horn 1 RAW	72	90	
Horn 2 RAW	72	55	Horn 2 heat load may be higher in the ME location.
Decay Pipe RAW (Upper)	80	138	Scaled from MARS simulations of NuMI Design (400kW)
Fan Coil Unit	60	0	Cools the NuMI power supply and RAW rooms
Target Pile Chiller Heat Exchanger	28	0	No Change for NOνA Upgrade
New Target Pile Air Handling Unit	N/A	0	New for NOνA Upgrade
Total	**312**	**238**	

Table 8.21: Systems served by the MI-65 Secondary Chilled Water. The total estimated heat load of 440 kW is greater than the current capacity of 310 kW.

This system will be modified to provide additional cooling as required by NOνA. The above described pumps and heat exchanger will be replaced or modified to meet the new heat load requirements. Piping will be routed to the target hall through the utility passageway above the labyrinth.

8.6.5.5 NuMI Electrical Infrastructure

Increases in the capacities of the RAW water systems may require increases in the capacity of the electrical utilities serving the NuMI Target Hall. The scope of this task is limited to addressing electrical service modifications needed to handle the upgraded water systems. It is anticipated that the service supplied to the locations is substantive enough for skid upgrades, and that electrical modifications will be mainly for circuit breakers, contacts, and minor associated wiring, for only the skids that receive significant upgrades.

It is currently assumed that all systems receiving pump and other extensive upgrades will require electrical service upgrades. However, this may not be the case, as present system equipment may be sufficient. For example, a system with a 3 Hp pump, being upgraded to a 5 Hp pump, may already have breakers and contacts sufficient for the new load. All upgraded systems will be looked at, to verify the appropriateness of currently installed hardware, and, if required, determination of proper upgrades.

8.6.6 NuMI Radiological Safety Issues

8.6.6.1 Overview

Safety issues are an important consideration for NovA. Fermilab is committed to maintaining a safe work place, minimizing worker exposure to radioactive material, and protecting the environment. Radiological concerns are of particular concern for the NuMI beamline given the intensity of protons directed on the target. The NovA upgrades will be installed during shutdowns occurring after the NuMI beamline has been operational for several years. At this time residual radiation does rates in the target hall will be significant and advance preparations are necessary to perform the installation work safely and with exposure to radiation as low as reasonable possible.

The NuMI/MINOS Shielding Assessment [38] has recently been updated to 500 kW operation. It will need to be updated again for NovA operation at 700 kW. In order to run at 700 kW, the shielding assessment needs to address ~850 kW operation for a safety margin of ~20% over the 700 kW operation. Potential environmental impacts include radioactive air emissions, groundwater protection, prompt radiation doses, and tritium production. These issues are discussed in some detail in the following sections. More details on the radiological releases for the NuMI facility can be found in FERMILAB-TM-2375.

8.6.6.2 Earth shielding assessment:

The NUMI extraction line would require 23.8 ft. of earth shielding for NOvA operation at 850 kW beam power (based on a safety margin of ~20% over the 700kW operational level) if the berm is categorized as minimal occupancy. The nominal shielding for the NUMI extraction line is 24.5 feet and because of the 3 degrees down slope of the carrier pipe, there is sufficient earth shielding for the rest of this beam line [14,39].

8.6.6.3 Groundwater and surface water:

Activation levels of ground water from beam line operations would remain below applicable regulatory limits [40]. The result in Table 8.22 indicates the concentrations of radionuclides immediately outside the NuMI tunnel. These concentrations will be significantly reduced due to the further mixing with the NuMI tunnel inflow water [41, 42, 43, 44, 45].

Type of Operations	Estimated Maximum Tritium Level	Estimated Maximum ^{22}Na Level
NuMI/NOvA at 850 kW	4 pCi/ml	0.4 pCi/ml
Groundwater Regulatory Limits	20 pCi/ml	0.4 pCi/ml

Table 8.22: Estimated radionuclide concentrations in the water immediately inside the NuMI tunnel that would be expected during the running of the NuMI facility under NOvA operating conditions at 850 kW of beam power.

The design of the NuMI tunnel ensures that groundwater in its vicinity continuously flows into the tunnel, where it is collected and continuously pumped through the industrial chilled water system eventually ends up in the surface cooling ponds. The cooling ponds are underlain with naturally occurring clay, therefore preventing direct contact of radionuclides such as tritium or ^{22}Na produced during the MINOS and NOνA experiments with surface water [46].

The estimates for the pond water concentration would be conservative because they assume drought conditions. In drought conditions the volume of water in the Fermilab pond system would be reduced resulting in a higher concentration of radionuclides. Estimates of the tritium and ^{22}Na concentration that would result from running NuMI under the NOνA operating conditions are summarized in Table 8.23. All of these concentrations are predicted to be well below the regulatory limit for surface water.

Phase	Tritium Levels (NuMI Sump Water)	Tritium Levels (Pond Water)	^{22}Na Levels (NuMI Sump Water)	^{22}Na Levels (Pond Water)
NuMI/NOνA	57 - 114 pCi/ml	14 - 28 pCi/ml	< 0.7 pCi/ml	< 0.2 pCi/ml
DOE Surface Water Regulatory Limits	2,000 pCi/ml	2,000 pCi/ml	10 pCi/ml	10 pCi/ml

Table 8.23: Estimated concentrations of tritium and ^{22}Na in the NuMI sump and Fermilab ponds during NuMI operations for the MINOS experiment and for the NOνA experiment at 850 kW of beam power.

8.6.6.4 Air emissions:

Tritium and other short lived radionuclides are also produced as a normal by-product of NuMI operations. The airborne radionuclides produced in the NuMI facility are released into the atmosphere through vent stacks to the surface of the Fermilab site. Environmental emissions are limited by minimizing the ventilation of the tunnels during beam operations. Ventilation is maximized for personnel access, however, by allowing sufficient time for decay after beam shutdown, and before accessing thus air emissions are still limited. Air from the ventilation stacks is monitored for radionuclide emissions.

The total activity released from NuMI stacks in 2006, the extrapolated quantities to NOνA beam powers, and the estimated maximum dose rate at the site boundary from these releases is summarized in Table 8.24. This dose rate at the site boundary is assessed for a hypothetical member of the public who would spend the entire year at the location of maximum exposure at the Fermilab site boundary. Total releases are reported annually to the IEPA and the U.S. Environmental Protection Agency (EPA) in accordance with conditions of the relevant NESHAP permit [47].

The operations of the NuMI facility for the MINOS experiment have not caused Fermilab to approach the regulatory limits for total activity releases or for the dose limit at the site boundary [48, 49].

	2006 measurements Ci/yr	Scaled to NOνA beam power Ci/yr
EAV1	22.0	77.0
EAV2	8.7	30.5
EAV3	2.9	10.2
SR3	2.7	9.5
Total(Ci)	36	127
DE (μrem)	28	97

Table 8.24: Estimated maximum release of radionuclide air emissions and estimated maximum dose at the Fermilab site boundary during operations of NOνA at 850 kW of beam power.

With no further mitigation, total emissions at the site boundary produce 0.097 mrem/yr, which is less than the EPA limit. EAV1 is the largest contributor to the total NuMI emissions. The EAV1 source can be reduced significantly with out any significant affects on the experiment by reducing the flow rate or using a different exhaust location to allow longer decay times for the radioisotopes.

8.1.1.1.1.1 Primary radio-active water (RAW) systems:

Primary cooling water for the target, horns, decay pipe and the absorber become radioactive. ^3H and ^7Be are the relevant radioisotopes. Usually in a few hours all the other radioisotopes have decayed away. Most of the ^7Be is trapped in the de-ionization bottles. Table 8.25 shows the estimated annual amount of radioactive isotopes ^7Be and ^3H produced in the cooling water [50]. RAW tanks are sampled frequently [51]. RAW systems concentration levels, the neutrino program schedule, operational impact to other parts of the accelerator complex, and ALARA principles are all considered in determining the appropriate schedule for water replacement.

At 850 kW	^3H (Ci)	^7Be (Ci)	Volume (Gallons)
Target	0.1	1.0	30
Horn1	4.5	22.5	115
Horn2	1.1	6.7	100
Decay Pipe	0.0	0.1	725
Hadron Absorber	0.0	0.1	135
Total	5.7	30.4	1105.0

Table 8.25: Estimated maximum production of long lived radionuclide in the radioactive water systems during operations NOνA at 850 kW of beam power.

8.6.6.5 Residual radioactivity and the work cell upgrade:

The original NuMI Target Hall Work Cell (Fig 8.59 and Fig 8.60) and associated Waste Stream Plan were developed with 2 key concepts in mind. The first was that components

(Target/Baffle, Horn 1 & Horn 2 [52]) would not be repaired in the Work Cell, but only replaced. The second was that failed, radioactive components would be long term stored in a shielded pit, called "the Morgue" (Fig 8.61 and Fig 8.62) with no plans for radioactive component removal up-shaft for disposal. Practical lessons learned from 2 years of operational experience of NuMI and the proposed upgrades for NOνA have altered those fundamental concepts and require re-designing the Work Cell and Waste Stream Plan. These changes need to be implemented for NuMI operation, regardless of NOνA, thus they are off project operational upgrades. Residual dose rates have been predicted for the various stages of the NOνA Project [53]. They are shown in Table 8.26. The last row of Table 8.26 shows the predicted residual activity of NuMI beam devices after three years 850 kW beam operations.

Time	Protons on Target	Power (kW)	Scale Factor	Target (**R/hr**)	Target module/carrier (mrem/hr)	Horn 1 (**R/hr**)	Above Horn 1 Module, by "ears" (mrem/hr)	Horn 1 T-Blocks Top (mrem/hr)	Horn 2 (**R/hr**)
MARS predicted	1.40E+20	400				160	4	4	
Spring 2006 shutdown	1.40E+20	250	1	1.20	50 to 150	80	200	75	5 to 8
At time of first NOνA shutdown	9.00E+20	250-400	1.2 to 2	2.40	100 to 300	120	300	110	8 to 12
At time of second NOνA shutdown	1.20E+21	400	1.7	2.64	170	136	340	127.5	11.05
Running NOνA for three years	6E20/yr	850	4.9	**6**	486	**389**	971	364	**32**

Table 8.26: Summary of the predicted residual dose rates, after one day of cool down, of the beam devices after three years of NOνA beam operations at 850 kW.

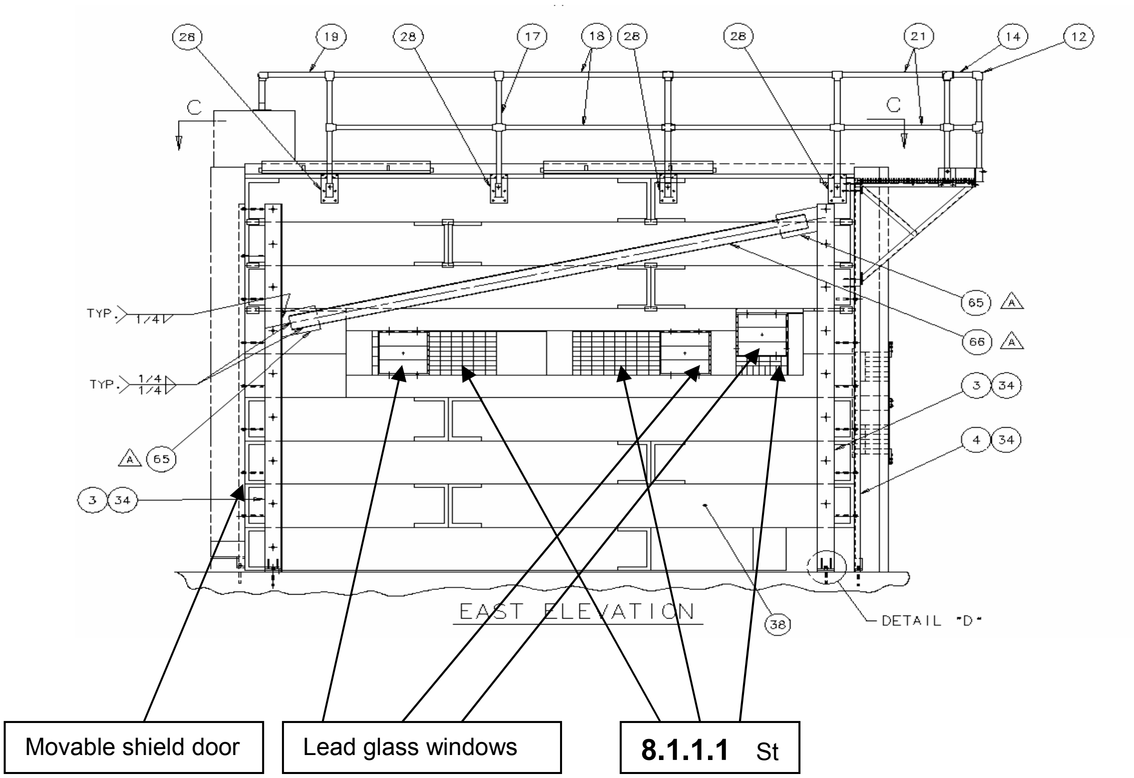


Fig 8.59: East Elevation view of existing Work Cell.

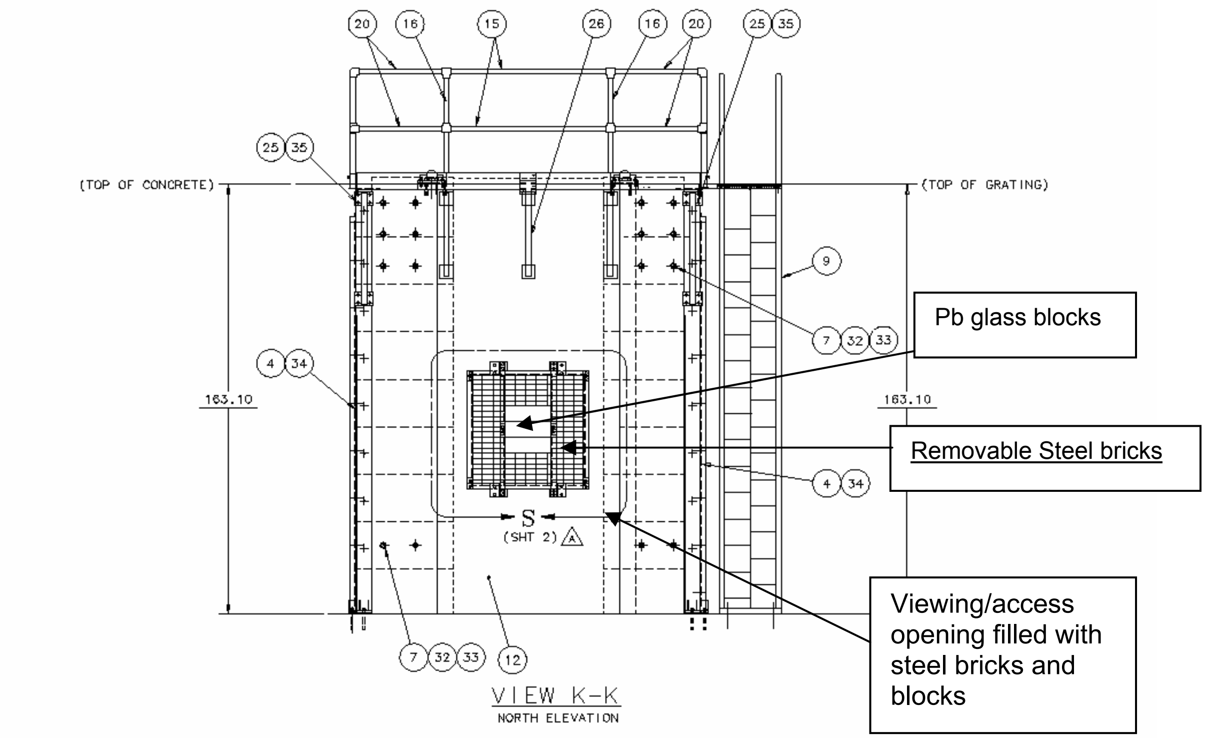


Fig 8.60: North Elevation view of existing Work Cell

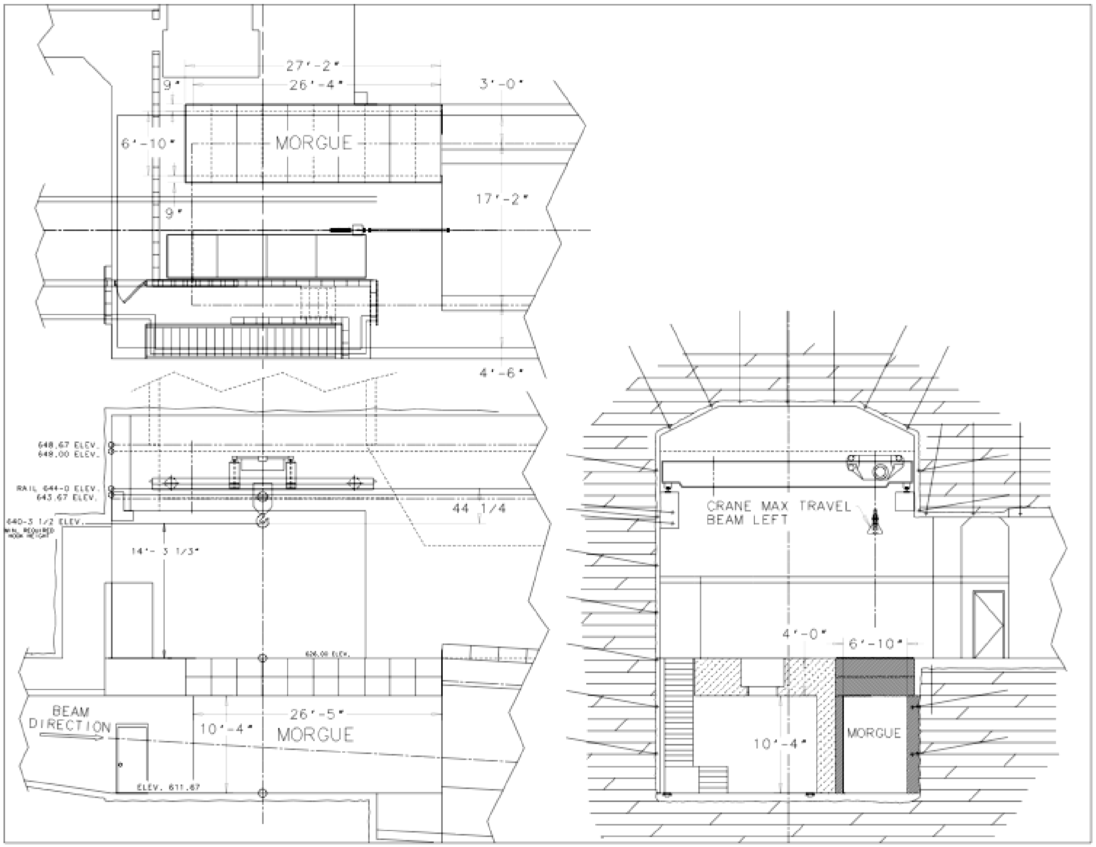


Fig 8.61: Plan and elevation views of existing Morgue area.

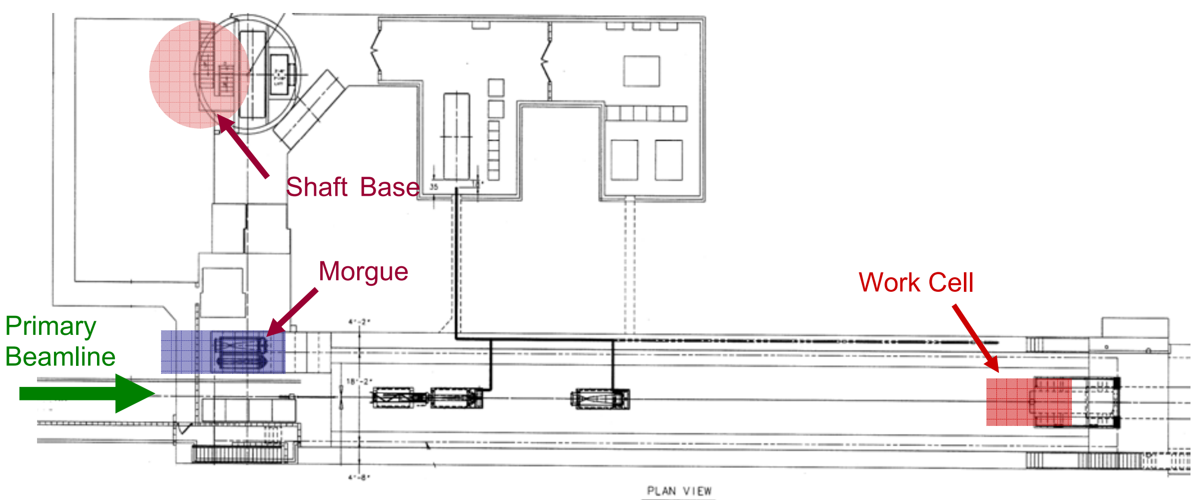


Fig 8.62: Plan view of Target Hall showing relative locations of Morgue, Work Cell, and MI-65 shaft base.

The design concept for the Work Cell upgrade is to design and fabricate a (possibly reconfigurable) set of shielding walls that can be assembled to form a shielding extension to the current Work Cell. The Work Cell upgrade will include at least one set of tele-manipulators and a lead glass window unit to allow remote repair activities without excessive dose to workers. If space constraints do not allow the shielding extension to remain in an erected configuration, then the shielding extension and tele-manipulator station will need to be designed for easy erection and disassembly to keep access times for repairs short. It may also need to be designed to allow storage in the limited space of the Target Hall when not in use. Thus it is envisioned that a modular design will be pursued such that the shielding extension can be custom configured to place the manipulators at the proper location for the repair work at hand while providing adequate shielding for workers.

With operations at the NuMI Target Hall for NOνA now projected to extend beyond 2012, capacity of the Morgue is inadequate for storage of radioactive components. It is conceivable that NOνA components could require storage at a rate of 2 components per year, on average. In addition, component modules, previously not considered replaceable, may need to be replaced during the NOνA era. The Radioactive Component Removal Plan must be developed to include short-term storage of components and possibly modules in the Morgue, removal of those components up-shaft, and subsequent long-term storage.

8.6.6.6 Prompt radiation:

There are several labyrinths and penetrations in the NuMI tunnels and halls for personnel access, connection to equipment, air inlets and exhausts, survey risers and an air-cooling labyrinth [38]. Prompt radiation from the penetrations and labyrinths are estimated by calculations and extrapolation from measurements during the operation of NuMI [54,55]. The results of the radiation attenuation calculations for these labyrinths and penetrations are given in the Table 8.27 and the discussed below. Dose rates due to losses under normal and accident conditions are given. An accident is defined as five sequential full intensity proton pulses. Normal losses depend on the location. Near the target and baffles it is full beam loss during an hour and 0.01% of the full beam at other locations.

Region	Normal Loss		Accidental Loss	
	Exit Dose Rate (mrem/hr)	Comment	Exit Dose Rate (mrem/hr)	Comment
Survey Riser SR-1	7.3	existing plug is ok	192	Existing plug is enough
Air Vent EAV-1	0.001	OK (loss rate 1E-4)	0.001	OK
Survey Riser SR-2	0.45	existing plug is ok	11.8	Existing plug is enough
Target Hall labyrinth	0.009	OK	0.2	OK
Target Hall Equipment Door	1.6	Post as Controlled Area Min. Occup.		
Stripline Penetration	290	Existing shielding ok	Current shielding is sufficient	
RAW Penetration	0.13	Pipes will fill voids		
Survey Riser SR-3	0.007	OK		
Vent EAV-2	0.002	OK		
Vent EAV-3	0.001	OK		
Absorber Labyrinth	1.1	Post as Controlled Area Min. Occup.		
Bypass tunnel (muons)	1.7	Post as Controlled Area Min. Occup.		
Muon Alcove 2	0.4	Door posted and interlocked		
Muon Alcove 3	0.024	Door posted and interlocked		
Muon Alcove 4	0.001	Door posted and interlocked		

Table 8.27: Dose rates at the exit and mitigation where needed for the NuMI labyrinths and penetrations during 850 kW operations.

As the table shows the horn strip line penetration was a concern. The section of the penetration between the horn and the top of the module is not considered here, since the target hall is not accessible during the beam operation. Only the section of penetration between the target hall and the power supply room is needed to calculate the dose to personnel in the power supply room. The source term is calculated at the entrance to this penetration using MARS [56]. The neutron spectrum at the entrance to this penetration is mainly composed of neutrons of energy less than 1 MeV. Polyethylene, which is an effective absorber of these neutrons, was effectively used to shield this penetration. The dose rates in the power supply room are less than 0.25 mrem/hr.

Because of the muons and the radiation leaking out of the Hadron Absorber labyrinth and Muon Alcove 2, the bypass tunnel starting at Muon Alcove 4 will most likely need to be posted as radiation area for the 850 kW beam operations.

8.6.6.7 Summary

The NuMI/MINOS Shielding Assessment will need to be updated to address NOνA operation. No upgrades, other than posting changes, are anticipated to be necessary. Planned off project operational upgrades to radioactive component removal, repair and storage will facilitate component replacement for NOνA operations.

8.6.7 Changes in the NuMI Upgrades Design since the CDR

A number of changes have been made to the scope of the NuMI upgrades since the writing of the CDR for the NuMI Upgrades [36].

There is no longer a need to build six new quadrupole magnets for the primary beamline. Enough magnets exist in the A1 beamline that can be removed and transferred to the primary beamline. The A1 beamline is used to transfer antiprotons from the Main Injector to the Tevatron and will not be needed upon the completion of Collider Operations.

Further analysis of the ME target has been performed by IHEP. The study reached the conclusion that the instantaneous pressure rise in the water cooling channels will not pose a problem. Therefore a bubbler system to protect the target water cooling lines from thermal shock is not necessary and has been removed from the scope of the project.

Only minor modifications to the Horn 1 are needed in order to handle the increase in the beam power from 400 kW to 700 kW. Essential the only change needed is to reduce the thickness of the outer conductor. Since the horns are consumable with a lifetime of ~1-2 years, the necessary modifications to the horns can be made during the normal spares/replacement production cycle. This task is thus off project.

A complete redesign and construction of a new Horn 1 module is not necessary. The present Horn 1 module is capable of handling the higher energy deposition. Modifications to the stripline block will still be needed, but these can be done independently of the Horn 1 module. Thus the horn 1 module is not longer on project.

Upgrades to the target chase chiller are expected as part of the continuing operational improvements of the NuMI beamline. The upgrades are presently in the design stage and expected to be complete by the fall of 2007. The upgrades are consistent with the ANU project but will not completely cover the cost of future upgrades needed to operate at the higher power. The completion of this work will allow a reduction in the cost and scope of the target chase cooling upgrade, but the magnitude will not be determined until the operational improvements are completed.

8.6.8 Remaining Design Work for the NuMI Upgrades

Further analysis and design of the IHEP medium energy target is required to add water cooling to the outer casing and to understand the cooling of the windows at the entrance and exit of the target.

Modifications to the target carrier are necessary to handle the larger diameter of the ME target that will be used for the NOvA experiment. The design and engineering work for these modifications are needed before proceeding with the construction

The University of Texas – Austin designed and built the first hadron monitor that is now in use for the NuMI beamline. With the increased beam power the hadron monitor may need modifications. The necessity or extent of the modifications has not been determined yet, but the project does include a task to review the existing design.

It is important that a detailed study of the available space in the Target Hall be conducted that aims to develop a comprehensive new layout plan for the various target hall activities. As a result, new equipment (mostly in the form of structural supports) will be designed to help with the transport and staging of shielding blocks during shutdown activities, in a way that optimizes use of the target hall space.

As discussed in earlier sections, the Duratek shielding blocks at the inner chase wall are predicted to reach very high temperatures (113ºC) due to the increased beam power, especially downstream of Horn 1. Thermal radiation between the hot wall surfaces and sensitive chase components (such as horns, target, and stripline) is of concern. The comprehensive 3-D finite element analysis (FEA) model will be used to compute the amount of heat transfer (primarily radiation heat transfer) from the shielding blocks to the chase components. This additional heat input will be included in the thermal analyses for these components to determine whether radiation heat shields will be needed.

A more comprehensive thermal and structural FEA of the horn 1 stripline is needed to more accurately predict temperatures and stresses under the 700kW condition. In summary, by making relatively minor changes to Horn 1's water cooling components, preliminary studies indicate that the Horn 1 stripline and stripline block will survive the 700 kW beam power scenario [34]. More detailed and sophisticated FEA plus air velocity measurements need to be performed to confirm this preliminary conclusion

A final determination of the heat loads in each of the RAW systems is needed before proceeding with the detailed design of the RAW system modifications.

8.7 Beam Physics

8.7.1 Overview

The Accelerator and NuMI Upgrades (ANU) activity achieves an 80% increase in proton throughput over the Proton Plan[2] [57] by moving the slipping portion of the injection and slip-stacking processes from the Main Injector to the Recycler, otherwise maintaining the production process of the Proton Plan. For the Booster, the additional issue will be the need to increase throughput by 80% through an increased rate of pulses (the rate planned to be achieved by the Proton Plan). The Main Injector will have the slipping process offloaded to the Recycler, but will have to cycle faster and more often. The Recycler was not built to store high-intensity proton beams, but the similarity of its lattice and aperture with the Main Injector make it capable of doing so; the beam dynamics within the Recycler will be similar to those in the Main Injector.

This overview summarizes the beam physics issues associated with implementing the ANU design and achieving the planned beam power. The following sections detail the beam physics efforts as part of the NOvA ANU subproject. The Beam Physics efforts are organized into three sections:

- **ANU Demands on the Proton Plan** analyzes the dependencies of the ANU design on the Proton Plan design. Implementing ANU relies on the sustained operation of existing machines, as well as improvements that are to be achieved through the Proton Plan.
- **Machine and Process Analysis** is a collection of theoretical, experimental, and simulation studies on existing machines and the planned ANU processes. The results will be documented and used as reference for commissioning and operation with the ANU schemes.
- **Proton Projections** produces a method for realistic predictions of future ANU performance. This primarily includes designing a set of reasonably measurable performance metrics for the accelerator and NuMI complex. These metrics will be measured during the ANU project and used to produce updated projections.

[2] The Proton Plan Design Handbook is found on its webpage: http://www-accel-proj.fnal.gov/internal/Proton_Plan/index.shtml. A public site viewable outside Fermilab is: http://www-accel-proj.fnal.gov/Proton_Plan/index.shtml.

8.7.1.1 The ANU Beam Cycle

The ANU Recycler cycle involves stacking 12 batches of 8 GeV booster beam in the Recycler, accelerating the beam in the Main Injector, and extracting the beam to NuMI. An approximate timeline is shown in Fig 8.63 and is described in this section.

The Linac and Booster will accelerate beam on 12 successive cycles spaced at 15 Hz (67 ms). Such operation is presently typical for the Proton Source. The Linac beam will provide its typical beam: debunched 200 MHz bunches at 400 MeV and intensity of ~ 10^9 H^- ions per bunch, with ~ 20 μs pulse length.

The Booster will accumulate the Linac beam and accelerate it to 8 GeV. The extracted beam will be bunched at 53 MHz and have an intensity of 4-5×10^{12} protons per batch (~81 bunches). On every Booster cycle, the Booster must rebunch the beam from the Linac and accelerate it through transition; beam loss is experienced early in the cycle after debunching and at transition. The extracted beam will use the MI-8 collimators (installed as part of the Proton Plan) to reduce the tails of the transverse and momentum distributions.

Each Booster batch will be injected to a particular location on the Recycler azimuth with respect to the beam already circulating[3]; the batches are injected every 1/15 s. The first six batches are injected such that they lie adjacent to each other, within the limitations set by the injection kicker[4]. The Recycler 53 MHz RF will be active to keep the beam bunched, using about 100 kV; whether one or two frequencies will have voltage will depend on the optimized details of slip-stacking. After the sixth injection, the six revolving batches must be accelerated or decelerated to a different orbit. The Recycler, being seven times the circumference of the Booster, would then have one additional slot for further injections[5]. Beam is then injected six more times into that gap; the momentum difference induces slipping which moves the newly injected beam out of the gap in the time between injections. Two RF frequencies will be used to keep each of the beams bunched. After the final batch is injected the beams slip again for 1/15 s, reestablishing the gap for extraction. A kicker system pulses before each injection and extraction to clear beam from the needed gap, sending it to the abort instead; this system is necessary to prevent injection losses from exceeding acceptable levels.

The Recycler beam is extracted in a single-turn into stationary 53 MHz RF buckets in the Main Injector, for a total intensity of ~5×10^{13} protons. For twelve batches being merged into six, the Main Injector will have charge in about 500 of its 588 buckets. The buckets are sized to each contain two slip-stacked bunches[6] using about 1 MV/turn among the 20 cavities. The beam is accelerated and collimated as in the Proton Plan, except that the ramp rate of the magnets will be increased to 240 GeV/s (from 205), and an additional two RF cavities will increase the ring voltage by 11%. Extraction will occur in a single turn, sending the entire beam to the NuMI beamline; this extraction is presently in place for NuMI operation.

The NuMI primary line optics will remain the same as the original design, except that the final focus may be changed to enlarge the beam size on target for survivability[7]. However, the

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[3] The first batch is not sent to a particular location as there is no beam already circulating in the Recycler.

[4] We expect that there will be three vacant buckets between 81-bunch batches.

[5] This assumes that the injection kicker has sufficiently short rise and fall times to fit in the seventh batch, as designed. If the kicker is not fast enough, a double-length slot must be made by injecting only five batches before slipping, reducing the total beam power to NuMI by 8%.

[6] The two bunches are initially separated by momentum, but not azimuth.

[7] The present spot size is typically 0.8-1.2 mm RMS in both transverse directions. The larger beam sizes are correlated with higher intensities. The design of the primary beamline allows the spot size to be tuned by a simple adjustment of the last few quadrupole magnets.

line will need to operate at an increased rate from its design, forcing some changes in magnets and power supplies. Target hall components will have to deal with greater average power deposition, though the intensity per pulse will be the same as in the Proton Plan.

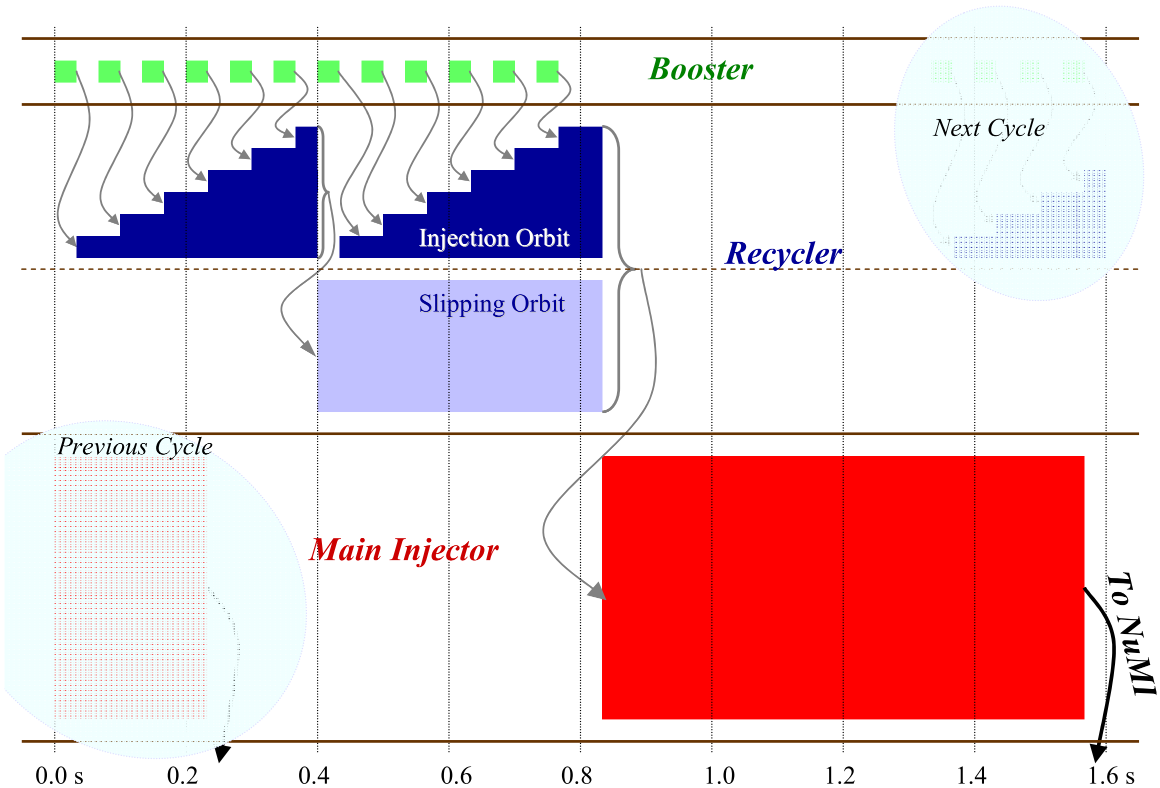

Fig 8.63: A diagram of the timeline for the slip-stacking process. The vertical height of each bar is proportional to the amount of beam. The zero is set arbitrarily at the time of first injection from the Booster; an operational timeline will likely start earlier.

8.7.1.2 Slip Stacking

Slip stacking is a set of RF manipulations which merges two sets of bunched beam into one, doubling the bunch intensity (or conversely halving the azimuth used for the two beams). The distinguishing component of slip stacking is the use of two RF systems with slightly different frequencies; the RF is used to keep two separate bunch trains bunched, while being at different energy from each other and thus having different revolution frequencies. The RF voltages are just high enough to keep the beams bunched, but low enough to allow the two beams to slip past each other. When the two are coincident in azimuth (separated in energy), a significantly more powerful RF system is turned on. The third system operates at the mean of the two initial frequencies and is powerful enough to keep beam contained in its large amplitude RF buckets, preventing further slippage. Compared to other stacking procedures, the advantage of slip stacking is that it occurs quickly, because it does not require debunching, rebunching, or other slow processes.

The procedure of slip stacking was first developed and demonstrated at CERN [60], but the gains were not sufficient to offset the increased losses in the CERN PS or SPS; so slip stacking was never used in regular operation at CERN. At Fermilab, slip stacking was proposed in the

Main Injector as part of the Run II luminosity upgrades[8] [58], where it would improve antiproton production rates by increasing the number of protons delivered to the antiproton target. A scheme was developed through which the Main Injector could support slip stacking for antiproton production, while also providing (unstacked) beam to NuMI. This mode of operation has been in place since 2004 [59] and typically provides batch intensities of 8×10^{12} protons, concurrent with an additional 22×10^{12} of unstacked beam for neutrino production.

Slip stacking, as operational in the Main Injector, combines two Booster batches into one for antiproton production. Typically, an additional five batches are injected after the initial two, but are not slipped – these do not directly affect the slipping process. To accommodate slipping, two RF systems change between four different RF frequencies: $\{f_0 - \Delta f, f_0 - \Delta f/2, f_0, f_0 + \Delta f/2\}$. f_0 = 52.8114 MHz is the Main Injector injection frequency; Δf ≈ 1400 Hz is the frequency separation between the beams at injection and capture.

As shown in Fig 8.64, the beam is injected into the first RF's buckets at f_0, and then decelerated to $f_0 - \Delta f$. 1/15 s after the first injection, the second batch is injected into the second RF at f_0. In a sequence that maintains a minimum frequency difference[9], the frequencies of the two beams are adjusted so that they finish at $f_0 \pm \Delta f/2$ and the time integral of Δf between the second injection and capture must equal the azimuthal separation of the batches at the second injection. In the sequence shown in Fig 8.64 the frequency difference is modulated, reaching a maximum near 2 kHz, leading to an integral of around 130 buckets. The batch length is only 84 buckets; the greater initial separation minimizes interference of the injection with beam leeched from the first batch due to the two RF frequencies. Some of the freedoms in choosing the above parameters are reduced when slipping more than two batches, as in the Proton Plan and ANU.

[8] The Run II project homepage is http://www-ad.fnal.gov/run2upgrade/. Slip stacking was an addition to the original Run II designs.

[9] A minimal criterion for stability is that $\alpha = \Delta f / f_s \geq 4$, where f_s is the synchrotron frequency of the beam under the influence of a single RF system. For a typical voltage of 100 kV/turn f_s =280 Hz, and scales with the square root of voltage. For details, see. Boussard and Mizumachi [60] or the F. E. Mills reference [61].

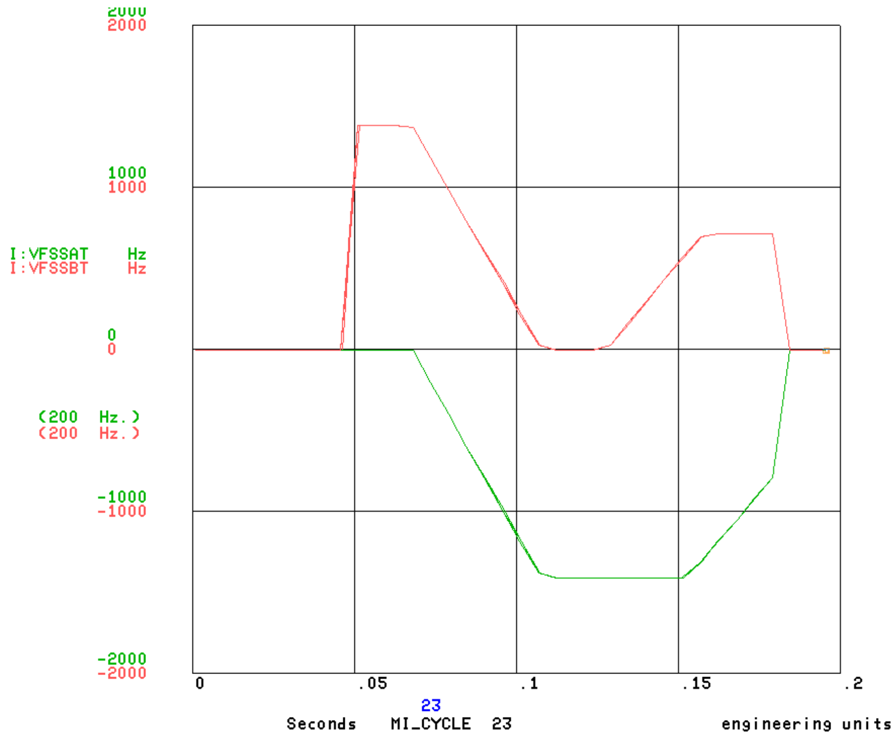

Fig 8.64: Operational frequency curves for two-batch slip stacking. Beam is injected on the central frequency (0 Hz) at ~ 0.06 and 0.12 s. The frequencies of the two beams are adjusted (also changing the energy) until they slip fully and bracket the central frequency, at which time they are captured (0.18 s).

The Proton Plan is extending slip stacking to NuMI by injecting 11 batches of beam into the Main Injector: two for antiproton production and nine for neutrino production. These batches will be injected in groups of 5 and 6, and then slipped together. The procedure is conceptually similar to two-batch stacking and is illustrated in Fig 8.65 and Fig 8.66. The obvious difference in the procedure is that more injections take place (5 on the first RF, 6 on the second) and the process takes longer. Additionally, the frequency difference is constrained to be the spacing between batches, which is nominally 84 buckets. So, $\Delta f = 84 \times 15 = 1260$ Hz and cannot be significantly modulated. This constraint limits the voltage that can be applied to the two RFs and will also apply for ANU.

To produce the two azimuthally separated bunch trains for antiproton and neutrino production (as shown in Fig 8.65), only 11 batches can be injected into the Main Injector, while it could in principle hold 12 and preserve a single abort gap. This is shown in sequence 6 of Fig 8.65, where the last batch is displaced an additional 42 buckets. Allowing for the slippage of the additional gap requires an additional 1/30th second. Additionally, the fall time of the 8 GeV injection kicker is slow enough that several bunches of beam are kicked out of the machine. A similar loss will occur if 12-batch injection is attempted for NuMI. To control this loss ANU will have faster injection kickers.

The Proton Plan has achieved 11-batch slip stacking in the Main Injector with very good efficiency (96%) at moderate intensity ($3.8\text{x}10^{13}$), and moderate efficiency (92%) at high intensity ($4.5\text{X}10^{13}$). Advances and experience in the Proton Plan is expected to improve the efficiency and intensity. The losses will also be controlled by a collimator system in the Proton

Plan. After the above improvements, 11-batch operation will be the standard mode of operation (presently expected late 2007).

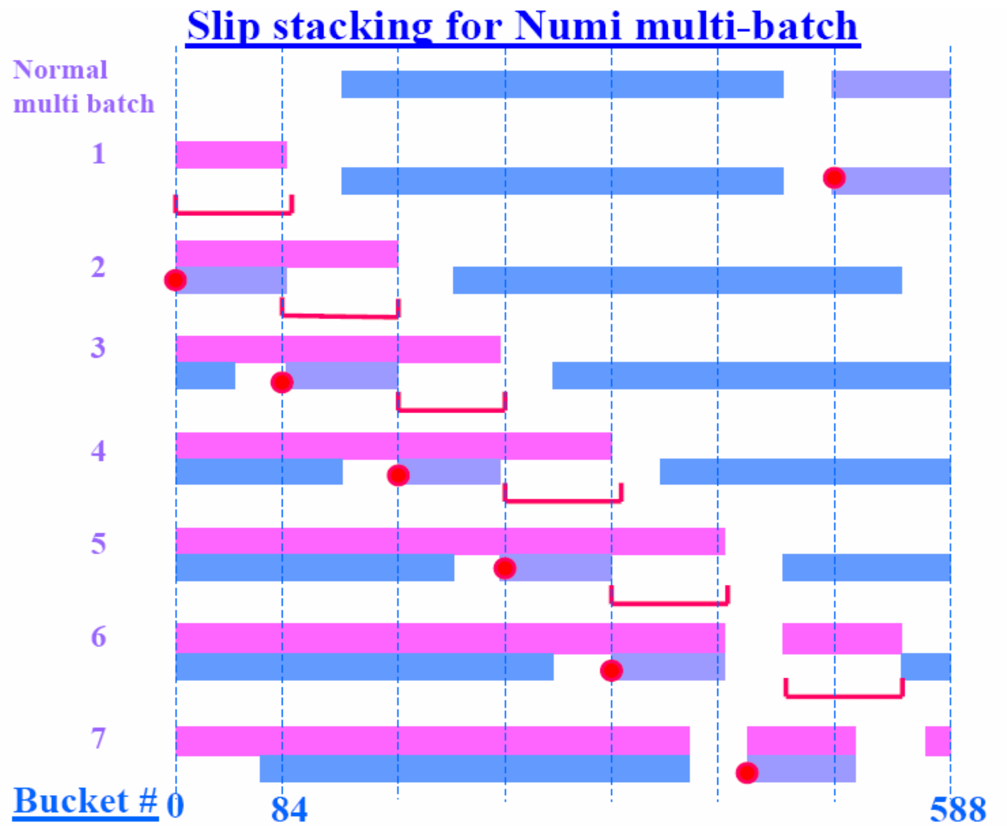

Fig 8.65: Illustration of batch positions at various times throughout the slipping process of the Proton Plan. The blue bars show the position of beam on a slipping orbit, i.e. slipping relative to injected beam. Sequences 1-6 indicate the last 6 injections, each injection indicated by a red bracket. Sequence 7 shows the position of the beams at the time of recapture.

There are several disadvantages or issues related to slip stacking in the Main Injector. The process always dilutes longitudinal emittance, even under ideal circumstances. The dilution occurs because the bunches must be separated in energy, but combined into a single bucket. The interior area is then filled by filamentation. The total longitudinal phase space is increased by at least 50% (over the sum of the initial two). Furthermore, longitudinal emittance is minimized by maintaining a lower RF capture voltage, but that leads to slippage of the uncaptured tails, which contribute to losses elsewhere. In typical operation, the longitudinal emittance of slipped beam is ~ 80% greater than the combined emittances of the original beams.

Another issue is that the RF manipulations make use of a large portion of the momentum aperture. The beam centroids are moved from $f_0 - \Delta f$ to $f_0 + \Delta f / 2$. Additionally, the momentum distribution of the beam contributes. The total used aperture is then[10]:

[10] Here, δp = 8 MeV/c is the momentum width of the incoming Booster beam; p = 8.89 GeV/c is the momentum of the Booster beam; and η = -0.0087 is the slip factor of the Recycler.

$3\Delta f/2 + 2f_0|\eta|\delta p/p$, which is 2700 Hz or 52 MeV/c. While this usage is large, the Main Injector and Recycler apertures are adequate.

Beam loading in the Main Injector RF cavities has long been recognized as a possible limitation to slip stacking performance [62]. The induced transient voltages on the main RF cavities could only be controlled through an aggressive system of beam loading compensation using both feedback and feedforward loops [63]. Even when compensation allows acceleration of beam to the production target, there are always increased losses with beam current. The dominant effect is that beam is not properly contained within the slipping buckets [64]. Those particles are then moved to higher amplitude along the separatrices. If the particles are not immediately lost they can then slip to an empty area of the ring and be lost at injection, extraction, or during acceleration. ANU will have to mitigate these losses through several methods described below.

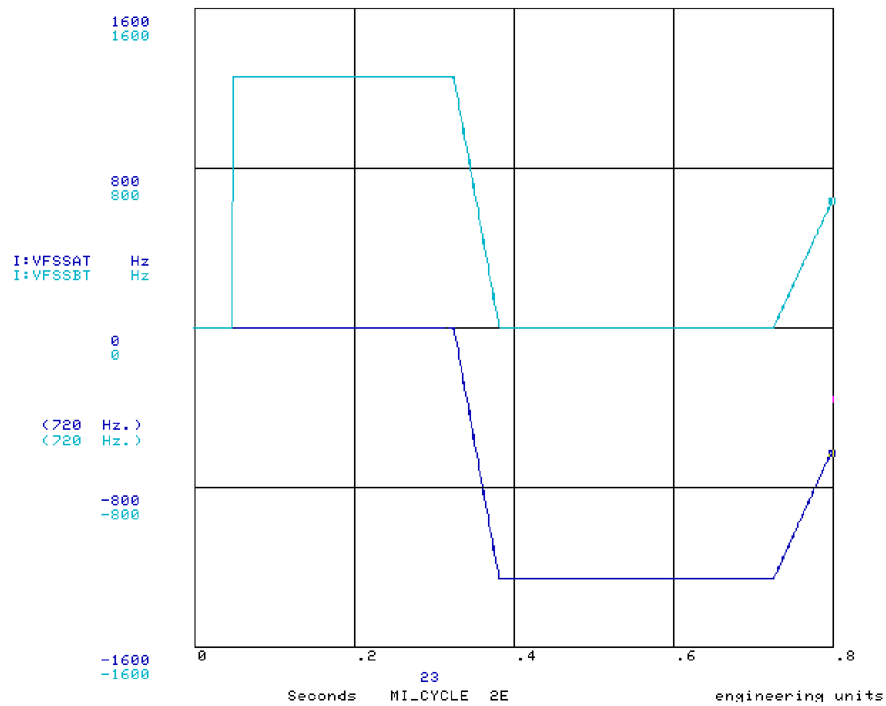

Fig 8.66: Study frequency curve for the 11-batch slip stacking of the Proton Plan. Beam is injected on the central frequency (0 Hz) 11 times between 0.06 and 0.66 s. The frequencies of the two beams are adjusted (also changing the energy) until they slip fully and bracket the central frequency, at which time they are captured (0.8 s).

The ANU implementation of slip stacking in the Recycler will be entirely derived from the Main Injector experience with Run II and the Proton Plan [64]. The Recycler's circumference and gross lattice characteristics will be identical to the Main Injector's[11]. The RF used to keep the beam bunched while slipping is a moderate voltage of ~ 100 kV. As the Recycler will not be called upon to accelerate beam, it can have significantly fewer RF cavities, each designed with smaller geometric factor[12]: R_s/Q. The reduction of shunt impedance and number of cavities will

[11] The Recycler presently has a modified lattice in the area where electron cooling takes place

[12] The geometric factor is the ratio of the cavity's shunt impedance to its quality factor. This ratio describes how much reactive power from the beam is stored in the cavity; power which can disrupt later bunches. The change in reactive power must be compensated by the RF system.

significantly improve the beam-loading situation. Additionally, a compensation system similar to the Main Injector's can be implemented.

The frequency scheme can also be optimized in the Recycler to reduce the number of acceleration/deceleration cycles and use less of the momentum aperture. A potential frequency schedule is shown in Fig 8.67. The first six batches are injected at a momentum corresponding to a frequency higher than the central by half the separation. The separation frequency is fixed, as in the Proton Plan, to 1260 Hz. Those batches are then decelerated to an orbit below the central frequency by half the separation[13]. The other six batches are injected on the second RF. The beam can be extracted as a whole to the Main Injector without any further acceleration or deceleration.

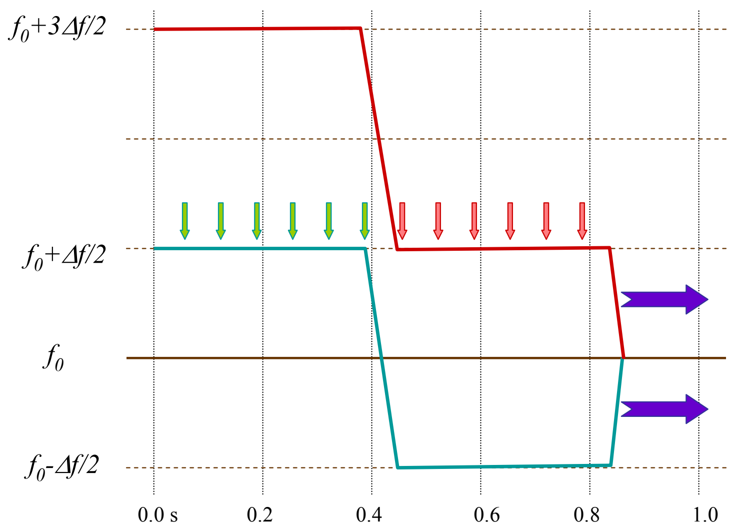

Fig 8.67: Proposed frequency scheme for Recycler slip stacking. Beam is injected six times above the central frequency by half the separation frequency. That beam is decelerated to below the central frequency to a slipping orbit and six more injections take place on the injection orbit. The beams are extracted in a single turn when they overlap in azimuth, one Booster tick after the last injection.

Slip stacking is expected to operate well in the Recycler for ANU, but it cannot be tested until actually installed. The risks associated with slip stacking are that the loss levels will not be reduced sufficiently by the advances of the Proton Plan, the move to the Recycler, and other ANU mitigation schemes. In such a case, the Recycler can still be used to increase the proton throughput of the complex. At the conclusion of the Proton Plan, the Booster is expected to be able to deliver batches of 20-30% greater intensity than those useful for slip stacking[14]. These batches could be boxcar stacked in the Recycler[15], leading to 20-30% production gains. Additionally, the proposed scheme of batch compression using barrier buckets [65] might be

[13] Batches cannot be injected at different frequencies because the transfer line may not be able to handle the momentum difference, and because different frequencies are not compatible with the notch cogging system in the Booster.

[14] These larger batches from the Booster are possible by filling a larger longitudinal emittance than useable for slip-stacking.

[15] The bunches in the Booster would require bunch rotation to fit inside the 300 kV buckets capable at this stage of the upgrades; the amount of rotation necessary would be less than that for slip stacking. If an additional two RF cavities are installed, so that 600 kV are available, then bunch rotation would not be needed at all.

possible in the Recycler as long as the LLRF system remains intact[16]. Batch compression has not been used operationally, as slip stacking has, but it has similar or greater potential for increasing proton throughputs. These two contingencies provide greater certainty that the ANU Recycler upgrades will improve proton throughput.

8.7.1.3 Booster

The Booster will be called upon to deliver 12 successive batches of 4.3×10^{12} protons every 1.33 s for the ANU program. The Proton Plan goals include being able to deliver equivalent batches to the Main Injector for slip-stacking by 2009. Compared to the Proton Plan, ANU will use 80% more protons from the Booster for the Main Injector; however, the Proton Plan will have an additional number of protons for the 8 GeV neutrino program which can be redirected to ANU.

The critical factors in the Booster that are most likely to affect ANU are loss control and longitudinal emittance conservation. The Booster proton throughput is limited by proton losses; the Proton Plan is designed to reduce these losses, but the necessary proton rate for ANU has not yet been demonstrated operationally. The momentum spread of the beam from the Booster is a primary factor in slip stacking efficiency. The momentum spread of ± 8 MeV/c (at 95%) is achieved by constraining the longitudinal emittance to no more than 0.08 eV·s and a bunch rotation. The Booster's transverse emittance is set by the injection and early capture process. A 95% normalized emittance of 15 π mm·mrad is typically achieved in each plane and adequate for operation.

While the devices in the Booster may be able to operate at 9 or 15 Hz, beam can only be accelerated if losses are sufficiently controlled. The Proton Plan improvements are designed to decrease and control losses such that throughput can be improved. At the conclusion of the Proton Plan, the Booster is estimated to provide 18.9×10^{16} protons/hour, with a fallback number of 13.0×10^{16}. Those estimates make assumptions about the users of the protons with regard to cogging which is estimated to incur 20% greater loss; adjusting to ANU uses the limits would be 17.2×10^{16} and 12.7×10^{16}. The anticipated ANU usage is 13×10^{16} protons/hour, which is slightly above the fallback and well below the design capability. The ANU proton consumption from the Booster will be achievable if the Proton Plan at least achieves its fallback goals.

8.7.1.4 Recycler

The Recycler is a permanent magnet 8 GeV storage ring with the same circumference as the Main Injector (7x that of the Booster), and similar gross lattice features of beta functions, tunes, dispersion, and momentum compaction. The Recycler is presently used to store and cool antiprotons for Run II. When suitably modified for ANU, it will accept twelve batches of Booster beam, merge them into a length of six batches through slip stacking, and transfer them to the Main Injector in a single turn.

The Recycler will use the same scheme as the Main Injector for slip stacking, so it will require similar control of beam loading distortion [63]. However, such control will be substantially simpler in the Recycler as it will only have two 53 MHz cavities, instead of the MI's 18 or 20. Additionally, the new cavities for the Recycler are being designed to have smaller R_s/Q by a factor of five. Nevertheless, a beam loading compensation system is expected to be necessary [59]; duplicating the features of the MI system will be adequate.

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[16] Batch compression involves debunching, compression, and rebunching into 53 MHz. 300 kV is inadequate for a complete rebunching, so either time must be spent in the Main Injector for bunching, or two more RF cavities must be installed in the Recycler.

The transverse instability arising from the resistive wall effect is suppressed in the Main Injector through the use of negative chromaticity at injection and a bunch-by-bunch damping system [66]. The damping system is necessary to keep the chromaticity to reasonably small values. Instabilities are typically seeded by injection errors [67]. The Recycler beam pipe is smaller than the Main Injector's, leading to a comparable, but somewhat larger resistive wall effect. The growth rate of oscillations should be no more than 50% greater in the Recycler than Main Injector. The transverse dampers in the Main Injector presently have a 500% gain margin; though at the Proton Plan intensities this margin may be reduced[17]. A similarly designed system for the Recycler will accommodate the transverse instability.

Explicit longitudinal damping is not performed in the Main Injector for slipping beam[18], and is assumed to not be necessary in the Proton Plan. Damping is implicitly performed through beam loading compensation in the Main Injector, which will also be present in the Recycler.

No widespread formation of electron clouds is expected in the Recycler for ANU. In the Main Injector only minimal and local electron activity has been observed for bunched beam. No electrons have been observed for slipping beam and no associated beam instabilities have been observed. The Recycler parameters will be substantially similar to the Main Injector. The electric field will be slightly higher at the beam pipe due to the smaller cross section, but the distance available for acceleration will also be smaller.

The space charge tune shifts experienced in the Recycler will be greater than those presently experienced for antiprotons. However, the marginal loss of lifetime will not be relevant for a beam that persists in the Recycler for less than one second, compared to tens of hours for antiprotons.

8.7.1.5 Beam Cleaning

The ANU design includes an additional abort kicker in the Recycler that will ensure that the azimuthal gap used for injection is clear of beam prior to injection. The beam cleaning will substantially reduce the uncontrolled loss that would otherwise heavily irradiate the injection region.

The process of slip stacking in the Main Injector is known to have an inefficiency of about 5% in ideal circumstances with high-intensity beam. However, the 5% of the beam is not immediately lost; instead it escapes from the slipping buckets and transits around the azimuth. The beam is then typically lost in two ways: further injections displace the escaped beam into a series of magnets, producing a local area of high irradiation; if not displaced, the beam will fail to be accelerated once the main ramp begins and be lost longitudinally. Additionally, some portion is captured into the main RF's accelerating buckets; that portion of the beam is not typically lost, but does produce larger tails in the longitudinal distribution.

The losses from accelerating the beam will not occur inside the Recycler, only the large injection loss. From experience in the Main Injector, we can predict that the injection loss would be on the order of 1000 W for ANU. Even spread over a larger area of up to 100 m with bumps

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[17] From intensity scaling exercises the margin of 300% would be expected. The margin may ultimately be greater due to the longer bunch length of the beam injected for slip stacking. However, the details of how to damp injection oscillations in the Main Injector for Proton Plan have yet to be worked out. The immediate slipping of the beams complicates the procedure, potentially leading to a reduced damping efficiency. The possibility of using a narrow-band damping system for the dominant mode may alleviate the complication.

[18] Longitudinal damping is performed for captured beam and other types of acceleration, leading to a reduction in longitudinal emittance. In ANU such beam conditions will still be limited to the Main Injector, not the Recycler.

(as is currently done in the Main Injector), the loss would lead to large radioactivation and potential component failure.

Instead of suffering the injection loss, the ANU design includes an additional kicker system, identical in kick to the injection kicker, but designed to extract circulating beam to the abort. This kicker would pulse immediately before injections (and the final extraction) to remove all beam from the injection and extraction gaps. Considering the rise and fall times involved, the beam cleaning system could reduce the injection losses by 95%.

8.7.1.6 Main Injector

The Main Injector will operate almost identically in ANU as in the Proton Plan; the differences being that the slipping process will no longer occur in the MI, and that the ramp rate will be increased to reduce the cycle time. The improvements made in the Proton Plan will be necessary to run the Main Injector with reasonable losses.

Removal of the slipping process from the Main Injector to the Recycler reduces the low-voltage requirements on the MI RF system. Cavities will no longer need to provide zero voltage and will no longer have to deal with the detailed transients of slip stacking. Nevertheless, the cavities will sustain a large DC beam loading and still have the transient of the abort gap. The Proton Plan beam-loading compensation will be adequate for these loadings.

A set of collimators will be installed in the Main Injector for the Proton Plan to intercept the beam that fails to accelerate, and to provide a limiting aperture [68]. These collimators are necessary for ANU to intercept the same type of loss.

8.7.2 ANU Demands on Proton Plan

As described above, the ANU designs are upgrades to the existing Fermilab accelerator complex. That complex is the sum of already operating machines and the Proton Plan upgrades presently being performed. To assure that ANU operations meet expectations, the project will monitor the progress of key Proton Plan upgrades and determine whether their performance is adequate for ANU.

Several items have been identified as meriting particular attention:

- Booster performance in terms of proton delivery rate, protons per pulse, and longitudinal emittance are to be improved by the Proton Plan. ANU relies on each of these improvements. The major outstanding upgrade in the Booster is the complete replacement of its corrector magnet systems. This major upgrade is scheduled to be installed by the end of the 2008 shutdown, and to be commissioned thereafter. The time between corrector commissioning and ANU installation may be short; however, we are fortunate in that the Booster is already close to the proton needs of ANU.
- The MI-8 collimators need to remove large amplitude (transverse and longitudinal) particles in the transfer between the Booster and Main Injector. Removing these protons reduces losses in the Main Injector. These collimators are installed and undergoing commissioning. Their impact is part of several activities needed to decrease losses in the Main Injector.
- 11-batch slip stacking in the Main Injector must perform at the necessary intensity and efficiency. The Recycler implementation may be marginally improved from the Proton Plan scheme, but the process must still be proved by the Proton Plan. The 11-batch scheme has been partially demonstrated in the Main Injector and awaits further tuning and installation of the collimators. Once operational, the long-term prospects for intensity and efficiency will be established.

- Collimators are being planned in the Main Injector that will control a substantial portion of the Proton Plan losses in the Main Injector. The collimators are to be installed in the 2007 shutdown and commissioned thereafter. For the Proton Plan, the collimators will intercept beam loss occurring at the extended period at 8 GeV and the loss occurring at acceleration from uncaptured beam. In ANU the collimators must also intercept the acceleration loss. Once 11-batch slip stacking and the collimators are implemented the utility of the collimators for ANU can be well estimated.

The above items will be analyzed, once commissioned, to assure that they will meet the needs of ANU. Quantitative results of efficiencies and other metrics will be documented and used as inputs to estimations of ANU proton production and efficiencies. The ANU tasks will also serve notification if any of the needed upgrades fall short of the needed improvements.

8.7.3 Machine and Process Analysis

The ANU stacking and acceleration schemes are derived and extrapolated from those already in place at Fermilab. Nevertheless, commissioning and operation of the upgrades will need extensive documentation of the machines and beam physics analyses of the involved processes. This set of tasks will perform measurements, simulations, and calculations pertaining to each of the machines in their new roles in ANU. We assume that substantial analyses of the machines and processes occurs outside of the project, but focused more on the machines' roles in present operations (Run II, NuMI, and the Booster Neutrino Beam) and the Proton Plan. The items that have been identified as needing further analysis and documentation for ANU are:

- Beam simulations and calculations of the slip stacking process in the Recycler, and optimization for ANU. These will be mostly longitudinal analyses of the process, focused on minimizing the beam lost outside of the RF buckets.
- Beam dynamics simulations in the Recycler and MI. Beams of the ANU intensities and characteristics need to be studied theoretically for collective effects. These analyses will be used to estimate loss patterns in the Recycler from those in the Main Injector.
- Further measurements in the Main Injector to study loss mechanisms and transition crossing during acceleration. Of particular interest will be locating areas of impedance.
- Once the Proton Plan has commissioned 11-batch slip stacking and the Main Injector collimators, ANU will measure the spatial loss pattern in the Main Injector. This will be correlated with radioactivation data and the Recycler simulations to estimate the loss pattern in the Recycler for the ANU 12-batch slip stacking.
- Some ANU–relevant beam measurements in the Recycler can take place in its present configuration. These measurements will be limited as the Recycler does not have the ability to maintain the 53 MHz bunching of beam.
- Formation of the electron cloud can be measured directly through the use of a dedicated electron counter. Such a device exists in the Main Injector, but needs to be installed in the Recycler in such a way that does not impact its role as an antiproton storage machine. The electron cloud is not expected to significantly impact the ANU beam, but must be monitored to ensure its low impact.
- The electron cloud needs to be simulated and analyzed for the ANU beam. The cloud does form in the Main Injector during high intensity operation, but does not negatively impact the beam. Simulation will be developed to form a model of the electron cloud that conforms to observations, and can be extrapolated to ANU operations.

- The new ANU transfer lines are short lines, designed to well match the Recycler and Main Injector lattices. These lattices need to be documented and have tuning protocols developed.
- The ANU beam cleaning system is an important part of loss control in the project. Once the ANU 12-batch cycle is analyzed in terms of anticipated losses and the kickers have predicted waveforms, the beam cleaning system can be analyzed in terms of how much of the losses will be directed to the Main Injector abort.

The above analyses will be performed and combined into an ANU Beam Physics Source Book. The Source Book will be used for future reference in commissioning and operating the ANU beam.

8.7.4 Proton Projections

Realistic and accurate projections of the number of protons delivered through the ANU schemes are required for estimating the eventual measurement precision achieved by the NOvA experiment. ANU wishes to provide realistic long-term estimations of the number of protons that the experiment can expect. These estimations depend on how intense and efficient the ANU beam eventually is, and the amount of time that beam can be delivered to the NuMI target. ANU will maintain estimates of both of the above factors, anticipating that they will evolve with further knowledge of how the present accelerator complex performs.

The accelerator division and NuMI operations personnel keep track of a large amount of information about performance of the current complex. ANU will develop a set of performance metrics that are derived from the present measurements, and can be extrapolated to the ANU beam, producing justified projections of proton performance.

8.7.5 Changes in the Beam Physics Design Since the CDR

Since the CDR was written, the Main Injector department has achieved 11-batch slip stacking for the Proton Plan. This achievement proves, in principle, that 11-batch slip stacking is possible and increases the likelihood that the ANU stacking scheme will be successful as designed.

8.7.6 Remaining Design Work for Beam Physics

No design work remains for beam physics. Substantial additions to the Proton Plan or modifications of the ANU designs would require additional validation within ANU – Beam Physics (none are presently envisioned).

8.8 ES&H and Quality Assurance

NOvA has a Quality Assurance Plan (QAP) [69] and an Integrated Safety Management Plan (ISM) [70]. The ANU subproject implements and continues to implement both these plans. Design reviews are carried out before all procurements that have risk associated with them either from a cost, schedule, technical or ES&H viewpoint. These reviews are in the resource loaded schedule. A table of elements that will be used by the ANU subproject, the basis of their design and comments on other risk elements is used by the project to determine which elements need design reviews [71]. This table and management input is used to determine how detailed and extensive the review and review committee is for the review.

Many different types of reviews will occur within the ANU subproject. “Internal” Design Reviews for the new designs or major modifications to existing designs of technical components often included ES&H Personnel. Other reviews occur within the department in which the item is designed. Each department, whether in AD or TD or elsewhere, has its own internal design review guidelines. Often these reviews included detailed checking of calculations and/or Engineering Notes. The third type of review is performed by the NOνA ESH/QA Review committee. These vary in detail, depending on the item being reviewed. These reviews always cover the ESH issues. The NOνA ES&H/QA review committee is in the process of being formed to look at ES&H and QA issues related to design, construction, installation and operation. This committee will be composed of people with expertise in mechanical, electrical, structural, radiation and conventional safety.

Inspection and acceptance testing, quality improvement, prototypes for high risk items are all used for improving quality and safety during all phases of the project.

8.9 Risks

Risks are managed as described in the NOνA Risk Management Plan [72]. Risks are mitigated through the processes described in Section 8.9 and as described in the NOνA Risk Management Plan. Details on risks and risk management for the ANU subproject are entered into a risk registry using WelcomRisk©. They are then ranked and for those that rank high, a NOνA Risk Form is filled out. Nearly 100 risks associated with ANU have been entered into the WelcomRisk© risk registry. Mitigations are listed along with the risks. The high risk items have been entered into the NOνA High Risk Registry (see NOνA docdb #1323) and have had detailed Risk Forms filled out for them.

All ANU risks are listed by number, score and tolerance in NOνA docdb #1983. Several risks on the same topic in the WelcomRisk© risk registry are entered into one form for the above NOνA High Risk forms.

8.10 Value Management

Value management is an integral part of the planning, design, construction and installation process. Many items are re-cycled or refurbished (many different kinds of magnets, TeV LLRF system, software, etc.) for ANU. This saves money in all phases of the project and leads to the use of known, reliable systems. This also saves in decommissioning costs where these items would have to be disposed of in some manner, with some being radioactive.

Within the 9 months, the injection line design has changed to simplify installation and to minimize the number of powered elements near the Recycler Ring. The main design change in the extraction line was to move the injection point in the MI. This allows us to use the same ceramic beam tube and magnet for this kicker as we are using for the Recycler extraction and abort kickers, thus eliminating a separate design for both the ceramic beam tube and the magnet. We have decided to accept 81 Booster bunches per Booster batch instead of 82. This change loosens the kicker rise/fall time specifications from 38 nsec to 57 nsec with ~1% loss of protons to the NuMI target.

The position of the MI collimators needed for the Proton Plan and NOνA has been finalized such that they do not interfere with the NOνA injection line from the Recycler to Main Injector. As a result no collimator moves need to be included in the MI Upgrades required for NOνA. We also have a design for the manufacturing of the bus bars for the cavity tuners that greatly simplifies the installation and does not require the use of an external crane and removal of parts of the roof from the MI-60 building.

To greatly simplify moving Horn 2 to the medium energy neutrino beam location, a new "dummy" horn module will be built identical in dimension to the existing design, but without all the associated penetrations, drive system, or horn support system. This "dummy" module assembly will essentially act as a shielding plug and work could begin on its installation during the first shutdown after the completion of Collider Run II operations. Another advantage of having two module assemblies is that it will allow Horn 2 to be easily moved back to the low energy position if the need arises in the future.

There are many other examples of Value Management on the ANU subproject. Many are described in the text within the subchapters of this section.

8.11 Chapter 8 References

1. "Proton Projections", R. Zwaska, NOVA-doc-1698, (2007).
2. The MinervA Collaboration, D. Drakoulakos et al., 'Proposal to perform a high-statistics neutrino scattering experiment using a fine-grained detector in the NuMI beam'.
3. The Proton Plan web page is http://www-accel-proj.fnal.gov/Proton_Plan/index.shtml.
4. "NOvA Beam Requirements", M. Messier, NOVA-doc-1632, (2007).
5. See the documents associated with MI BPM requirements in the BeamsDoc Database, event id = 29 (https://beamdocs.fnal.gov/AD-private/DocDB/ListBy?eventid=29&mode=conference).
6. "Recycler Injection Kicker Configuration in the Nova Era", D.E. Johnson ,NOVA-doc-1495, (2007)
7. "Recycler Injection Line Options for the Nova Project", D.E. Johnson, NOVA-doc-1501 (2007)
8. Web page "ANU Magnet Naming Cheat Sheet" helps to explain magnet names.
9. "The Proton Driver Design Study", Fermilab-TM-2136, December 2000.
10. "Recycler BPM Requirements for Nova ANU", P. Derwent, M.J. Hu, NOVA-doc-1799 (2007)
11. "Main Injector and Recycler Kicker Apertures for the Nova Project ", D.E. Johnson, NOVA-doc-1843 (2007)
12. "MI Pond Water Modeling for ANU Increased Heat Loads", Stephen F Krstulovich, NOvA-doc-1895.
13. Main Injector Shielding Assessment 1998
14. Main Injector Shielding Assessment, October 2004
15. Fermilab Radiological Control Manual
16. MI8 Beamline Collimation Design, B.C. Brown, Beams-doc-1977, 9/30/2005
17. "Accelerator-based Neutrino Beams", Sacha E. Kopp, Submitted to Phys.Rept., http://arxiv.org/PS_cache/physics/pdf/0609/0609129.pdf
18. "Optimization of Target and Horn Locations for NOvA", M. Messier, NOVA-doc-2606, (2007).
19. "The NuMI Technical Design Handbook", www-numi.fnal.gov/numwork/tdh/tdh_index.html
20. "NuMI Primary Beam Upgrade for SNuMI", Sam Childress, NOvA-doc-1571
21. Conversation with D. Harding from Technical Division
22. "MARS Simulations of the NuMI Primary Beamline", Sergei Striganov, NuMI-NOTE-SIM-1022, 17 May 2004.
23. "Technical Design of the Target Pile Protection Baffle," S.Filippov et al., NuMI-B-1092, April 30, 2002.
24. The medium energy target is documented in NuMI-B-675, IHEP report, "Dynamic Stress Calculations for ME and LE Targets and Results of Prototyping for the LE Target." August 10, 2000. See also Beams-doc-676.
25. See drawing 7538-00-00-00.dwg for the ME target. (/afs/fnal.gov/files/home/room2/garkusha/ME_target). In this drawing there are 14 graphite plates and the drawing has not been updated to reflect the change to 12 graphite plates. In this drawing there is also a special graphite plate at the downstream end for vertical alignment. The drawing has not been updated with this piece removed.

26. “Design Study of the NuMI Medium Energy Target for Higher Power Beams”, V. Garkusha, A. Ryabov, T. Ryabova, F. Novoskoltsev, V. Zarucheisky, State Research Center of Russia Institute for High Energy Physics, November 27, 2006, NOvA-doc-619.
27. “Ion Chamber Arrays for the NuMI Beam at Fermilab”, D. Indurthy, *et al.*, Particle Accelerator Conference (PAC 05), Knoxville, Tennessee, 16-20 May 2005. (Also, FERMILAB-CONF-05-108-AD.)
28. M. Messier, “NOvA Beam Requirements”, NOvA-doc-1632.
29. S. Tariq, E. Chi, “Brief Analysis of the “R” Shielding Block for the New Loading Case”, NOVA-doc-2621.
30. Z. Tang, “Target Chase Shielding Thermal FEA documents”, NOvA-doc-2620.
31. S. Tariq, “Notes on meeting to scope Target Chase Cooling Upgrades”, NOvA-doc-2416.
32. Salman Tariq, “Horn 1 Vertical motion in 700 kW operation”, NOvA-doc-1572
33. Salman Tariq, “Horn 1 Horizontal motion in 700 kW operation”, NOvA-doc-1586
34. P. Hurh, “Summary of Horn 1 Stripline/Stripline Block Cooling Concerns”, NOvA-doc-1787.
35. Bob Wands, “Qualifying the NuMI Decay Pipe and Hadron Absorber for SNuMI Loads”, NOvA-doc-1622.
36. “Conceptual Design Report: Proton Plan 2”, NOvA-doc-1375, November 9, 2006.
37. K.E. Williams, “MI LCW and Pond Water Temperature Studies”, NOvA-doc-1573.
38. NuMI Shielding Assessment, October 2004.
39. NuMI Safety Assessment Document 11/1/2004.
40. N. Grossman, G. Rameika, “Methodology for Determining Radionuclide Concentration in Groundwater in the Vicinity of Accelerator and Beamline Enclosures”, NuMI Note 970, July 2004.
41. F. Breen, “Evaluation of Boundary Conditions for the Two Dimensional Groundwater Model Simulations, Technical Memorandum, June 12, 1999.
42. Earth Tech Draft Groundwater Modeling Report, dated, May, 1999”.
43. NuMI Tunnel Modeling Project Report, August 1999.
44. Earth Tech, Inc., “Two Dimensional Groundwater Flow Model, Results Estimated Inflow to NuMI Tunnel”, May 1999.
45. Breen GeoScience Inc., “NuMI 3D Groundwater Model Update”, August 2004.
46. D. Cossairt, “A Model for Calculating Radionuclide Concentrations in Fermilab Cooling Ponds”, June 2006.
47. Illinois Environmental Protection Agency, Lifetime Operating Permit - National Emissions Standards for Hazardous Air Pollutants (NESHAP), Issued March 2, 2006, and application number 79070012, dated March 1, 1991.
48. Fermilab Annual Environmental Report
http://www-esh.fnal.gov/pls/default/esh_home_page.page?this_page=12831
49. Title 40, Code of Federal Regulations, Part 61, Subpart H, “National Emission Standards for Emissions of Radionuclides Other Than Radon From Department of Energy Facilities”.
50. K. Vaziri, “SNuMI beamline radiological safety”, NOvA-docdb-1635, 2007.
51. “Beams Division Routine Monitoring Program”, BDDP-SH-1003, Rev 0.
52. See NuMI TDR Chapter 4.2.10 for details.
53. N. Grossman, “Residuals Estimates for SNuMI”, NOvA-docdb-1580.
54. D. Harris and N. Grossman, “Radiation Dose Estimates for the Monitoring System”, NUMI-NOTE-BEAM-845, 7/8/2002.
55. N. Grossman and D. Harris “NuMI Muon Rates” March 2004, -updated July 2004. NuMI Note 1025.
56. N.V. Mokhov, "The MARS Code System User's Guide", Fermilab-FN-628 (1995); N.V. Mokhov, O.E. Krivosheev, "MARS Code Status", Proc. Monte Carlo 2000 Conf., p. 943, Lisbon, October 23-26, 2000; Fermilab-Conf-00/181 (2000); N.V. Mokhov, "Status of MARS Code", Fermilab-Conf-03/053 (2003).

57. The Proton Plan Design Handbook is found on its webpage: http://www-accel-proj.fnal.gov/internal/Proton_Plan/index.shtml. A public site viewable outside Fermilab is: http://www-accel-proj.fnal.gov/Proton_Plan/index.shtml
58. The Run II project homepage is http://www-ad.fnal.gov/run2upgrade/. Slip stacking was an addition to the original Run II designs.
59. K. Seiya *et al.*, "Status of Slip Stacking at Fermilab Main Injector" PAC 2005, MOPA004; FERMILAB-CONF-05-110-AD.
60. B. Boussard and Y. Mizumachi, "Production of Beams with High Line-Density by Azimuthal Combination of Bunches in a Synchrotron", IEEE Trans. Nucl. Sci., NS-26. No.3, June 1979, pp. 3623-5.
61. F. E. Mills, BNL Internal Report AADD 176, 1971.
62. S. Shukla *et al.*, "Slip Stacking in the Fermilab Main Injector", 1996 DPF / DPB Summer Study on New Directions for High-Energy Physics, eConf C960625:Acc015, 1996.
63. J. Dey and I. Kourbanis, "53 MHz Beam Loading Compensation for Slip Stacking in the Fermilab Main Injector", PAC 2005, TPPT027, FERMILAB-CONF-05-175-AD.
64. K. Seiya and I. Kourbanis, "Slip Stacking in MI", FNAL-Beams-doc-2179, 2006.
65. G. W. Foster *et al.* "Beam Manipulation and Compression Using Broadband RF Systems in the Fermilab Main Injector and Recycler" EPAC 2004, TUPLT149, p. 1479.
66. P. Adamson et al., "Operational Performance of a Bunch by Bunch Digital Damper in the Fermilab Main Injector", PAC 2005, MPPP015, FERMILAB-CONF-05-145-AD.
67. V. Balbekov, "Recycler Transverse Instability in Context of the Proton Plan (Rigid Modes Instability at Dominating Space Charge)", internal Recycler note, 2006.
68. B. Brown *et al.*, "Beam collimation in the Main Injector at Slip-Stacking Injection", FNAL-Beams-doc-2330, 2006.
69. NOvA Quality Assurance Plan (QAP), NOvA-docdb 1353
70. Integrated Safety Management Plan (ISM), NOvA-docdb 1925
71. ANU Design Review Table, NOvA-docdb-2052
72.NOvA Risk Management Plan, NOvA-docdb-185