

## Chapter 21. Upgrade of Beamlines

### 21.1. NuMI Beamline

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#### 21.1.1 Introduction

It should be pointed out that there is a difference in beam intensity and beam power between the NuMI baseline and the Main Injector baseline parameters. For the former, they are  $4 \times 10^{13}$  protons per cycle and 0.4 MW, respectively; for the latter,  $3 \times 10^{13}$  protons per cycle and 0.3 MW, respectively.

The NuMI beamline (see Figure 21.1) is designed to handle 0.4 MW of proton power, and it will not be trivial to upgrade it to withstand a proton power of 2 MW. In this chapter we describe which elements would survive such an upgrade, and which elements would need to be modified. Where possible, rough estimates have been made for how much those modifications cost; these are tabulated in Appendix 1.

The neutrino beam at NuMI is created when 120 GeV protons from the Main Injector strike a 0.94 m graphite target located roughly 40 m below ground in the NuMI tunnel. Secondary mesons are then focused in a two-horn focusing system, and directed towards a 675 m long decay pipe. The uninteracted protons and particles that did not decay hit a hadron absorber located about 725 m from the upstream edge of the first horn. Finally, there are beamline monitors both upstream and downstream of the absorber, as well as in two alcoves embedded in the dolomite following the absorber alcove. The target, the horns, and the decay pipe itself all must be water cooled, and the entire beamline has an impressive amount of shielding to prevent groundwater contamination.

The design parameters for the primary beam for both the NuMI design and the proton driver upgrade are given in Table 21.1. In the following sections, we will address what major items would or would not need to change for this new set of parameters. Smaller aspects of the experiment that also would need to change are not addressed.

#### 21.1.2 Primary Beam

The NuMI primary beamline is designed to match the dynamic aperture of the Main Injector. Therefore, although the protons per cycle will increase by almost a factor of 4, the primary beam optics should not need to be changed. This assumes that the losses per minute can be maintained at the same level as for nominal running, or the fractional losses per pulse have to be reduced by a factor of 5. To do this may require the addition of collimators in the NuMI beamline. With the 1.5 second repetition rate, the power supplies on the primary beam optics (ramps, controls) also should be adequate, with the exception of the kicker power supply, which would need a larger charging power supply. Thus, the LCW for this system, assuming the optics does not change, can also remain the same.

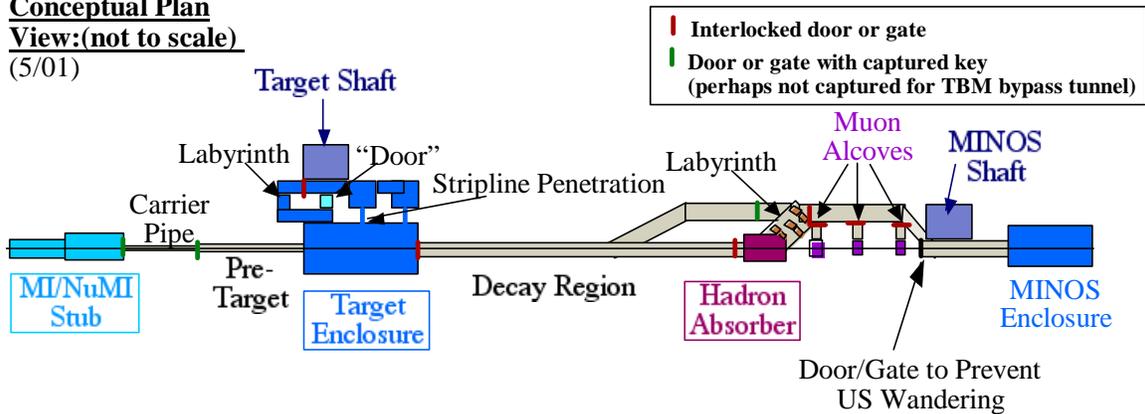
**Table 21.1.** NuMI Baseline Design Parameters vs. Proton Driver Era Parameters

	NuMI Baseline	Proton Driver Era
Beam Energy (GeV)	120	120
Protons per cycle	$4 \times 10^{13}$	$1.5 \times 10^{14}$
Cycle Time (sec)	1.87	1.53
Protons per second	$2.13 \times 10^{13}$	$1 \times 10^{14}$
Average Beam Current (mA)	3.4	16
Target Beam Power (MW)	0.41	1.9
Normalized Transverse Emittance (mm-mrad)	$40\pi$	$40\pi$
Longitudinal Emittance (95%, eV-s)	1	0.2
Momentum acceptance	$\pm 0.7\%$	$\pm 0.7\%$
Dynamic Aperture	Matches that of the MI	$>80\pi$

**Conceptual Plan**

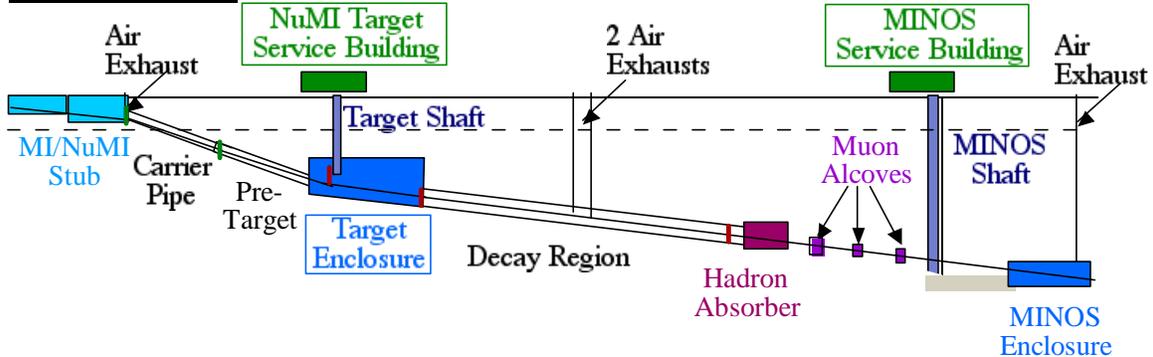
**View:(not to scale)**

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**Conceptual Elevation**

**View:(not to scale)**



**Figure 21.1.** Conceptual Diagram of the NuMI Beamline

### **21.1.3 Target and Horns**

If the proton beam were to maintain the same spot size, then the current design of the NuMI target would not withstand the increased proton power, because the temperature of the graphite would be too high. However, it has been shown that if the proton spot size were three times as large, and the target were also three times larger in the transverse direction, then the graphite would not yield for 2 MW proton power. In this case a different scheme for cooling the target would also have to be designed.

The horns could probably handle the increased pion flux and the increased repetition rate, although the life expectancy for a given horn might be reduced. In fact most of the wear and tear on the horns is due to the pulsing, not the passage of the produced particles. The life expectancy for a NuMI horn pulsed at 1.87 seconds is at least one year; so the lifetime for a horn in the upgrade might be reduced to 9 months. The NuMI prototype horn has been pulsed 1 year equivalent of pulses with no problems, and once the experiment is running the true lifetime of these horns will be much better known. The horn power supply could be modified to operate at a higher repetition rate at minimal cost.

### **21.1.4 Target Area Cooling**

The cooling for the horns and target area (which has a total extent of about 48 m) is one of the hardest things to upgrade. Right now the target area is being cooled by a very high flow rate of air through the region. With 5 times the proton power it is likely that the region will have to be water cooled instead. Rebuilding this area for water-cooling will take a large amount of planning, since that region will be extremely radioactive after NuMI runs. We estimate ~\$5.5 million to re-design, fabricate, de-install and re-install the Target Hall cooling and shielding to accommodate the increased heat load.

### **21.1.5 Decay Pipe and Cooling**

The decay pipe window has aluminum in the center, surrounded by an outer ring of steel. This design was adapted over a solid one-material window design because if there were to be an accident where the proton beam missed the target and hit the upstream window of the decay pipe several times, the window would break. Replacement of this window, due to the high level of radioactivity, would be difficult. If the proton intensity were increased by a factor of 4 without changing the spot size on the target, then it is likely that the dual material window would not survive. From the target studies, however, we know that the target would not survive either, so it is likely that the proton spot size would be considerably larger in a proton driver upgrade scenario. If the proton spot size increases by a factor of three in both the horizontal and vertical directions, and the proton intensity only increases by a factor of 4, then the upstream vacuum window of the decay pipe would not need to be changed. The downstream window of the decay pipe is not a concern and would not have to be changed regardless of the proton beam spot size.

The most challenging aspect of an upgrade would be the decay pipe itself. Here the heat loads will increase by a factor of five. The existing cooling lines are conservatively designed for the NuMI heat load, and measurements with NuMI running would need to be made (and planned for by design) in order to determine what upgrades are needed. One can expect the bulk temperature of the cooling water in the current design to increase to 60° F and the mean metal temperature in the decay pipe steel to increase even more dramatically. If additional cooling were needed, it would be needed for a fraction of the decay pipe's length. The costs for the additional cooling for the decay pipe are very roughly estimated at a million dollars.

### **21.1.6 Hadron Absorber**

The Hadron Absorber for NuMI consists of a water-cooled Aluminum core, surrounded by un-cooled steel blocks. The temperature rise in the hottest module in the aluminum core in normal running is 60° C above the cooling water, and in the first steel block downstream of the aluminum, the temperature rise is about 300° C above the cooling water. An increase in the proton beam intensity alone would be acceptable for the aluminum core, but the first steel block after the absorber may be too hot. Thus some modification of the Hadron Absorber would be needed. If the proton spot size and target increases in size by a factor of 3, then taking into account multiple scattering in the target, the area of the beam at the absorber would be about 3.5 times bigger, and an integrated rate 5 times higher. This would minimize the modifications needed for the Hadron Absorber cooling.

### **21.1.7 Beamline Monitors**

Because of the high radiation rates that are expected in the monitoring locations for nominal running conditions, the beamline monitors are being constructed entirely of radiation-hard materials: ceramics or metals. In nominal running the muon monitors will see tens of Megarads, while ceramic has been tested to above the Gigarad level. Therefore an increase in the proton power of a factor of 5 should not be a problem. At the expected fluxes in nominal running, the monitors are not expected to saturate, and even at these higher levels (increase in pulse per spill of a factor of 4) they should at the worst only be saturating by a few percent.

### **21.1.8 Radiation Safety**

#### *21.1.8.1 Groundwater*

Groundwater activation has been a big issue for the NuMI Beamline due to the majority of the beamline being located in the aquifer, which is considered a "Class I" groundwater resource. Contamination limits for drinking water supplies and for Illinois "Class I" groundwater resources (water that potentially could be drinking water) are the same. The radionuclides of concern are <sup>3</sup>H (12.3 year half-life) and <sup>22</sup>Na (2.67 year half-life). Table 21.2 lists the limits for these radionuclides for both surface and drinking water. For mixtures of radionuclides, a weighted sum is used. The annual average concentrations must be below the limits.

**Table 21.2.** Regulatory Limits for Accelerator Produced Radionuclides in Drinking and Surface Waters

Regulation	Water Use Type	Annual Dose Equivalent (mrem)	<sup>3</sup> H (pCi/ml)	<sup>22</sup> Na (pCi/ml)
40CFR Part 141/35 IAC 620	Drinking	4	20	0.4 (inferred)
DOE Order 5400.5	Surface	100	2000	10
DOE Order 5400.5	Drinking	4	80	0.4

For NuMI, conservative estimates have been made of the expected concentrations relative to these limits, including uncertainties, to ensure that the levels produced by the NuMI beamline will be below them. For the Proton Driver upgrade, measurements from NuMI running will be available from which one can extrapolate. We do not expect any measurable levels of <sup>3</sup>H or <sup>22</sup>Na in the groundwater monitoring wells due to NuMI operation. Extrapolating from these measurements will show that an intensity increase of a factor of 5 will similarly show negligible levels relative to the regulatory limit in the monitoring wells. Similarly, measurements will be made of the levels of radionuclides in the water pumped from the NuMI tunnel and released to the surface waters. These levels are expected to be at least a factor of 20 below the surface water limits. Thus with an intensity increase of a factor of 5, we would still be below the surface water limits.

The main area of concern for groundwater activation is in the “interface region” between the glacial till and the dolomite. This is where the NuMI primary beam is in the lined carrier tunnel. Here the water is in the aquifer and the tunnel is lined and the water flows at the rate of the regional gradient towards the Fox River. Normal operational losses in this region drive the groundwater concerns, not accident conditions. In most areas of the NuMI primary beamline, the estimated upper limit on normal loss levels for NuMI operation is  $2.1 \times 10^9$  p/sec, either due to groundwater activation concerns or residual activation concerns. In the carrier tunnel interface region, the upper limit is estimated at  $2.1 \times 10^7$  p/sec. The calculations assume a constant loss at this level. For other beam intensities, these loss rate limits would still apply. As a result, depending on the Proton Driver beam parameters, Main Injector collimators may be necessary to reduce beam halo to keep losses in the beamline to a minimum.

Not related to radiation safety, but of concern, is the temperature of discharged water to surface waters. Temperatures of 60° - 90° F are expected for NuMI, and will be higher with the Proton Driver intensities. Most likely additional cooling ponds will be needed.

#### 21.1.8.2 Airborne Activation

The air within the Target chase is the main source of air activation for NuMI. This air is sealed within the chase and re-circulated. Still, some amount will leak out. For 5 times the intensity, the chase would need to be much better sealed in order for NuMI to keep the release rate below ~40 Ci/yr, the agreed upon level. The air permit that FNAL has with IEPA could be modified to allow larger annual releases for the laboratory as a whole

and this would relax the requirements on NuMI as well as other areas at Fermilab. Another way that releases for NuMI could be reduced is by decreasing the ventilation rate from the Target Hall to the vent and from the Hadron Absorber to the vent. This would increase the humidity levels in the decay tunnel and reduce the air-cooling in that region. To know the extent to which these measures would need to be taken, measurements with NuMI operation need to be made. The cost estimate listed in Appendix 1 for upgrading the Target Hall cooling and shielding includes the cost for increased sealing of the target chase. Similarly the Hadron Absorber upgrade cost also includes required additional sealing to keep the activated air contained.

#### *21.1.8.3 Prompt Radiation, Labyrinths and Penetrations*

The area to the Target Hall upstream shaft side of the equipment door may become a radiation area. Since people would not need to be in the area for any length of time with the beam on, this does not present a problem. Similarly, the dose rate through the transmission line penetration to the power supply room may be above 5 mrem/hr. There is also little reason to work in this area extensively with the beam on.

The portion of NuMI in the Main Injector would need additional earth shielding, as would the Main Injector. When the Main Injector shielding in this area is upgraded for increased intensity, the NuMI portion will also be upgraded as part of the Main Injector.

#### *21.1.8.4 Residual Dose Rates*

Residual dose rates above the Target Hall shielding would still most likely be below 5 mrem/hr in most areas. There may be some hot spots where localized shielding would need to be increased by an additional layer of 1.5 ft. concrete blocks if one wished to have rates below 5 mrem/hr everywhere. Below the concrete cap, where people would need to connect and disconnect water, electricity, etc. to the horn, the dose rates in most places would be below ~50 mrem/hr. Localized hot spots could be shielded when the concrete cap is removed.

Dose rates along the emergency egress pathway along the decay tunnel might reach 500 mrem/hr. This is due to the activated concrete and rock. The concrete and rock will cool down relatively quickly. The emergency egress is not envisioned to be occupied except for maintenance and search and secure. The Hadron Absorber area will be ~100s of mrem/hr. The concrete side will cool down quickly. The steel portions will be hotter and not cool down significantly. They might need to be covered in concrete, depending on access needs.

Clearly all components in the chase (horn, target, T-blocks) and the Hadron Absorber core would be highly radioactive and very difficult to work on. Present estimates range from 100 R/hr to several thousand R/hr (for the target and horns). These estimates would have to be increased by a factor of about 5. Once NuMI runs, measurements will be made of the residual dose rates from various components. These can then be used to more accurately extrapolate to 5 times the intensity and thus more accurately determine the upgrades needed.

### **21.1.9 Operation at 1-second Repetition Rate**

Operation at a 1 second repetition rate and five times the intensity would require major changes to the beamline power supplies, cooling systems, horns, target etc. This would be a large investment that one cannot begin to quantify at this stage without a large engineering effort.

### **21.1.10 Summary**

The main upgrades needed to the NuMI beamline are those associated with cooling. The Target Hall shield pile, decay pipe, and Hadron Absorber cooling would all need to be upgraded. A new target would also need to be designed, built and installed. Due to air activation concerns, the Target Hall and Hadron Absorber shielding would need to be more tightly sealed. Some minor upgrades would be needed for the kicker power supply and perhaps the primary beamline would need a few collimators. Radiation safety issues do not drive any costs. The overall cost for the upgrade to 5 times intensity and 1.5 second repetition rate would be between \$5 and \$18 million dollars, with an estimated expected cost of \$9 million. The cost breakdown is listed in Appendix 1. To then be able to run at a 1 second repetition rate and the same intensity would be a significant additional cost.

## **21.2. MiniBooNE Beamline**

P. Martin

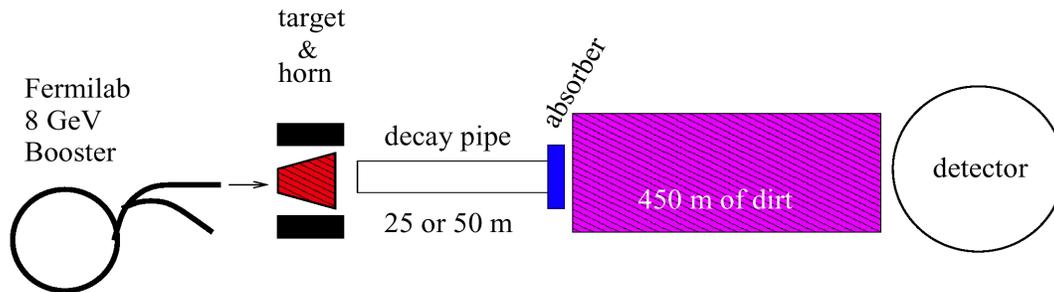
The MiniBooNE target station is comprised of the following main elements (Figure 21.2):

- beryllium target
- horn
- horn power supply
- target pile
- decay region
- beam absorber

The baseline design for the MiniBooNE target station is a 1.6  $\mu$ sec beam pulse of  $5 \times 10^{12}$  protons at an average rate of 5 Hz. This corresponds to a beam power of 30 kW. The beam is delivered by energizing a switch magnet at the downstream end of the MI-8 beamline. In addition to the issues of the target station elements themselves, air activation and groundwater are two major concerns that need to be addressed when considering an intensity increase. Beam-on radiation in the MI-12 Service Building and over the decay region are also issues requiring discussion.

### **21.2.1 Spill duration impact on MiniBooNE**

The horn and horn power supply were designed for operation with a 1.6  $\mu$ sec beam spill, at a repetition rate of 7.5 Hz (with operations expected at 5 Hz.) The current pulse is a



**Figure 21.2.** MiniBooNE Beamline Layout

half-sine wave with a width of 140  $\mu\text{sec}$ . Changing the beam spill to 10  $\mu\text{sec}$  has little impact on the horn focusing; the current is still uniform over the spill to better than 1%. A 1-msec long pulse of beam delivered directly from an 8 GeV linac would require a total redesign of the horn power supply. The present cooling is near the limit of what can be achieved with sprayed-water cooling and precludes a high repetition rate. In addition, the longer pulse duration would seriously impact the experiment, which relies upon a short spill time for signal to background enhancement.

### 21.2.2 Intensity impact on MiniBooNE

The target itself absorbs around 1 kW of beam power. Increasing this five-fold (as will be discussed below) requires a new target design with a larger surface area for cooling, and a larger beam size to reduce the peak energy density. A new cooling system may also be required to remove the higher heat load.

The larger target requires a new horn design with a larger inner diameter. Joule heating from the current pulse dominates the horn temperature rise. Beam heating is a minor factor at the nominal baseline design of  $2.5 \times 10^{13}$  protons per second. A larger diameter alone should be adequate to provide the additional cooling for the higher beam power since it provides a larger area for cooling, and the smaller resistance (for the same wall thickness) reduces the Joule heating. If necessary, reducing the horn current by a few percent also reduces the total power absorbed.

The target pile absorbs around 10 kW of the beam power in the baseline design. Increasing this five-fold should be possible. The steel is cooled on three surfaces by water-cooled panels. While the temperature in the interior of the pile will rise, there are no concerns in this regard.

The decay region and the beam absorbers capture over half of the beam power. This heat is removed by a series of cooling pipes surrounding the decay pipe. These pipes are used to circulate air that removes the heat through an air-to-air heat exchanger. The system was designed to remove 15 to 20 kW of beam power. Increasing this five-fold

may be possible with the existing system, although the temperature of the decay region would rise considerably. To go beyond a factor of five would probably require changing to using water as the cooling medium. This may be possible, but there would be some reluctance to introducing water in these lines due to their close proximity to the decay pipe and the resulting activation of the water if there were any leaks in this system.

### **21.2.3 Radiation issues**

*Beam-on Radiation.* The expected levels in the MI-12 Service Building are expected to be on the order of 0.1 mrem/hr. Increasing this five-fold is not a problem. The levels on the berm over the decay region are expected to be about 1 mrem/hr; increasing this to 5 mrem/hr would require fencing the entire region.

*Air activation.* Calculations indicate that MiniBooNE will release around 10 Ci/yr. Until there is some experience with how difficult it is to achieve this level, one can only speculate that with additional effort, it would be possible to reduce this by a factor of five to handle the increased beam power.

*Groundwater.* The decay region is surrounded by a double-walled liner to exclude water from the vicinity of the decay pipe. Although this liner has failed at the bottom, presumably due to inadequate compaction of the underlying soil adjacent to the MI-12 enclosure, a plan is in place to dewater this region by using the monitoring wells to continuously pump water. Calculations indicate that the level of activation of any water that accumulates in the lower portion of this region will reach the levels of what is permissible for discharging to surface waters. An increase of a factor of five in beam power may require this water to be pumped into holding tanks and sampled before being released, or, if the levels are too high, of disposing as liquid waste. This would be very expensive for the tanks and manpower for sampling, and prohibitively expensive to dispose of the waste if required. Again, until there is experience with the system at the baseline design intensity, one can only speculate as to what the pumping volumes and activation levels will be.

*Horn changing procedure.* Another issue to consider is the need to change a failed horn. The residual activation of the horn will scale with the beam intensity. A much longer cooldown period may be required before changing the horn. Here again, experience with the baseline intensity will help clarify the magnitude of this problem.

### **21.2.4 Summary**

There are a number of areas in which a large intensity increase begins to have substantial impact. Foremost among these are air and groundwater activation, and cooling of the decay region. One could reasonably expect that these aspects could be handled for a five-fold intensity increase, but that is probably near the limits of what can be done.

### **21.2.5 Cost considerations**

The beam is delivered to the MiniBooNE target by a beamline that begins near the end of the MI-8 beamline, just before injection into the Main Injector. The extraction is presently accomplished by energizing a pulsed “switch magnet” just downstream of quad Q851 in the MI-8 line.

Major modifications to this portion of the beamline would be required for any scheme of proton driver that does not utilize the existing MI-8 beamline for injection. In particular, in the proposed 8-GeV superconducting linac scheme, one must assume that a new means of extracting to the MiniBooNE target must be developed.

*Extracting from the Main Injector.* To extract from the Main Injector directly, a kicker would need to be placed just downstream of Q100 and a Lambertson magnet after Q102. This would be followed by a beamline with much harder bend than presently exists to point beam towards the target hall. While no optics design has been done, it is assumed that a solution may exist, but such a solution may require design and fabrication of new magnets for this bend, to achieve the ~60 degrees of bend in a shorter space than presently exists. This would require demolition of the MI-10 Service Building, excavation and demolition of some portion of both the MI and MiniBooNE beamline enclosures, and the reconstruction of the enclosures and building. A rough estimate for the cost of this work would be \$8 M. A major drawback of using the Main Injector for this purpose is that this will require dedicated use of the Main Injector during the period of time the beam is being delivered to MiniBooNE, roughly one-third of the time at the assumed 5-Hz average spill rate.

*Extracting from the Recycler.* To extract from the Recycler, it may be possible to avoid demolition of the MI-10 Service Building and the MiniBooNE beamline enclosure, but a section of the Main Injector enclosure in the vicinity of quads Q636 - Q100 would need to be excavated, demolished and reconstructed with a larger enclosure to accommodate a new transfer line connecting the Recycler into the MiniBooNE beamline before it enters the jacked pipe. This will be considerably cheaper than the option above, but would still cost several million dollars. Again, no optics design has been done, but it is assumed a solution may exist. A major drawback of using the Recycler for this purpose is that this will require dedicated use of the Recycler. In addition, either the proton driver must also be capable of injecting directly into the Recycler, or the Main Injector must also be dedicated to MiniBooNE operations for one-third of the time. Table 21.3 compares the proton pulse length and protons per pulse for the two schemes: Synchrotron at 5 Hz ( $1.25 \times 10^{14}$  protons per second, or 5 times MiniBooNE design), and Linac at 1 Hz ( $1.5 \times 10^{14}$  protons per second, or 6 times MiniBooNE design).

**Table 21.3.** Proton pulse length and protons per pulse

8 GeV synchrotron	1.6 $\mu$ sec pulse	$2.5 \times 10^{13}$ protons/pulse
8 GeV linac, via MI or RR	~ 10 $\mu$ sec pulse	$1.5 \times 10^{14}$ protons/pulse

### **21.3. The Meson, Neutrino, and Proton External Beam Areas**

C. Brown

During the 1990s, the Tevatron routinely delivered, via the External Beams Switchyard, up to  $1 \times 10^{13}$  /min. 800 GeV protons to the Meson, Neutrino and Proton Experimental Areas. During FY2002, the F-sector Main Ring Remnant and the Switchyard are being modified to transport 120 GeV protons from the Main Injector to the Meson Area. Due to shielding limitations in many places along the 1.5-mile journey from the MI to the Meson Area, the intensities delivered to the Meson Area will be limited to  $5 \times 10^{12}$  protons per 3-second MI cycle.

In a Proton Driver era, it would be relatively easy to deliver 120 GeV protons to any or all of the existing Meson, Neutrino, and Proton Areas through the existing Switchyard. If the full intensity capabilities of the Proton Driver were needed for some experiment in one of these areas, shielding upgrades would be needed. Until the current Shielding Assessment Document for the Meson 120 GeV beam project is completed, and until the details of a high intensity experiment in one of the three External Beam Labs are known, the extent of the shielding modifications required cannot be reliably estimated.