Accelerator Improvement Options for NuMI Proton Intensity

The NuMI Proton Intensity Working Group
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Abstract

In order to meet the needs for protons for MINOS and other experiments, substantial improvements will be necessary in the Booster and Main Injector. We have evaluated a number of improvements which would yield an increase in the number of protons on target for NuMI and Mini-BooNE in the years 2005-2008. We outline a possible program of improvements in the Booster and Main Injector which can be implemented in steps over a five year period and which could result in an increase in proton intensity through the Main Injector which is approximately four times what is currently possible. We provide a list of specific improvements and suggest a possible schedule for the implementation.

1 Introduction

The rate at which statistics can be accumulated in many experiments scales directly with the number of protons which can be accelerated to the appropriate energy and delivered to that experiment. Proton intensity is a crucial issue for neutrino oscillation experiments. For these experiments, one typically builds the largest mass of detector which meets the experimental requirements and can be afforded. For world-class experiments, not only must the detector be very massive (and expensive) but the source of protons must be very intense. The Fermilab Main Injector is well suited to become a world-class proton facility for neutrino beams. However, the capabilities of the Main Injector will be stressed by the demands from the coming round of neutrino oscillation experiments. Upgrades to the accelerator complex will be essential.

In this report, we evaluate the current state of the ability of the Fermilab complex to deliver protons, extrapolate to the 2005 experimental program (Collider, MINOS and Mini-BooNE) and make some projections regarding the longer-term future of the complex and proton economics prior to the commissioning of a possible new proton driver. In some cases, we anticipate that upgrades to the Main Injector which will also be essential for a new proton driver and will already start to deliver additional proton intensity even before the proton driver itself will be commissioned. We believe that such upgrades present a highly attractive and cost-effective investment path for the laboratory.

2 Proton Economics for MINOS and Mini-BooNE

2.1 The Current and Near-Term Situation

Up to now, the Main Injector has run primarily for antiproton production for the collider. In the current mode of operation, a single batch of $\approx 4.5 \times 10^{12}$ protons is first accelerated in the Booster to 8 GeV and then injected into the Main Injector and accelerated to 120 GeV before being delivered to the antiproton production target. The current cycle for the Main Injector is 2.46 seconds, determined by the cycle time for Pbar source. The resulting number of protons accelerated per year is about $3-4 \times 10^{19}$, in both the Booster and Main Injector. In the most recent six month period a total of 0.82×10^{19} protons were actually accelerated through the Main Injector for anti-proton production. This accentuates the point that for production to be at its peak value that the complex must work together as a whole.

Recently, the demand for protons accelerated in the Booster has gone up dramatically with the commissioning of Mini-BooNE. The current request is to run the Booster at 5 Hz acceleration cycles for Mini-BooNE whenever it isn't being used for filling the Main Injector. Improvements are required in the extraction septum and power supply and also reduction in proton losses are necessary in order to achieve this rate for Mini-BooNE.

In early 2005, MINOS will also begin to run and place yet more demands on both the Booster and Main Injector. MINOS requires that the Main Injector run in "Multi-Batch" mode where six batches of protons are injected from the Booster in every MI cycle. At the same time, because of physics demand for Mini-BooNE to operate in anti-neutrino mode as well as neutrino mode, it is likely that both MINOS and Mini-BooNE will run simultaneously placing additional demands on the Booster. We note that the Fermilab baseline plan (1998) for MINOS running calls for 3.8×10^{20} protons per year delivered to the NuMI target [1, 2], roughly 10 times the number of protons currently accelerated to 120 GeV. Also by 2005, it is expected that the number of 120 GeV protons delivered for anti-proton production will double by use of some type of stacking scheme [3]. Given these demands, the total number of protons which will have to be accelerated through the Booster will have to be roughly 20 times what has routinely been accelerated.

One additional consideration is that the laboratory is currently building the ability to extract Main Injector beams for test beams and experiments (one of which is already approved, E907) in the Meson area. These experiments will not substantially increase the demand for protons, but they will affect the integrated proton intensity by requiring an extended Main Injector cycle (flat top) for slow extraction.

The first step in moving towards the future has already been taken in preparations for the intial running of Mini-BooNE. Upgrades to the shielding around the Booster have been added at some locations in order to ensure that external radiation limits will not reduce the number of protons which can be accelerated. In addition, beam "notching" has been introduced to reduce the exposure of critical devices to radiation at extraction. Even with these improvements, the number of protons which can be delivered to Mini-BooNE over the next year or so will be limited not by any intrinsic features of the Booster but rather by proton losses causing the machine to become too radioactive. Work is underway to improve that situation by adding additional RF controls and strategic collimation where protons will be lost rather than in critical devices such as RF cavities. In order for Mini-BooNE and MINOS to run simultaneously, yet another factor of two improvement will be needed in the loss of protons compared to what is expected from current Booster improvement projects.

Once MINOS begins running, the Main Injector must run in "multi-batch" mode. Currently, high-intensity, multi-batch mode is in a distinctly developmental status. Multi-batch operation of the Main Injector was briefly demonstrated when it was first commissioned in 1999. For that demonstration, six batches containing a total of 2×10^{13} protons were accelerated to 120 GeV. For a variety of technical reasons, it is not currently possible to replicate this intensity, but with some investment in the complex it is anticipated that this should certainly be feasible again within the next year or so. In December of 2001, the study of multi-batch acceleration was once again undertaken by a group interested in studying and developing the capabilities for MINOS. The current ability to accelerate protons in multi-batch mode is limited to about 1.5×10^{13} protons per cycle. Main Injector experts believe that improvements in the RF feedback and damping will permit multi-batch operation to accelerate up to 3×10^{13} protons per cycle by 2005 with one (of six) of those batches going to antiproton production and the remaining five going to NuMI/MINOS. Note that achieving even this intensity of protons requires that the average number of protons in a Booster batch must be 5×10^{12}.

2.2 The MINOS+Collider Era, 2005 to 2008

Starting in 2005, the Fermilab accelerator complex will face an unprecendented demand for numbers of protons. Current Beams Division planning assumes the following operating scenario for 2005:

- Booster operation will be improved so that a total of 5×10^{12} protons will be delivered per batch with acceptable losses so that 10^{21} protons per year can be accelerated.
- Main Injector operation will be improved so that a total of six batches (each with 5×10^{12} protons) can be reliably accelerated with a cycle time of 1.9 seconds. Note that this already assumes that the pbar stacking rate is improved from the current 2.5 s. There is some ambiguity regarding the impact of slip-stacking for Run IIB which could increase the cycle time.

- A total uptime of 1.8×10^7 seconds of production acceleration cycle per year will be realized for a total of $\approx 2.8 \times 10^{20}$ protons accelerated to 120 GeV per year.
- One-sixth of those protons will go to anti-proton production and five-sixths will go to the NuMI target. It is assumed that running for other fixed target experiments and/or test beam will impact the total protons accelerated by no more than 10%. (This may come in a number of different forms.)

Although the above scenario appears realistic, we note that the program is already going to be short of nominal expectations and anticipate that the following issues need to be considered:

1. Under the above scenario, the number of protons delivered to the NuMI target will be only 2.4×10^{20} per year rather than the Fermilab original design plan of 3.8×10^{20} per year.
2. As mentioned, a preliminary plan exists for slip-stacking one batch of protons into the Main Injector to increase the anti-proton production [3]. The slip-stacking will increase the cycle time of the Main Injector once implemented, nominally reducing the number of protons delivered to the NuMI target by 10%. It is unclear whether it is possible to slip-stack additional batches for NuMI. It may be possible to slip stack a total of six batches (two for pbar and four for NuMI) and then add another 3 batches for NuMI, but this will increase the cycle time of the Main Injector so that the gain will be relatively small (if any) for NuMI and the relative protons for pbar production will go down compared to slip-stacking just two batches. We believe that stacking in the Main Injector is a very serious issue for the laboratory to consider. An alternative to slip-stacking has been studied, barrier RF stacking. This has the advantage that it may permit more beam to be stacked in the same time (or less) than slip stacking. We believe that barrier RF stacking (or variations on this approach) must be considered with high priority.
3. Another part of the planning for RunIIB is that $\bar{p}$'s will be transferred once every 15 minutes from the accumulator to the recycler via the Main Injector. It is estimated that it will take about one minute of the Main Injector for this operation (although currently it takes about one hour). If we assume that it takes one minute of every 15 that will result in an 7% additional loss of protons for NuMI.
4. Simultaneous MINOS+Mini-BooNE running. Either a way to accelerate more protons in the Booster per hour by a factor of two must be developed or running MINOS and Mini-BooNE simultaneously will reduce the proton intensity to MINOS by a factor of two.
5. Should a substantial test-beam program be undertaken, one may anticipate an additional 10% reduction in protons delivered to NuMI.
6. We note that actual accelerator complex "up times" may not quite meet the expectation due to a variety of reasons. Although the recent performance, as noted in section 2.1 is due somewhat to the

fact that the maximum possible production was not yet attempted, some is also the result from "unexpected" downtime. During NuMI running additional losses at the 10% level due to complex downtime would not be too surprising.

Hence, we observe that in order to meet the overall needs for protons during 2005-2008 that a factor of two improvement will be needed in the time-averaged number of protons which can be accelerated to 8 GeV in the Booster compared to any current plan and that a separate factor of at least two improvement will also be required in the ability to accelerate protons in the Main Injector to 120 GeV compared to any existing plan. In fact, some of the plans currently being pursued for Run IIB are almost certain to actually further reduce the number of protons delivered to the NuMI target. In this time-scale, it is clear that improvement will not result from a new proton driver.

3 Overview of Improvements

In this section, we present an overview of upgrades to the Booster and Main Injector which will help to meet the demand for protons in 2005 and beyond. For each item presented here, there is a corresponding section in the appendix which expands on some details. We believe that all of the improvements listed here can be implemented over the next few years and we describe a possible time-line for that in the following section. In some cases, a specific budget and schedule have already been established by Beams Division for the listed work. Where we know that to be the case, we note that by stating "already planned". We note that our working group is not privy to all of the internal planning in Beams Division so it is possible that not all instances of work already planned have been so noted here.

It is worth noting that all of the improvements listed here have been suggested by various individuals within Beams Division and much of the technical information has been supplied by relevant system experts as much as possible. Where they exist, we make an effort to explicitly reference notes previously written on a number of these topics. We have also circulated this report to various Beams Division experts in order to solicit their advice and feedback on the technical issues presented. The suggestions and advice of many members of Beams Division have been invaluable in producing this report. This input also leads us to believe that the upgrades which we present here have a good probability of providing the suggested increases in proton intensity. That said, we realize that the aggregate increase in intensity will likely be somewhat poorer than the nominal increase one might expect simply by multiplying many factors together. The aggregate increases which we present in section 4 take some account of a "reality factor".

3.1 Booster Improvements

Proton acceleration in the Booster is currently limited by the rate at which proton acceleration cycles can be executed and by beam instabilities at high intensities leading to radiation from proton losses and extracted beam with poor properties for transfer and acceleration in the Main Injector [5]. Booster upgrades can both directly increase intensity and make for higher MI intensity by providing clean beams for stacking and easier acceleration.

An additional important improvement is in the acceleration cycle time. In any scenario, the Booster acceleration cycle rate ($\leq$ 15 Hz magnet cycle rate) contributes significantly to the cycle time for the Main Injector. The limitations are primarily on the average acceleration cycle rate. For example, if six batches are accelerated in the Booster in a 400 ms "burst" every 1.9 seconds (for filling the Main Injector) the corresponding average acceleration cycle rate is 4.2 Hz. (We note that two "pre-pulses" are executed on the extraction magnet systems prior to such acceleration cycles.) If we add ten additional accleration cycles for Mini-BooNE in the "extra" 1.5 seconds then the average accleration cycle rate is 9.5 Hz. If we then add another 6 cycles for MI barrier stacking (stretching the MI cycle time to 2.3 s) the average rate climbs to 10.4 Hz. If the Main Injector cycle time is lowered to 1.0 s then the maximum possible Booster cycle rate of 15 Hz will be demanded if both Mini-BooNE and MINOS are to run simultaneously and even 12 Hz will be required just for loading batches into the Main Injector with barrier stacking.

Loss of protons creates radioactivity both at the surface and activates machine components. From a personnel radiation dose perspective, the most critical components to activation are the RF cavities since the power amplifiers atop the cavities are the highest maintenance item in the Booster tunnel. Current proton loss rates result in residual activation at these locations of typically 50 mrem/hr and as high as 200 mrem/hr at a distance of 1 ft from the cavities [7]. These rates are based on Booster running primarily just for anti-proton production with beam pulses less than once per second. The current Beams Division goal is to limit activation increases to just a factor of 2 above current levels. It is anticipated that downtime due to "cooling off" periods will remain acceptable at these levels. However, since the future operation scenarios call for much higher increases than just a factor of 2 in the number of accelerated protons, it is critical that the per-pulse dose to the RF cavities be reduced through both better beam control and collimation.

Limitations in the direct intensity increase are not completely understood, but many experts estimate that it should be possible to increase intensity from the current typical operation, $\approx 4.5 \times 10^{12}$ protons per batch, to $\approx 6 - 7 \times 10^{12}$ protons per batch. The cost of most of these systems for the Booster are very modest compared to the cost of a new proton driver, but the returns are correspondingly modest, though much needed.

- New hardware to help stabilize the beam and reduce proton losses including:
    1. Improved longitudinal damping.
    2. Ramped correctors (installed).
    3. New RF damping hardware.
    4. New collimators (installed but not yet shielded).
    5. Resonant halo extraction during acceleration (being studied).

    6. Cogging and notching capabilities to limit beam losses during extraction (already planned).
    7. Larger aperture RF cavities (A prototype is under construction and some plan exists for a complete set but there is no explicit funding allocated at this time).
    8. Inductive inserts.
    9. Additional acceleration RF and controls to permit the beam to be stretched out, reducing losses due to space-charge.

- Hardware upgrades to permit higher average acceleration pulse repetition rates. The Booster magnets cycle at 15 Hz but not all of the components for acceleration can cycle at that average rate. Although the instantaneous acceleration cycle rate can be 15 Hz, the current components require a lower average acceleration cycle rate. The current average accleration cycle rate is limited to about 3 Hz. Several upgrades are already in progress:
    1. New extraction septum power supply: should permit 5 Hz. Ready soon.
    2. New extraction septum magnet: should permit 7.5 Hz. In fabrication. Note that at this point, the rate is limited by cable heating. Adding additional cable penetrations would allow the extraction septum to be pulsed at the full 15 Hz rate.
    3. As discussed above, additional rate increases, beyond those already planned are very attractive. Although the existing RF system is nominally designed to operate at 15 Hz, its reliability in such a mode is not known and may require substantial upgrades [6]. We recommend that upgrades with rate capability approaching 15 Hz should be undertaken (this may be staged over several years).

We note that although budget has been planned for some of the above activities that manpower resources have not yet been assigned in some cases. It is important that work begin soon on many of these activities in order to avoid serious proton shortfalls in 2005.

3.2 Main Injector Improvements

Improvements in the Main Injector fall into three main categories; decreasing the cycle time, improvements to permit the machine to accelerate more protons per cycle, and proton stacking injection schemes. As the total number of protons in the machine is increased, it will be necessary to add some extra RF power and damping under any circumstance, and this will be particularly true with proton intensities that could become available with a new proton source. Hence, much of that investment can be viewed as “on the path” of a new proton source.

Although outside the scope of this report, we note that the pbar production rate can have an impact on the intensity of NuMI protons. Unless the Main Injector can ramp roughly twice as fast as the pbar source can cycle, it is likely that the MI cycle rate will be tied to the pbar cycle rate during collider operation (most of the time for the operations under discussion in this note). Hence, it is essential that effort is invested to bring the pbar cycle time as low as possible over a period of several years, hopefully matching the rate at which it is possible to cycle the MI in multi-batch mode. Since this is of importance to the collider run we expect that this is the plan of everyone involved and we certainly expect this to happen. Here, we simply wish to point out that it is relevant to NuMI, even though it nominally would seem not connected.

A more serious issue for NuMI proton intensity, and one where we see a potential conflict between NuMI and the collider program is the plan for using slip-stacking to increase the proton intensity to pbar. It is not clear that slip stacking will provide any benefit for NuMI, and it may reduce the protons available for NuMI by as much as 10% if implemented only for pbar production. We believe that the option of Barrier RF stacking, discussed in section C.6 and references [13, 14], may provide a better path for the laboratory to pursue to maximize the physics potential of all of its experiments in this time frame. There may be other stacking variations which use RF barriers in somewhat different ways. An example has recently been suggested by Foster and MacLachlan which uses an RF ramp along with barrier buckets to possibly provide relatively better longitudinal emittance beams for pbar production [15].

- Additional RF power to handle extra proton intensity. Note that this may also contribute to reduction in cycle time.
- Reduction in cycle time (from the nominal 1.9 s which is planned) by "tuning" the acceleration cycle. This probably would require very little new hardware and could result in a reduction in cycle time of 5-10%. (Note that all reductions must be quantized in 67 ms steps in order to be effective due to the Booster cycle time.)
- Reduction in cycle time by increasing magnet power. It is possible to increase the power supplied to the MI magnets, reducing the total MI cycle time to as little as 1.0 s. Some relatively small investment is needed to bring stable operation at 1.5 s cycle time. (Note that this corresponds to the 1.9 s cycle time used for the nominal multi-batch operation when one takes into account the time at 8 GeV while the Booster injects six batches of protons.)
- New RF damper electronics and components. Necessary to go to higher intensity and more sophisticated and expensive as the intensity goes ever higher.
- Collimators to protect critical components from beam losses.
- Yet more RF power with cavity modifications and/or new cavities coupled with significant additional new magnet power to reduce the MI cycle time down to 1.0s.
- Slip stacking: May not work well for multi-batch operation due to the long time required to slip the beams and technical difficulties in multi-batch operation. However, should a single batch be slip-stacked for the collider this will reduce the protons available to NuMI by about 10%.

- Barrier RF stacking (or variants thereof): Appears promising for increasing protons accelerated to 120 GeV by 60%. Requires well-behaved Booster beam and new barrier RF systems in Main Injector. Operates on principles already in use in the Recycler [16]. This would simultaneously increase the protons available for pbar production and for NuMI. For the same rate of protons delivered to pbar production, using barrier RF stacking could deliver as much as a factor of 1.8 times more protons to the NuMI target compared to use of slip stacking. This appears to be the single most important technical issue which we can identify for NuMI proton intensity in the plan we present compared to the current Beams Division planning [3].

4 A Possible Implementation Schedule

Implementation of the improvements listed here will require money to invest in hardware, manpower to study the accelerators and develop and implement the ideas, and time to do the work in a way which is consistent with the ongoing running of the collider. Hence, it is clear that the suggested program will need to be staged over a period of a few years. Here, we propose an implementation schedule which we believe is realistic and consistent with other Laboratory activities and priorities.

Note that some of the work is already a part of the existing planning for the Laboratory. Where that is the case, we note it by stating "already planned" following the task. However, most "already planned" tasks will likely benefit from additional effort. For each year, we show the expected number of protons which can be delivered to the NuMI target in 1.8×10^7 seconds of operation (in earlier years it is clearly hypothetical) in that year given that the work for previous years has been completed and assuming no competing experimental program for protons other than the collider and Mini-BooNE.

- **2002;** 1.6×10^{20} **NuMI protons:**
  1. Continue to re-establish multi-batch operation in the Main Injector (underway).
  2. Study characteristics of high-intensity MI beam in the accelerator and in Proton 150 (underway).
  3. Implement ramped correcters in Booster (underway).
  4. Start implementing dampers in MI (already planned)
  5. Continue Booster collimation studies (underway).
  6. Begin design of additional Booster RF for reducing space charge.
  7. Start machine studies for barrier RF stacking in Booster, MI and Recycler (sort-of planned?).
  8. Start Booster and MI acceleration cycle time reduction studies.
  9. Add notch in Booster for multi-batch operation.
- **2003;** 2.4×10^{20} **NuMI protons:**
  1. Continue Booster beam studies. Bring operation to 5.0×10^{12} protons per cycle (already planned?)

2. Fabricate and install Booster inductive inserts.
3. Install and commission prototype large aperture cavity (already tested). Start acquisition and fabrication of larger aperture Booster RF cavities (already planned but we wish to emphasize the need).
4. Complete design of additional Booster RF for space charge reduction. Start fabrication.
5. Complete first phase of Booster beam repetition rate increase (bring rate to 7 Hz).
6. Complete implementation of MI dampers (already planned).
7. Start acquisition of equipment for additional MI RF and magnet power.
8. Start design of barrier RF stacking components.
9. Start design of MI collimators to eliminate internal and external radiation issues should adiabatic capture studies show these are needed. (Otherwise, don't do now.)

- **2004;** 2.6×10^{20} **NuMI protons:**
  1. Bring Booster operation to 5.5×10^{12} protons per cycle.
  2. Continue fabrication and acquisition for Booster acceleration cycle speed-up (bring to 8 Hz).
  3. Install and commission additional Booster RF for space-charge reduction.
  4. Continue acquisition and fabrication of large aperture RF cavities for the Booster.
  5. Continue fabrication of barrier RF components and start to install and commission.
  6. Continue acquisition of additional MI RF and magnet power. Start installation and commissioning.
- **2005;** 3.9×10^{20} **NuMI protons:**
  1. Bring Booster operation to 6.0×10^{12} protons per cycle.
  2. Continue fabrication of larger aperture Booster RF cavities. Start installing and commissioning.
  3. Continue to increase Booster beam repetition rate (bring to 11 Hz).
  4. Complete acquisition of additional MI RF power. Continue acquisition of additional MI magnet power. Reduce MI cycle time to 1.70 s.
  5. Complete fabrication of barrier RF stacking components. Start to commission stacking.
  6. Start fabrication of additional MI RF cavitities.
- **2006;** 4.9×10^{20} **NuMI protons:**
  1. Continue to increase Booster beam repetition rate (bring to 13 Hz).
  2. Complete fabrication of larger aperture Booster RF cavities. Continue installing and commissioning.

Item	Costs ($k) per FY						Total
	02	03	04	05	06	07	Cost
Spending Profile	250	1500	3000	8000	8000	5000	26000

Table 1: Suggested funding profile for implementation of the upgrades described in this report. Clearly, other profiles can also be adopted but the profile presented here is based on what should be technically achievable and is consistent with the implementation schedule presented here. The costs include purchase of equipment and the cost of engineers and technicians. The costs presented here are without contingency. We note that given the conceptual status of many of the proposed upgrades that an overall contingency in the range of 50-100% should be assigned. However, because much of the cost is for purchase of components with already understood costs, we believe that an average contingency in the range of 50% is most appropriate. Physicist manpower costs are not included but it is assumed that adequate (and substantial) physicist manpower is available.

   3. Continue to improve stacking operation by tuning in Booster and MI. Fabricate additional control devices as necessary.
   4. Continue acquisition of additional magnet power for MI. Continue installation.

- **2007;** 5.1×10^{20} **NuMI protons:**
   1. Complete Booster repetition rate increase program (bring to 15 Hz).
   2. Complete acquisition and installation of magnet power in MI.
   3. Bring MI cycle time to 1.0 s.
- **2008 and beyond;** 6.0×10^{20} **NuMI protons.**

We note that under this plan that the integrated number of protons delivered to the NuMI target in 3 years of running will be $\approx 14 \times 10^{20}$.

5 Approximate Costs and Summary

The bottom line is that it appears that increasing the proton intensity within the existing accelerator complex will certainly be possible within the timescale of 2005-2008. Table 1 shows an approximate suggested funding profile which should be technically achievable given available manpower and access and which is consistent with the implementation timescale which we have presented in this report. Because it is beyond the scope of the current work to produce detailed cost estimates, we provide these estimates only to offer guidance on the scale of the upgrade project. It is important that where items are not already part of the current planning that more detailed cost estimates be developed prior to approval. Table 2 shows approximate cost ranges for the various upgrade projects.

We note that some items can deliver increased intensity at relatively small cost. We recommend that these items should be pursued as the

Item	Cost Range ($k)
Booster	
Extraction septum power supply	< 300
Extraction septum magnet	< 300
Other duty factor upgrades	$1000 - 3000$
Ramped Correctors	< 300
Collimators	< 300
Cogging and Notching	< 300
Larger aperture RF cavities	$3000 - 10000$
Inductive Inserts	< 300
RF for space-charge reduction	$300 - 1000$
Main Injector	
Additional RF power	$1000 - 3000$
Additional magnet power	$10000 - 20000$
Cycle time reduction with tuning	< 300
Dampers	< 300
Collimators	$300 - 1000$
Barrier RF stacking components	$1000 - 3000$

Table 2: Approximate ranges of cost (including cost for engineering and technician manpower) for Booster and MI upgrades.

Labor Type	FTEs needed per FY						Total
	02	03	04	05	06	07	FTE-years
Technician	3	13	19	19	15	7	76
Engineer	3	9	9	7	4	2	34
Physicist	3	11	11	7	5	3	40

Table 3: The manpower profile and total manpower required to undertake the proposed upgrade program.

Investment level	Very Rough Cost	120 GeV Protons in 2005	120 GeV Protons in 2008
≈None	≈ $0	1.3×10^{20}	1.3×10^{20}
Small	≈ $5 M	2.8×10^{20}	3.0×10^{20}
Medium	≈ $15 M	4.0×10^{20}	4.5×10^{20}
Substantial	≈ $45M	5.0×10^{20}	8.0×10^{20}

Table 4: The total protons per year which can be expected to be accelerated to 120 GeV for several different levels of investment in the existing accelerator complex. It will take time for some of the improvement programs to be carried out. Numbers are shown for 2005 and 2008 assuming an adiabatic investment. Note that these are the total protons which are accelerated, some of which go to anti-proton production, some to NuMI and a few for other purposes. Note that the investment levels all include an assumption of twice the current number of protons acclerated to 8 GeV in the Booster than currently needed just for Mini-BooNE operation.

highest priority. The relatively more expensive investments also present very attractive improvements in intensity which we think also present a good value. We believe that it is of great importance that the laboratory pursue barrier RF stacking, or variants thereof, in order to address a potential strong conflict in its main experimental programs from 2005-2008. We note that the annual costs of the upgrade program discussed here are small compared either to the cost of building new large-scale detectors or construction of a new accelerator. To give some feel for how the proton intensity may scale with the overall level of investment (most suitably planned for a given total), table 4 lists the total number of protons which we expect can be acclerated to 120 GeV in 2005 and in 2008 (for all purposes) at a given level of investment (assuming a smooth funding profile as shown in table 1).

Table 3 shows the total FTEs required for technicians, engineers and physicists to carry out the proposed program of upgrades. As with the costs, the manpower estimates reported here should be taken only as guidance of the scale of the project rather than detailed estimates. The required manpower is substantial, but we believe that with a combination of Fermilab and MINOS collaboration manpower that it should be possible to meet these needs.

We conclude that with a modest investment that Fermilab will be able to meet the original planned proton intensity for MINOS, even in the light of other demands for protons such as Mini-BooNE. Conversely, if no new, directed investment is made, it will not be possible to deliver the design proton intensity to NuMI. With larger investment in the current accelerator complex, but with no fundamental changes, we believe that it will be possible to even substantially exceed the original design intensity. The upgrade program requires a series of improvements which will necessarily be stretched over several years. As a result, it is urgent to get started very soon in order to meet goals for NuMI running. We believe that a clear path does exist to meeting the charge to this committee to "identify a list of improvements which appear to have the best chance of delivering a total of 12×10^{20} protons on target for MINOS in a three year period starting in April 2005."

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	Vert. Emittance (π mm mrad)	Horz. Emittance (π mm mrad)
Injection	16	17
Extraction	16	21

Table 5: Transverse Emittance measurements

Injection		Extraction	
$\Delta p/p_{95\%}(\%)$	$\epsilon_{95\%}(eVs)$	$\Delta p/p_{95\%}(\%)$	$\epsilon_{95\%}(eVs)$
0.20	0.17	0.079	0.36

Table 6: Longitudinal emittance measurements for Main Injector beams. The $\Delta p/p$ values are without bunch rotation.

A Characteristics of the current MI 120 GeV beam

Given the tight limits on allowable losses in the NuMI primary proton beam line, it is essential to know the characteristics of the extracted beam from MI, mainly transverse emittance, momentum spread and size of beam halo. The present $\bar{p}$ stacking cycle, where protons are accelerated to 120 GeV as in the case of NuMI, is what is available to perform these measurements and it has been extensively used.

Transverse emittances have been measured in MI with the Flying Wire system. Table 5 summarizes measurements at injection (8.9 GeV) and extraction energies (120 GeV) at the highest intensity of 4.5×10^{12} protons/cycle currently available for the $\bar{p}$ stacking cycle. Variations of the order of 1 π mm mrad are usually observed in these values, reflecting Booster operating conditions.

Longitudinal emittance measurements have been performed on the circulating beam in MI by digitizing the signal from a Resistive Wall Monitor. Table 6 summarizes the results for a beam intensity of 4.5×10^{12} protons/cycle.

The observed increase from injection to extraction of a few π mm mrad in the horizontal transverse emittance and of about a factor 2 in the longitudinal emittance are being investigated. Measurements will be repeated after the commissioning of transverse and longitudinal dampers in MI and with the Booster dampers operating in steady conditions.

At least in the first phase NuMI will run concurrently with $\bar{p}$ stacking: six batches are injected into MI, one batch is first extracted to the $\bar{p}$ source and the remaining ones are extracted to NuMI.

In the last few ms of the flattop portion of the cycle at 120 GeV, bunch rotation is being performed to extract beam to the $\bar{p}$ source with a smaller bunch length. A sudden decrease of the RF voltage for a few ms causes oscillations in the bunch length at twice the synchrotron frequency and beam is extracted to the $\bar{p}$ source at the minimum of the bunch length.

Transverse emittance and momentum spread measurements have been performed in these conditions in the P1 line, by recording beam profiles on MW's, and about a factor of two increase in momentum spread has been observed, as roughly expected.

Bunch rotation is going to affect all batches in MI, and consequently also beam extracted to NuMI. The five batches for NuMI have to be extracted at the maximum of the bunch length, to provide, in principle, a reduction in momentum spread. Preliminary observation of the bunch behaviour show large phase oscillations for at least some of the bunches, which would increase the momentum spread. More investigations are needed on this issue, in particular after the commissioning of the longitudinal dampers in MI, which are supposed to provide a solution to this problem. Set up of instrumentation for the measurement of beam halo is underway.

Multi-batch operation has been recently resumed achieving an intensity of 1.5×10^{13} protons with six batches. Measurements of beam parameters in these conditions will be performed soon.

B Details on Booster Improvements

B.1 Hardware upgrades to permit faster cycle time

The Booster magnets cycle at 15 Hz, but not all Booster components are currently able to cycle that fast. The current accleration rate is limited to about 3 Hz. Several upgrades are already in progress:

1. New extraction septum power supply: should permit 4.5 Hz. Ready soon.
2. New extraction septum magnet: should permit 7.5 Hz. In fabrication.
3. As discussed above, additional rate increases, beyond those already planned are very attractive. Although the existing RF system is nominally designed to operate at 15 Hz, its reliability in such a mode is not known and may require substantial upgrades [6]. We recommend that upgrades with rate capability approaching 15 Hz should be undertaken (this may be staged over several years). New, large aperture cavities are already being considered, and these should certainly be designed to operate at 15 Hz, if built.
4. The "ORBUMP" magnets, which steer the beam through the stripping foils during injection, are currently limited to 7.5 Hz due to heating. We recommend that plans for new, cooled, magnets proceed on a timescale useful to NuMI.

It is possible that additional upgrades will be identified as the cycle time is increased and systems may be stressed beyond their nominal capabilities. Hence, a program for decreasing the cycle time should have adequate contingency assigned to handle such circumstances and some attempt to explictly estimate this would be useful.

B.2 Ramped correctors

While the primary lattice elements of the Booster all ramp with beam momentum, the trim dipoles have historically been operated at fixed currents. This means that as the booster cycles, the beam typically moves both horizontally and vertically. Also, there are certain locations, such as near collimators, where it's desirable to have positive, time-based control over the beam throughout the cycle.

For this reason, a set of programmable control cards have been installed in both the horizontal and vertical planes in order to control the trims currents as a funciton of time in the acceleration cycle. A program has been written to measure the deviations from the beam from an optimal orbit, as a function of time, and calculate the necessary currents to correct this. The program is presently being tested and improved.

B.3 Beam Collimation

At the moment, it's believed that there is a substantial halo on the Booster beam, which results in losses which are undesirable, both because they can occur at high energy and they occur at problematic locations in terms of tunnel activation and above ground radiation levels.

In order to better control protons losses, a new collimation system has recently been designed and installed [8]. This system consists of thin carbon primary collimators followed by thick copper secondary collimator/energy absorbers. Tests on the effectiveness of the current systems are underway. It is expected that the current design should be adequate for running for Mini-BooNE over the next couple of years. However, for combined MiniBooNE and NuMI running at ever higher Booster proton intensity it is expected that additional tuning of the collimation system will be necessary. Before such work can be undertaken, it will be essential to learn from the performance of the current system, along with the ramped correcters. We certainly support the current work which is underway and expect that some future work is likely necessary.

B.4 Additional RF hardware to spread beam out (reduce space charge)

One of the main limitations in accelerating more protons to 8 GeV in the Booster is that space-charge limitations at injection (400 MeV) cause unacceptably high losses to occur as the number of "turns" on which protons are injected from the Linac are increased. At present, the limits from proton losses require that no more than about 7×10^{12} protons be injected (of which $\sim 2 - 3 \times 10^{12}$ are lost prior to extraction).

One relatively simple and attractive way to reduce the space-charge effects is to spread the beam out more longitudinally during injection. This can be accomplished with the addition of another relatively low power RF system which will effectively produce wider total longitudinal focussing buckets. Since the space-charge effects are only at the low injection energies, it isn't necessary for this to operate up to high energies. It also isn't necessary for this RF system to provide significant acceleration power as most of the RF cavities do. However, it must smoothly "decouple" as the beam accelerates.

Implementation of this system requires construction of an additional RF cavity which would run at about 80 MHz with 10% of the power of the other RF cavities, power and control system. Although the total cost in these components is not very large (we estimate the total cost for parts and manpower less than about $1M), it is a relatively tricky system that will require significant design and tuning work. The starting point will be a complete ESME simulation. We anticipate that much of the design and tuning work can be done by physicists.

B.5 Inductive inserts

Inductive inserts have been proposed by Griffin [9] to provide passive compensation for space-charge effects. Inductive inserts are simple ferrite tubes which are heated so that the material properties are just right so that space-charge effects induce a longitudinal self-focussing. The principal has been demonstrated in a storage ring at Los Alamos and has been tested at Fermilab to show no obvious deleterious effects (there was some concern that it might due to a 74 MHz resonance). However, the Fermilab test used too little Ferrite to be effective against space-charge beam blowup. In order to provide enough of an effect, roughly 12 m total of ferrite tubes would need to be placed in the Booster. One issue is whether adequate space is available. The ferrite needs to be of high quality, but the cost is not particularly high, perhaps a few thousand dollars per meter. Hence, most of the work and cost will be in studying how to implement this system, the qualification of ferrites and the insertion into the Booster. The total cost will likely be less than about $300k.

B.6 "Gamma-t" (γ_t) System

The Booster is equipped with a set of pulsed quadruples whose purpose is shift the transition energy downward slightly. If these are pulsed just as the beam is entering transition, it will effectively cause the beam to "jump" through transition.

The system has been tested in the past and has proven quite effective at preserving longitudinal emmittance through transition. Unfortunatly, low emittance, high intensity bunches excite couple bunch instabilities in the accelerating cavities.

For this reason, the "Gamma-t" system is not typically used, and the emittance is *allowed* to blow up slightly at transition.

It's possible that in the presence of the new, improved damping system, a compromise can be found between reduced emittances and bunch stablity.

B.7 Larger Aperture RF cavities

A development program is underway to fabricate a new, larger aperture Booster RF cavity. The motivation for this is primarily to reduce the losses at the location of the cavities, since these require the most hands-on maintenance. (Present dose levels range from tens to hundreds of mrem/hr at one foot.) The present cavities have an aperture of 2.25", whereas the new cavities will increase this to 5". The first (prototype) cavity will reuse the existing tuners, but subsequent cavities would have new tuners along with the outer shell and drift tube.

The plan to fabricate new cavities as opposed to retrofitting the existing cavities is based on three considerations. First, retrofitting old cavities would involve a great deal of hands-on labor on cavity components that will be quite highly activated. Second, there is substantial concern about the longevity of portions that would not be reworked, in particular the water passages, given the already extended usage these cavities have seen. And lastly, retrofitting the existing cavities would require replacing two to four cavities during each shutdown, and retrofitting them prior to the next shutdown. This process would take too many years to accomplish the goal of replacing all cavities within the first year or two of NuMI operation.

The goal is to fabricate the prototype cavity by early calendar year 2003, test it extensively in the first half of the year, and install it in the Booster in the summer shutdown. A few weeks of in-situ operation should confirm if it is acceptable to allow ordering of parts for building an entire set of new cavities at the beginning of FY04. Completion of fabrication would be in FY05, followed by testing and installation.

The estimated cost for new cavities is approximately $5-6M. To meet the above schedule, it is imperative that adequate resources be devoted to this effort, including technicians (approximately 4), a mechanical engineer and an rf engineer. The level of effort of each of these is more than half-time. One of the major efforts will be to qualify ferrites. This can go on in parallel with the prototype fabrication.

The goal of installing new cavities with larger apertures is first to reduce losses in the areas requiring the most hands-on maintenance. Reduction of losses alone should increase Booster performance by a few percent. But removing the losses from the high-maintenance areas should allow pushing the intensity considerably higher than if the losses remain at these locations. While difficult to quantify, the gains could easily be another 10 to 20 percent.

There is a second goal for these cavities, not yet part of the current planning, which could be to reduce instabilities resulting from beam/cavity interactions by taking extra care in the design of these cavities to reduce higher-order modes with higher beam intensities in mind. This may be particularly beneficial if barrier RF stacking is employed and may also help provide overall lower emittance beams for the collider.

Clearly, these new cavities should be designed to operate at the full 15 Hz maximum booster operation.

B.8 Extraction Timing Issues ("Beam Cogging")

Early in the Booster cycle, a kicker is used to remove about 5% of the beam, creating a "notch". Extraction is timed so that this notch is passing the extraction septum while it is ramping up. This dramatically reduces extraction losses by preventing the beam from sweeping over the septum.

There are a fixed number of Booster revolutions between the creation of the notch and beam extraction, but for reasons that are not entirely understood, the total *time* it takes to make these revolutions varies from cycle to cycle on the order of several microseconds.

At the moment, this is not a problem because the Booster extraction determines the precise time for transfer into the Main Injector; however, obviously this scheme will not work when we go to any sort of multibatch injection. Some method will have to be found for fixing the time between the creation of the notch and the booster extraction. There have been some ideas successfully tested, they have never been demonstrated at high intensity.

It's important that work go forward to find a scheme to properly cog the Booster to the Main Injector, and hopefully to understand the mechanism which leads to these time variations.

It should be noted that this is an area of Booster performance which is of no concern to MiniBooNE and so will not likely receive a great deal of attention without a push from NuMI.

B.9 Improvements needed for Barrier RF stacking in MI

In order for Barrier RF stacking of Booster beams into the Main Injector to work efficiently, the longitudinal emittance of beams from the Booster must be reduced compared to current operation. With the existing damper systems working, the longitudinal emittance of the beam extracted from the Booster for a total of 4.5×10^{12} protons in a batch has been measured to be 0.15 eV-s/bunch. The main requirement for barrier RF stacking is a that the momentum spread of beam from the Booster when injected into the Main Injector should not be more than about 5 MeV. With appropriate bunch treatment, it is expected that this can be achieved if the longitudinal emittance of the Booster beam is 0.1 eV-s [14].

There is a trade-off in the Booster between the emittance and the total number of protons accelerated per batch as one approaches the maximum intensity. This is simply due to the fact that at high intensity, instabilities cause the beam losses to go up and these are what determine the maximum intensity. Hence, with the new ramped correctors and dampers that are already being installed and commissioned, it may be possible to find an operating condition with $> 4 \times 10^{12}$ protons per batch that will meet the longitudinal emittance requirements for barrier RF stacking. This will be interesting to test over the next few months. However, it is also possible that new systems will be needed for this purpose. One possibility is the implementation of additional RF controls (along with a new cavity?) which would permit phase rotation of the beam after acceleration to 8 GeV but before transfer to the Main Injector. Other improved RF control systems may also prove worthwhile. Finally, building the larger aperture RF cavities mentioned above could provide an important opportunity for reducing beam instabilities resulting from beam/cavity interactions. This is not necessarily intrinsic to the larger diameter cavities, but such cavities can be designed and built with high intensities in mind where the design should take particular care to provide damping of higher-order modes.

B.10 General comments on the Booster

Booster performance has not been a limiting factor in the experimental program for a very long time, and therefore does not typically receive much attention. This situation will change dramatically as MiniBooNE and NuMI come on line.

Although the Booster has a long history, in many ways it's the least well understood of the accelerators at Fermilab. For the Booster to achieve the performance that is being expected of it, this will need to change. Broadly speaking, progress needs to be made in three areas:

- Booster instrumentation. Recently, the introduction of some simple monitors, such as injection energy, have greatly enhanced the consistency of Booster performance. At present, a plan is under way to re-introduce a dedicated tune measurement into the Booster. We feel that it's vital that this go ahead, and that in the future, resources are allocated for other monitors of Booster performance.

- Beam simulation. Although a plethora of effects are explained with space charge, and a variety of solutions have been suggested, there is as yet no convincing model to support this quantitatively. Recently, progress has been made in simulation of injected bunches. It is very important that this work proceed at least to the point where the proposed space charge solutions can be modeled.
- Beam study. At present, dedicated Booster studies are very limited, unless they can be done parasitically with respect to studies on the other accelerators. It will be important to give the Booster the option of dedicated (destructive) study time during accelerator study periods. Something on the order of 2 to 4 hours per week would probably be adequate.

C Details on Main Injector Improvements

C.1 Additional RF power and voltage for higher intensity

C.1.1 Operating scenario and parameters

It is assumed here that in order to reach desired NUMI Main Injector beam the technique of longitudinal barrier stacking will be implemented so that twelve Booster batches may be injected and accelerated on each MI cycle for total beam intensity 6×10^{13} protons per cycle. With the Booster operating at the present 15 Hz rate, the total injection time will be 0.95 s (including 10-20 ms for adiabatic capture of the de-bunched beam in the MI following barrier stacking). Each Booster batch will contain 5×10^{12} protons in $\approx$ 82 (of 84) adjacent buckets, with longitudinal emittance 0.1 eV-s per bunch (which following all barrier stacking manipulations will result in a stacked longitudinal emittance of about 0.5 eV-s in the MI). The steady state dc beam current (during the passage of adjacent bunches), is $\approx$ 0.52 A. In order to decrease the MI cycle time and offset somewhat the increased injection time required by barrier stacking, it is assumed that the maximum MI ramp rate may be increased from the present 240 GeV/s to 260 GeV/s

The Main Injector RF system is assumed to contain the eighteen existing RF cavities, with a single Y567B (4CW150,000) power amplifier tube installed in each cavity. The cavities are assumed to have $R/Q = 120$ and $Q = 6500$ (at frequencies away from injection), giving $R_{sh} = 7.8 \times 10^5$ Ohms. The cavities are expected to operate with maximum accelerating voltage near 240 kV each, with voltage step-up ratio from anode to gap 12.25:1.

We assume that "local" amplitude and phase feedback systems with bandwidth substantially larger than the synchrotron phase oscillation frequency are installed and operative so that the cavities may be detuned such that the power amplifier load appears 'real' without concern for

Robinson stability or bucket area reduction factor. (The presently proposed amplitude control system will probably be adequate. Additional phase feedback may be required as the cavity tuning system may not have sufficient bandwidth.) Also a relatively fast feed-forward system will be required to prevent rapid excursions of the RF phase and amplitude during gaps in the bunch train.

We expect that changes will be required in ancillary equipment, such as solid state RF drive amplifiers, series tube modulators, anode or screen grid power supplies, or feedback systems, when existing systems are found not to be adequate to allow the RF cavity, with its existing power amplifier tube, to reach maximum power capability.

For constant acceleration rate and RF voltage, the generated bucket area reaches a minimum at $3^2\gamma_t$. Voltage, bucket area and power calculations are examined at 39 GeV/c.

C.1.2 RF Voltage and Bucket Area

For acceleration at 260 GeV/s the required accelerating voltage, $V_{ac}\sin\nu_s$ is:

$$V\sin(\phi_s) = \frac{2\pi R}{c}\frac{d(pc)}{dt} = \frac{260\times 10^9}{90.314\times 10^3} = 2.88\times 10^6 V. \tag{1}$$

With maximum cavity voltage, 240 kV, eighteen cavities generate 4.32 MV. The synchronous phase angle ϕ_s is 41.8 deg. and the 'moving bucket factor' $\alpha(\Gamma) = 0.195$, $(\Gamma \equiv \sin\phi_s)$. The bucket area is

$$A_b = \alpha(\Gamma)\frac{8R}{hc}(\frac{2E_sV_{\rm RF}}{\pi h\eta})^{1/2} = 0.195\times 8.1 = 1.6eVs. \tag{2}$$

C.1.3 RF Beam Power and Stability Considerations

The RF beam power required is

$$P = \frac{e\beta cV\sin\phi_s}{2\pi R} = 4.32\times 10^{-8}$$

watts per proton, or 2.6 MW at the design beam intensity (144 kW per cavity with 18 cavities). In this operating mode the tetrode anode dissipation is 146 kW and the cavity dissipation is 39 kW for total RF power delivered per amplifier 327 kW. The average tube cathode current is 24.7 A. All operating parameters of the amplifier tube are within the rated maximum values.

The total power dissipated in the tube anode and the RF cavity is slightly larger than that delivered to the beam. One of the Robinson stability conditions is that this ratio exceed unity. In this case the margin for stability adequate, but not great. It is assumed that an additional stability margin will be maintained through the several feedback systems installed. If those prove inadequate, stability can be enhanced by the installation of additional water-cooled RF loads on each cavity. The amplifier design is such that substantially more power can be developed by each of the tetrodes by the addition of larger cathode drive amplifiers and changes in the control and screen grid voltages. Such an addition would also require installation of additional dc power sources to the system.

C.1.4 Conclusions

Operation of the existing Main Injector RF system at beam intensity 6×10^{13} protons per cycle with minor modifications is described. The primary caveat appears to be a voltage limitation, not a power limitation. The 1.6 eV-s RF bucket area described above is barely adequate to contain bunches with emittance 0.5 eV-s. Such bunches may be anticipated with slightly improved Booster performance and very good barrier stacking performance. Additional longitudinal dilution may occur during transition crossing in the Main Injector. Several additional Main Injector RF cavities exist and could be installed and placed in operation with minimal effort.

C.2 Additional RF power and Magnet Power for faster cycle time

The rate at which protons can be accelerated in the Main Injector is determined in part by the rate at which RF power can provide the necessary energy, the RF voltage which is required to accelerate the protons in a given number of revolutions and the rate at which the bend and quadrupole magnets can be ramped up and then back down at the end of the cycle. Assuming that all other tuning of the system (discussed in section C.3) has been completed, any additional improvements in cycle time will require reduction in the “ramp times”. The current MI ramp times are primarily determined by the total magnet power supplies. The present rate at which the MI can be ramped (well, almost as discussed below) is about 0.5 seconds each for the ramp up and ramp-down times. Combined with all other features of the cycle this determines the overall minimum cycle time of 1.5 seconds. In a recent study (part of the proton driver upgrade study) the possibility of reducing the total cycle time to 1.0 seconds has been studied, with most of the gain coming from being able to ramp the magnets faster than the current power supplies permit [10, 11, 12]. The needs for additional RF power are mostly met within the envelope discussed in this document. (However the combination of both higher ramp rate and stacking may require more RF power than discussed here. We have not yet had time to consider the implications of both.)

According to the study presented by Wolff [11], relatively small improvments are necessary in both the bend magnet power supply bus and the quad power supply bus in order to provide reliable operation at 1.5 s cycle time. On the order of $200k is required for additional transformers and power supply components in each of these systems. No significant modifications will be needed in either system in terms of bus components, total power, or layout of the system.

For decreasing the cycle time to 1.0 s, substantial new investment in power supply components is necessary. The basic idea is to double the maximum power supply voltage in order to halve the time of the ramps. The nominal plan would add two additional bend supplies and one quad supply to every MI service building. This would increase the bend bus voltage to ground from 500 V to 1000 V. This may prove untenable in which case it would be necessary to increase the number of feed lines between the power supplies and the magnets. With the exception of MI 60, it appears that there is adequate duct space to accomplish this without new civil construction. Additional transformers and other components will also be necessary at the Kautz road substation. Some civil construction may be required to provide additional space in the MI service buildings. A rough cost estimate exercise has suggested that the total cost of these upgrades are in the neighborhood of $20M. It is clear that this will need several years to carry out all of the work and acquire all the components.

Although this is certainly the most expensive single upgrade option which we discuss in this document, we do not believe that it should be dismissed simply because of the relatively high cost. We note that the investments made here will provide better performance even at the time that a new proton driver would become available. Running the Main Injector at 1.0 Hz rather than 1.5 Hz given this cost will always be a relatively good bargain compared to increasing the statistics of neutrino events by building a detector which is 50% larger. Hence, although we realize that the relatively large cost of this upgrade will require it to be carried out over several years, we strongly recommend that it be considered as part of the total upgrade planning so that it can be taken into account in the other system designs and so that detailed planning work and acquisitions can get underway.

C.3 Reduction in cycle time (other than from more RF and magnet power)

The Main Injector cycle length for 6 batch operation is presently 1.867 s, with a maximum ramp rate of 240 GeV/s. One way to decrease the cycle time is to increase the ramp rate. This is discussed in section C.2. However, there are relatively more subtle modifications that may also permit a significant reduction in the cycle time. Careful adjustments of the various parts of the ramp as conservatively designed now might lead to a gain of about 100 ms and perhaps as much as 190 ms (5-10%). There are three main components of the ramp where it may be possible to reduce the current cycle time without significant invesment in new hardware.

1. The set of parabolas from 85 to 120 GeV: Optimizing these could result in a cycle time reduction of about 50 ms. It is necessary to demonstrate that this does not adversely affect the beam.
2. The flattop portion: In this time, the final RF frequency adjustment, bunch rotation and extraction are performed. It may be possible to reduce this to about 50 ms from the present 70 ms.
3. The reset part of the ramp: In this time, magnets are ramped down to 6.7 GeV to minimize the hysteretic contribution. Currently this takes 125 ms. Studies are necessary to determine how much this might be reduced. We note that at one time the Main Ring operated with no reset in the ramp. Instead, a different ramp cycle was used depending on the current hysteretic state. It is expected that at least 30 ms might be trimmed from this reset time and with careful attention to hysteretic condition it may be possible to reduce it even more.

Some initial studies are already planned regarding cycle time reduction [18]. In order to achieve the full reduction from this kind of tuning, additional performance studies will be necessary.

C.4 Dampers

The MI Dampers are a series of pickups and kickers which are used to stabilize the beam. The pickups get the signal from the circulating beam about its energy, position and motion of the beam as it goes through the accelerator. The analog information form the signal is used to provide feedback to the beam through the kickers. There are three damper systems necessary for controlling instabilities in the Main Injector:

1. **Longitudinal system:** Controls the beam energy and the time oscillation about some fixed reference. Most longitudinal focussing and control is provided by the high level RF system with the cavities and power amplifiers. The damper system provides perturbations on the main high level RF control signals.The timing and bunch length are measured with a stripline pickup located at MI-60, and the processing occurs in the MI-60 control room. The signals are then applied to the low level and high level RF controls.
2. **Narrowband transverse system:** Controls the variations in the transverse position of the beam relative to some fixed orbit resulting from transverse coupled bunch mode instabilities only closest to the fundamental mode.
3. **Wideband transverse system:** Controls the variations in the radial position of the beam relative to some fixed orbit resulting from transverse coupled bunch mode instabilities. The wideband damper system corrects instabilities related with betatron lines closest to the fundamentals but also around other revolution harmonics

When the MI was first commissioned in 1999, both the longitudinal and narrowband transverse dampers existed. The wideband transverse dampers have not yet ever been deployed. This permitted operation with six batches and a total of 2×10^{13} protons. At present no damper system is in use and in fact some of the control electronics for these systems has been removed for use elsewhere in the accelerator complex. However, the components installed in the MI ring are still there. New control hardware for the longitudinal damper systems exists but needs to be assembled and commissioned. The longitudinal damper can be recommissioned within a few months with part time effort of a physicist, engineer and technicians.

The existing pickups can be used to recommission the narrowband transverse system. It will be necessary to duplicate some low level electronics at a cost of about $10K. A high power RF switch will be needed to use the same damper alternatively between the proton and the pbar cycle. The high power RF switch is expected to cost about $15k but an appropriate commercial switch has not yet been identified. Assembling and commissioning this system will require a team comprised of a physicist, an engineer and a technician working for about six weeks. An alternative is to use separate power amplifiers and kickers for narrow band transverse dampers for proton and pbar damping. In that case, it will be necessary to build new kickers and order power amplifiers which will increase the time before this system can be implemented. This will cost about $65k.

The MI group is interested in commissioning a new digital wideband damper system which will be used to correct the instabilities related with betatron lines not only closest to the fundamentals but also around other revolution harmonics. The new system will analyse the data from pickups for instabilities in several modes, do a digital correction and supply the feedback for correcting several modes at the same time. This system is not yet known to be needed but may become necessary as the proton intensity is increased.

Existing pickups, kickers and power amplifiers can be used as inputs to this system. New processors and related hardware needs to be procured and will cost at least $100k. A team consisting of a physicist, an engineer and a technician can accomplish this within a year. The MI department expects to begin work on the damper system this year and expects to commission it in the spring/summer of 2003.

With all planned dampers in operation, and with proper tuning of the MI, it is expected that a total of $2.5 - 3.0 \times 10^{13}$ protons per cycle can be accelerated to 120 GeV. Additional information can be obtained from reference [19]. It is anticipated that the capabilities of the currently envisioned wide-band transverse damper will permit the operation to exceed 3.0×10^{13} protons per cycle.

C.5 Collimators

It is not yet clear whether any Main Injector collimators will be necessary for the proton intensities described here. For intensities as high as those discussed with a new proton source, it appears that such collimators will be needed in order to protect the components of the Main Injector from too much radiation damage due to even relatively small proton losses. These are described in the recent proton driver upgrade study [10]. It is our expectation that such collimators will not be necessary for the intensities discussed here.

C.6 Barrier RF stacking

At present in the Main Injector, all longitudinal focussing and acceleration is accomplished using the standard 53 MHz RF buckets. This works fine for normal injection and acceleration. However, if one wishes to do more complex operations, such as stacking more than six batches of protons, one needs another tool. In "slip stacking", two batches of protons from the Booster are injected at slightly different momenta, but both still contained within the acceptance of the Main Injector. One then waits ~ 100 ms for the beams to coalesce due to the slightly different velocities. It is not clear that this will work for more than just two batches of protons and it is unclear how efficient it will be even for two batches at high intensity.

Barrier RF stacking of Booster protons into the Main Injector was first proposed by Griffin [13]. A recent study has been carried out by Chou, Ng and others which further develops the concept [14]. In Barrier

RF stacking, batches of protons are all injected into the Main Injector at a fixed momentum but then a “travelling” RF square wave slightly accelerates each batch (only once) to a higher momentum and moves its location in the Main Injector by half a batch length. This permits a second Booster batch to be injected with an offset of 1/2 batch length to the first (and so on) up to a total of 12 batches. In fact, it is believed that this can be done within the 70 ms period of the Booster so that injections could occur at the full possible rate of 15 Hz (with appropriate Booster upgrades). Nominally, this will permit the MI to be filled with a total of 12 batches of protons from the Booster in 800 ms compared to 6 batches in 400 ms with no stacking. If we then assume that the MI cycle adds 1.5 s to these numbers the resulting increase in the rate of protons accelerated to 120 GeV is a factor of 1.65. Assuming that one “stacked batch” is extracted for pbar production, the rate at which protons are delivered for pbar production will be about the same as with slip stacking. The important difference is that the number of protons delivered for NuMI will go up significantly at the same time as the protons for pbar production are increased.

With slip stacking, it is possible that the intensity to NuMI could be decreased by 10%. Hence, the relative difference for NuMI with barrier RF stacking compared to slip stacking for the collider is a factor of 1.8. If it is possible to efficiently slip-stack in multi-batch operation, then the ultimate difference may not be as large as this nominal factor. However, we believe that the potential for a dramatic difference for NuMI, given the same performance for pbar production makes a rather strong argument in favor of pursuing RF barrier stacking as the highest priority stacking program. The goal should be to start to use RF barrier stacking in 2005. (It is possible that some use of slip stacking in the interceding years may prove effective for pbar production or even that some mixed use in future years could provide a best overall optimization of the program.)

The principles of barrier RF stacking in the Main Injector are already under demonstration in the Recycler [16]. In fact, the implementation in the recycler is more complex than needed for the Main Injector. The main requirements for barrier RF stacking in the Main Injector are:

1. Beams from the Booster with sufficiently small longitudinal emittance. It is estimated that an emittance of 0.1 eV-s should be acceptable. Even better emittances may help keep proton losses down and total efficiencies high. Two issues drive the need for small emittance. The first issue is that the momentum spread must be no more than about 5 MeV in order to avoid proton losses during the stacking process. The second issue is to limit losses at transition in the Main Injector. It is estimated that barrier stacking will increase whatever emittance comes from the Booster by at least a factor of 1.6, on top of the double width from stacking. Hence, the total anticipated longitudinal emittance of the beams in MI after stacking has been estimated to be 0.47 eV-s [14]. It may be possible to compensate for this using improved techniques for transition crossing. However, we note that this nominally should already be acceptable in the Main Injector [17], though it is generally not actually the normal operat-

ing mode at this time. This is something that could be tested in the near future.

2. Sufficient RF power in the Main Injector to handle the higher beam intensities and sufficient RF voltage to handle the larger longitudinal momentum spread of the stacked beams. As discussed in section C.1, we believe that this can be achieved relatively easily. However, this is also one of the more interesting things which should be experimentally demonstrated and argues for an early launch of a test of the barrier RF stacking in the Main Injector.
3. Implementation of barrier RF cavities and power and control system in the Main Injector. Studies must be done to understand exactly the number of cavities required. It is perhaps as few as two cavities and as many as four. This is in fact nominally all the new hardware which needs to be built. This requires several FTE-years including physicists, engineers and technicians to implement in period of about two years at a cost between $1-3M.
4. Ability to accelerate bursts of 12 batches of protons at the full rate of 15 Hz from the Booster, every 2.267 seconds (or faster if the MI cycle time is reduced). Although one can implement barrier RF stacking without this, the relative efficiency is improved with the highest acceleration rate from the Booster. We note that with MiniBooNE running at the same time that this will mean an average rate > 11 Hz.
5. Efficient adiabatic capture of the debunched stacked beams. Unlike slip stacking, the barrier stacked beams lose all memory of the 53 MHz structure. Hence, the 53 MHz RF must be applied slowly once stacking is complete or a large fraction of protons will be lost. It is estimated that if the adiabatic capture is done over a period of about 10 ms that 3% of the injected protons will be lost [14]. It may be best if it is arranged that these are lost in a dedicated collimation system. However, studies on this feature need to be done to better quantify the realistic capture.

Due to the relatively spread-out beams, it is expected that space-charge effects will not be a limiting factor for the barrier stacked beams. It remains to be seen whether there will be additional new stability control issues with beams of this type and at high intensity in the Main Injector.

C.7 Variations on Barrier RF stacking

Foster and MacLachlan have very recently suggested stacking which uses barrier buckets but also includes an RF ramp which does the main job of the stacking by compressing proton batches from the Booster by a factor of 2 in a period of 100 ms. Barriers are needed to help confine the ends of the batches (which are unbunched) but don't do the main work of the stacking in this approach. Once the batch is compressed, the RF is turned on and the protons adiabatically captured in buckets as in the barrier stacking. This may have the advantage that the resulting longitudinal emittance will be lower than for barrier stacking which is attractive for $\bar{p}$ production.

Several of the concepts, including the important issue of adiabatic capture are shared and could be tested along with the development of barrier stacking and then a future decision could be scheduled for which is the best technique to implement.

C.8 Proton safety envelope

As with the Booster, the Main Injector has a set of administrative operations constraints to assure that the integrated observed radioactivity in and above the tunnel is not too large, even under accident conditions. The current administrative limits are:

1. $< 5.7 \times 10^{16}$ protons per hour at 8 GeV.
2. $< 3.9 \times 10^{16}$ protons per hour at 120 GeV.
3. $< 3.3 \times 10^{16}$ protons per hour at 150 GeV.

These numbers have been set very conservatively for the start of MI operations and should be easily modified upwards following a necessary set of safety review procedures and measurements. We note that the nominal operations required to deliver all of the planned protons for Run IIB plus NuMI corresponds to about 8.3×10^{16} protons per hour at 120 GeV, more than twice the current administrative limit. However, those familiar with the design and initial shielding have suggested that no additional shielding needs are expected up to at least 10^{17} protons per hour at 120 GeV and the real limits may in fact be well beyond that. We note that 10^{17} protons per hour corresponds to the nominal maximum intensity which we discuss in this document.

Hence, the main impact of this limitation will simply be that work will be required along with careful monitoring to establish this new operational standard. In addition, should proton losses be higher and/or even higher intensities delivered it may be necessary to take additional measures to control losses, collimate losses, add shielding or some combination of these approaches. Again, a program of careful measurements will be needed in order to determine an ultimate safe operating limit.

D Issues in the NuMI Beamline

It was realized early on that intensity is a crucial concern in the design of the NuMI primary proton beam. Any losses which occur in a line of this intensity cause problems, first in irradiating components which may later need to be handled or worked on, and second, in leading to groundwater activation. The intensity assumed in design of the line is 4×10^{13} protons every 1.9 seconds. A significant feature of the design, a somewhat new concept, is a Permit System, which has the ability to abort further beam pulses if any single pulse shows unacceptable losses. In addition this system has the ability to inhibit any pulse before it is extracted if any beamline parameters are out of tolerance immediately before extraction. This philosophy, of limiting the number of unacceptable pulses to at most one, would continue to be viable for beam intensities as high as 10^{14}

protons per pulse; it would also continue to function well if the pulse rate were to increase.

Another subsystem which will be brought on line for NuMI is the Beam Loss Budget Monitor. In general Fermilab accelerators and beamlines are approved to run a certain amount of beam per hour, week or year. There will be similar restrictions, which are enforced administratively via the Beam Budget Monitor, on NuMI during commissioning. The rationale for limiting beam to any region is to assure that chronic losses in that region are kept below some level. In NuMI it is intended to monitor the losses themselves, and to impose an administrative limit on the amount of loss observed. Clearly if there are chronic losses in the beamline, the loss budget will be exhausted more quickly during high intensity running. Thus it is essential that both episodes and chronic losses be kept to an absolute minimum.

For most beamlines a prime consideration for losses is the possibility of prompt radiation near the surface. However for NuMI this is not the case. The downward slope of the line assures that after beam has left the MI60 region it is deep enough that surface radiation is not a serious consideration. While the beam is in the region of MI60 and the NuMI Stub it is covered by the MI berm.

A concern has been voiced that as the MI intensity rises its beam quality will deteriorate to some extent. The relevant measures of beam quality are the transverse emittance and momentum spread. If the transverse emittance were to grow too large the beam might be too spread out to be efficiently transmitted by the NuMI line and losses would ensue. Similarly, since there is dispersion in the line caused by the large vertical bends encountered, the momentum spread manifests itself as a growth in transverse beam size. Indeed it was shown convincingly that, for the line as originally designed, momentum spread as anticipated for high intensities could not be transported.

The recent redesign of the line has increased the acceptance in both emittance and momentum spread. These acceptances are now greater than that of the MI itself [20]. We endorse this modification to the beamline design and note that it is critical to future high-intensity operation.

There are still a few areas of concern in the current design for high intensity operation. A matter of particular concern is the third extraction Lambertson which appears to be too close to the beam in the current design. Additional studies are being performed to address this issue and we endorse the need for this additional work. The second concern is in the vertical plane at the trim magnet near station 230 m. This trim will be replaced by one with a larger aperture if operating experience indicates that there are significant losses here. Lastly there is a problem in both planes with the aperture at station 350 m. However this aperture is that of a collimator, which will be installed at that location to provide protection for the focusing horns from misbehaved beam.

If the cycle rate of the Main Injector is decreased to order 1 s, it will be necessary to increase the power of the ramped power supplies which drive the magnets in the NuMI beamline. The cost of upgraded power supplies is roughly $500k. There may be some additional infrastructure costs as well associated with cooling capacity and space. However the total cost for the NuMI beamline will be only a small fraction of the cost required for the upgrades in the Main Injector itself under any circumstance. This is not surprising given the relative number of ramped devices in the two locations.

We have discussed the possibility of inclusion of a collimator in the region between the Main Injector and the main vertical down-bend. It appears that the current beamline design will not require such a collimator with forseen operational intensities. However, we believe that prudence call for keeping such an option open for future upgrades.

E Charge to the NuMI Proton Intensity Working Group

The working group is charged with advising the Directorate and the MINOS spokesperson on the number of protons per year that the MINOS experiment can reasonably expect to have targeted and actions which can be taken to help maximize the total number of protons delivered in a three-year running period.

This advice should be based upon the following:

1. Document the present capability of the accelerator complex with respect to protons per cycle that can be accelerated to 120 GeV in the Main Injector in the mixed-mode expected for joint NuMI + pbar production operation. Document the beam emittance, both transverse and longitudinal, at 120 GeV, and the Booster losses per proton relative to the trip point of the interlocked detectors. The emittances and the losses are functions of intensity, so the above measurements need to be done over a range of intensities.
2. Document the number of protons per hour that can be accelerated in the Booster for the above operating cycle while staying within the safety envelope.
3. Document the number of hours per week that beam can expected to be available from the Main Injector.

Based on the above measurements, develop a plan of improvements, ordered in priority to the extent possible, that appear most attractive towards increasing the projected proton intensity per year. Assuming these improvements are implemented, what is the expected gain? Although it should not be taken as a limit, the working group should specifically identify a list of improvements which appear to have the best chance of delivering a total of 12×10^{20} protons on target for MINOS over a three year period starting in April 2005.

Where possible, the working group should identify specific manpower needs, from both inside and outside of Fermilab, in order to meet the suggested improvement goals.

A final report should be submitted by April 15, 2002. The working group should report at each MINOS collaboration meeting and NuMI PMG meeting until then.

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