FIRST REPORT OF THE PROTON STUDY GROUP
Recycling the Recycler

February 28, 2006

I. Introduction

An extended neutrino program is expected to be a core ingredient of the Fermilab program through the first half of the next decade. Elements of this program will likely include an extension of the present MINOS experiment and the Nova off-axis experiment, both using the NuMI beam line. The beam delivered to NuMI will be increased over the next few years through upgrades under the present Proton Plan, which is expected to be completed in 2008. The main elements of this plan aim at the reduction in Booster losses (and thus higher proton throughput in the Booster), a reduction in losses in the Main Injector, the development of slip-stacking or barrier-bucket stacking in the MI, and an upgrade in the MI RF system. The goal for NuMI with these upgrades is an average targeting rate in excess of 44×10^{12} protons (44 Tp) every 2.2 seconds.

The cancellation of the BTeV experiment opens other avenues for further increase in proton delivery to the neutrino program once the Tevatron collider program is terminated. While the ultimate program might be a high intensity Proton Driver facility, it is realistic that such an accelerator, if it were approved, may not be ready for operation at Fermilab by the end of this decade when the LHC is expected to become operational. Thus, viable concepts for upgrading and restructuring the Fermilab accelerator complex to maximize delivery to the NuMI beam line after the end of Run II need to be explored. The Proton Study Group was formed by the Accelerator Division Head to look at options and consider next steps following the conclusion of Run II, as well as the successful completion of the Proton Plan. The current Proton Plan[1] contains upgrades to the Booster and Main Injector to provide 44 Tp every 2.2 seconds from the Main Injector at 120 GeV, corresponding to an average beam power of 400 kW.[2] The scheduled completion date of this plan is in 2008.

[1] *The Proton Plan*, Beams-doc-1441 (2004).
[2] For scaling purposes, note that 100 Tp every 2 sec at 120 GeV corresponds to 1 MW.

A Staged Approach

Whatever changes or upgrades can be made to the existing Fermilab facilities to enhance the neutrino program, they need to be executed in a staged manner with minimal impact on the physics schedule. If a Proton Driver project materializes and proceeds rapidly ahead, then the current Fermilab complex can be upgraded according to funding and scheduling constraints, and the upgrades can be stopped at any stage along the way when the Proton Driver is ready for operation. Additionally, if a Proton Driver project is prolonged due to its own funding or scheduling issues, then the various upgrade stages can continue to be carried out until the full reach of the program is fulfilled.

One unique capability of the current Fermilab complex is high-rate antiproton production. It could be that interest in antiproton physics, similar to LEAR at CERN, or other applications would dictate that the facility remain intact. If the Recycler Ring were to continue to be used as an antiproton storage ring, then future upgrades to the complex for the neutrino program would be limited to the Booster and Main Injector only. Should an antiproton program only require the use of the Antiproton Source, then the Recycler could be used in the neutrino program as a "proton accumulator" prior to injection into the Main Injector. On the other hand, if it were decided to forego any further antiproton production at Fermilab, then the Antiproton Source and/or its infrastructure would be available for use in the neutrino program. In any scenario considered, upgrades to the Main Injector must "keep up" with the planned increase in proton throughput.

Before discussing the option of re-using the Recycler as a pre-injector, first a few words regarding the physics program are in order, in particular the needs of the neutrino as well as the Switchyard 120 fixed target programs.

Physics Considerations

Decisions regarding the physics mission of the lab are beyond the scope of this document; nevertheless, it is useful to give a brief overview of the physics landscape that may influence these decisions.

The major physics interest in extremely high proton fluxes comes form neutrino physics. At the time of this writing, the major users of protons at Fermilab are the MiniBooNE experiment, which uses the 8 GeV beam directly from the Booster, and the MINOS experiment, which uses the 120 GeV proton beam from the Main Injector.

At the end of the present Proton Plan, the NuMI beam line will be getting on the order of 3.5×10^{20} protons per year. This number will automatically increase to something over 4×10^{20} when protons are no longer needed for antiproton production. In addition, there will be about $1\text{-}2\times10^{20}$ protons per year available at 8 GeV for the MiniBooNE experiment.

Another experiment has been proposed which will utilize the NuMI beam line with a detector built roughly 10 mrad off axis. This configuration results in a narrower neutrino energy distribution, but also reduces the flux. With reasonable sized detectors, this experiment is not considered viable with the proton rates of the first stage of the proton plan. The most modest of the upgrades described in this document, bring the proton flux at 120 GeV to something like the 6-7x10^{20} protons/year range, at which at least the initial phase of an off-axis experiment becomes viable, but the ultimate physics results could only be achieved with the sort of intensities provided by the proposed proton driver.

Some of the more ambitious recent proposals have the potential to reach intensities on a par with the Linear Proton Driver *at 120 GeV;* however, whereas the Linear Proton Driver has significant excess proton capacity at 8 GeV, these solutions do not. It is possible 8 GeV protons would still be of interest on the timescale of these proposals, particularly if the MiniBooNE experiment sees a signal. If the numbers required are significant, this would reduce the amount available to the 120 GeV program.

Tevatron Fixed Target

At present, the Fixed Target program from the Main Injector (Switchyard 120) is often seen as a small impact on other operations, mainly due to interruptions in the facility "time line" for special 120 GeV Main Injector ramps for this purpose. On the other hand, one could say that beam time to the SY120 program has been limited due to the fact that it interrupts the other higher-priority programs at the lab, namely the production of antiprotons and the delivery of high intensity proton beams to the NuMI operation. The present amount of beam delivery is small (presently delivering ~1 Tp over 4 sec., every 2 min., for an average rate of 33 Gp/sec) but the demand for test beams may be greater than this current level, especially in light of the needs for NOvA, MINERvA, and particularly ILC.

Once the Run II program ends, the Tevatron will still be one of only four high-energy superconducting accelerators in the world. Of those four it is the only one that was designed with rapid cycling capability. Resurrecting a high energy (800 GeV) fixed target program would be expensive, with much of the infrastructure for this operation having been removed prior to the start of Run II. Power supplies and septa would need to be reinstalled and re-commissioned, as well as a high power beam abort system, and so on.

It is conceivable, however to use the Tevatron as a "stretcher ring" for 120 GeV Fixed Target operation to the existing Fermilab Switchyard. Ignoring the operational expense for the moment, one could imagine extracting beam from the Main Injector on two pulses separated by ~1.5 sec, and during the next several minutes performing resonant extraction from the Tevatron at 120 GeV to the Switchyard. The Tevatron would be re-tuned to operate DC at this lower energy. As a numerical example, consider filling the Tevatron with 40 Tp from the Main Injector every 25 min. This could provide an average spill rate of 30 Gp/sec to the Switchyard with a 99.9% duty factor and essentially no impact on the neutrino program. A fraction of the beam circulating in the Tevatron can be extracted "on demand" for short durations, at variable spill rates, for example. It may even be possible to decelerate slightly in the Tevatron to vary the primary beam energy to the Switchyard.

Note that the Main Injector could provide at least twice the above intensity to the Tevatron, but 40 Tp is already more than the Tevatron has ever handled during 800 GeV Fixed Target operations. However, during those days the intensity was mainly limited by beam instabilities at high energy. At 120 GeV, the intensity presented here may be realistic. Also note that the existing internal abort system should be able to handle the 120 GeV conditions, to the extent that we equate 40 Tp @ 120 GeV with 5 Tp @ 980 GeV, while today's Tevatron Run II conditions are 10 Tp @ 980 GeV. (Naturally, fault conditions, *etc*., would need to be verified.)

It is interesting to point out that beam transferred to SY120 from the Main Injector passes through the Tevatron Injection Lambertson Magnet. For today's SY120 operation, this magnet is left off, and the beam passes straight through and up into the SY120 beam line. In order to extract beam from the Tevatron this magnet needs to be turned on with reversed polarity. This is the process that was used during the final 800 GeV Fixed Target Run ending in 2000. An electrostatic septum would kick the resonant particles into the field region of this same magnetic septum and direct them up toward the SY120 beam line. The natural place for the electrostatic septum, assuming half-integer resonant extraction, would be the C0 straight section, which currently consists mostly of free space. The other piece of hardware required is the resurrection of the slow-spill feedback system, referred to as ``QXR," which consists of fast air-core quadrupoles and associated power supplies and electronics.

Since there will be no ramping of the Tevatron, then effects such as ``snap-back," tune and chromaticity drift, *etc*., will be of little consequence, and the quench margin will be much higher. The main drawback of this scenario which immediately comes to anyone's mind is the operating cost of the cryogenic system and of the supporting infrastructure for the four-mile ring to support a 120 GeV fixed target program. However, the 120 GeV fixed target program may be asked to not run year-round operation.

While the costs of running a 120 GeV Tevatron program may be high, it is worth pointing out the capability of the synchrotron should the user community find it worthy.

II. Possible Modifications to Existing Facilities

A general approach toward higher beam throughput within the existing proton program is to stack charge in an upstream accelerator during the ramping of the next downstream accelerator. For example, the Main Injector cycle time is presently 2.2 sec, 0.7 sec of which is spent loading the MI with beam from the Booster, as depicted in Figure 1. If the Recycler Ring were available, for instance, one could contemplate accumulating protons from the Booster directly into the Recycler during a 1.5 sec MI ramp, and then single-turn inject into the MI. This would give approximately a 50% increase (2.2/1.5) in the 120 GeV targeting rate. It may be possible to employ similar techniques using other upstream accelerators, such as the antiproton Accumulator Ring, and/or by replacing the existing Debuncher ring with a new high-intensity booster synchrotron.[3]

Below, the Recycler Ring option is presented after first briefly mentioning the limiting potential of the existing Booster. The use of the Recycler for pre-injection charge accumulation is the most straightforward option, which has the largest gain in throughput for the least expense, and thus is the natural first step toward higher beam power. The increase in beam power, generated by the shorter cycle time, places no new demands on the Main Injector beam intensity above that anticipated in the present Proton Plan. In addition to the shorter cycle time, the interference of antiproton production is removed which adds another 30% to the possible throughput to the 120 GeV neutrino program.

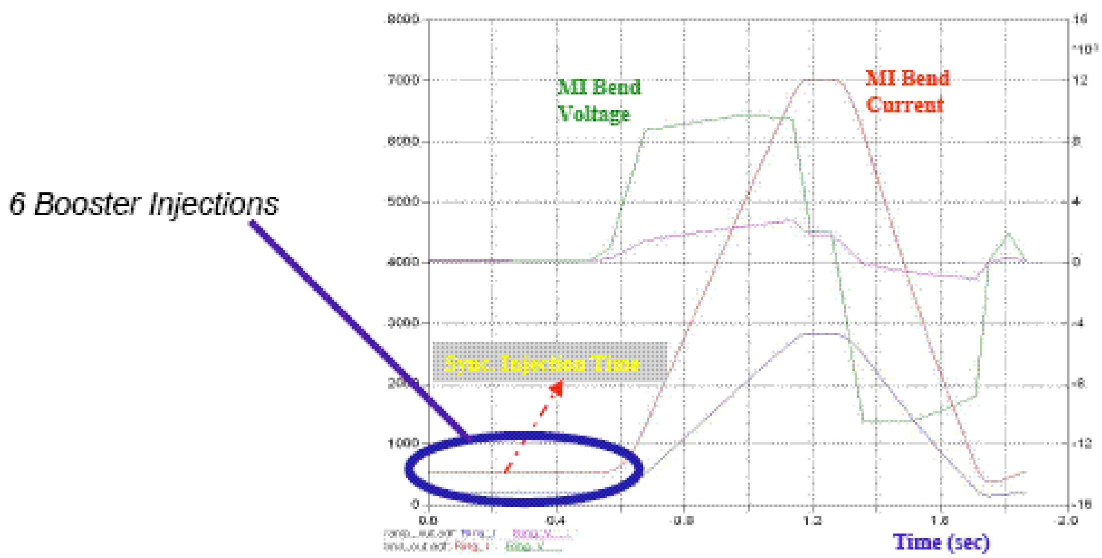

Figure 1 – Present Main Injector cycle, showing dwell time for 6 Booster injections.

[3] D. McGinnis, "A 2 MW Multi-Stage Proton Accumulator," Beams-doc-1782 (2005).

Comments on Existing Proton Source

Further upgrades beyond the existing Proton Plan will focus on increasing the total proton throughput of the Main Injector; however, the implications of these plans with regards to the total output of the Proton Source should not be forgotten.

The current Proton Plan calls for the Booster to reach a potential output capacity, based on beam loss, of 1.8×10^{17} protons per hour by the end of the collider program. However, at that point, the repetition rate will still be limited to about 9 Hz by a number of factors. Assuming 5 Tp batches, this will limit the total Booster output to about 1.3×10^{17} protons per hour, recalling that two conditioning pre-pulses must be accommodated for every 1.4 second Main Injector cycle.

In the basic Recycler concept, 12 batches would be slip-stacked into the Recycler every 1.4 sec. cycle. (Eleven batches may need to be used, in order to maintain an abort gap at all times during injection. However, for this discussion we will assume 12.) Adding an additional null batch for slip stack phasing, and two conditioning pre-pulses gives us a total Booster repetition rate of 9.3 Hz, which is not guaranteed to be possible at this point. Insuring this repetition rate will require at least the replacement of transformers in half the Booster RF bias supplies.

Of course, once the Main Injector loading time is reduced to a negligible level, there will be pressure to decrease the cycle time, which will dramatically increase the load on the Proton Source. If, for example, the Main Injector cycle time could be reduced to 1 sec, the total proton rate goes to about 2×10^{16} protons per hour, which is slightly beyond the Proton Plan design goal, but the Booster repetition rate would go to 14 Hz, at which point we would certainly just run it at a continuous 15 Hz. In addition to the modifications above, running the Booster at 15 Hz would likely require an upgrade to the 480 V power distribution system, and possibly a feeder upgrade to the Booster galleries.

The exact scope and cost of increasing the Booster repetition rates beyond 9 Hz are currently being investigated as part of Proton Plan WBS element 1.2.1.

Stacking Protons in the Recycler

Overview

The basic concept behind using the Recycler as a proton accumulator is to reduce the time it takes to load the Main Injector with protons on each acceleration cycle. Presently, in a mixed-mode cycle the Main Injector loads seven Booster batches (at a 15-Hz repetition rate) in about 0.5 seconds. All batches have intensities of about 4.5 Tp in a 80-bunch train structure with 0.12 eV-s (90%) longitudinal emittance per bunch. Two out of seven Booster batches are slip-stacked in the Main Injector. These batches are used for the antiproton production. The remaining five batches are sent to NuMI. Thus the present proton flux to NuMI is 23 Tp per one mixed-mode cycle or about 27 Tp per NuMI only cycle.

It takes 1.4 seconds to ramp the Main Injector to 120 GeV and back down to 8 GeV. Thus, the present MI cycle is about 2 seconds long. In a NuMI-only cycle, therefore, the Main Injector delivers 270 kW in beam power.

It is conceptually possible to reduce the injection time to 0.1 second by accumulating the protons in the Recycler while the Main Injector is ramping. Two scenarios are possible:

1. No slip-stacking in the Recycler. Under this scenario six Booster batches (28 Tp) are sent to the Recycler while the Main Injector is ramping. The Recycler can transfer its proton load to the Main Injector in a single turn which results in a reduction in cycle time from 2 seconds to 1.5 seconds. The delivered beam power would increase to 360 kW.

2. Slip-stacking in the Recycler. The Recycler momentum aperture is ±20 MeV/c, about the same as that of the Main Injector. With this in mind, the slip-stacking operation can be used with the same frequency separation as in the Main Injector operation. Under this scenario 12 Booster batches (about 50 Tp) are sent to the Recycler. This will take 0.8 seconds. The six batches are slipped with respect to the other six and at the time when they line up, they are extracted to the Main Injector in a single turn. The six resulting batches are captured in a single RF waveform in the Main Injector. This scenario would allow the beam power to increase up to 720 kW.

Further decrease in the MI cycle duration is only possible after upgrading the MI magnet power supplies. A MI power supply upgrade, needed to reduce the MI cycle to 1-1.1 seconds, has been estimated to cost approximately $6M.

RF Requirements

Presently, the Recycler is not equipped with a 53-MHz RF system. The Recycler would therefore require an RF system that has the same frequency as the Booster RF system at 8.9 GeV/c (53 MHz). Because such a system would only be used for slip stacking, which only requires low RF voltages (100 kV), only two 53-MHz RF cavities need to be installed in the Recycler. It may be possible to reuse cavities from the Tevatron RF system.

Recycler Upgrades

To accept the protons in the Recycler and deliver them to the Main Injector the following Recycler sub-systems have to be installed, removed, or upgraded.

Removal:

- Stochastic cooling tanks (kickers and pickups);
- Present aperture-limiting transfer lines to and from the MI.

Installation:

- New 8-GeV injection line from the Booster;
- New 8-GeV extraction line to the MI;
- New full-turn (10-μs flattop) extraction kicker;
- New collimation system;
- Possibly new beam abort line or capability;
- 53 MHz RF system.

Upgrades:

- BPM system upgrade to 53 MHz bunch structure;
- Instability damper;
- Low-level RF system;
- Beam loss monitoring system.

Beam Line Modifications

Protons are delivered from the Booster to the Main Injector through the MI-8 beam line. Since the two reside in the same tunnel, direct injection into the Recycler rather than the Main Injector would require modification only to the very end of the MI-8 line. The beam line modifications that would be required for this purpose have been investigated and a preliminary design has been generated, as indicated in Figure 2. The modifications would require no new civil construction; the connection is performed in the existing MI tunnel. The optical design is straightforward and achievable with existing magnets. Magnet aperture requirements will need to be analyzed and further understood. However, it is clear that the transfer line modifications would have minimal cost implications.

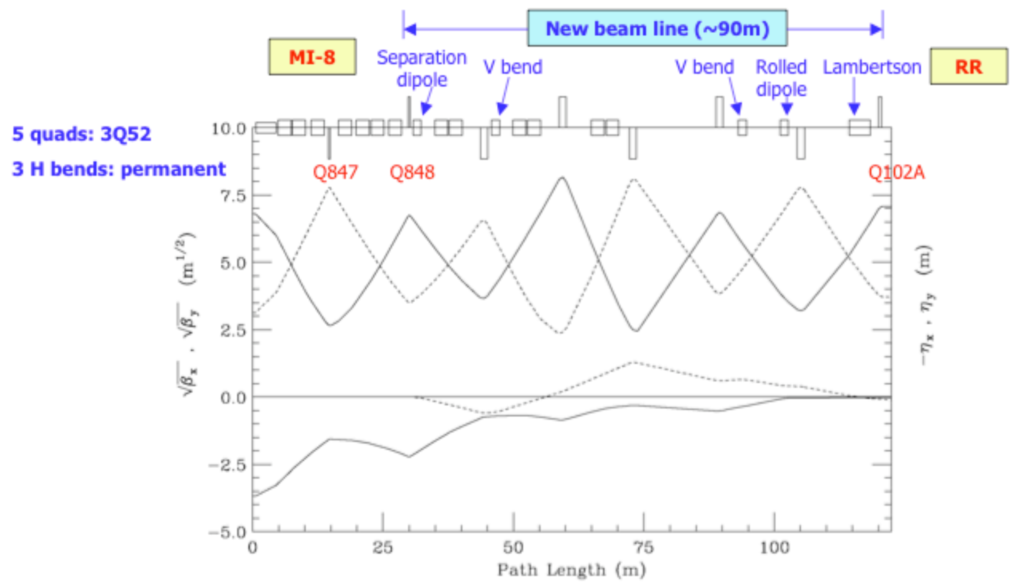

Figure 2 – Example solution for MI-8 beam line re-matched for Recycler injection.

As for beam transfer between the Recycler and the Main Injector, two beam lines already exist for this task, used for transfer of protons (counterclockwise) and antiprotons (clockwise) during present operations. However, both of these beam lines, while adequate for proton-antiproton operation for the Collider program, likely have too small an admittance for high intensity (and thus, presumably larger emittance) proton beams foreseen for the new application. The optical matching and extraction/injection schemes used today would still be adequate for future operations. Naturally, only the counterclockwise beam line would be required for proton-only operation. Thus, the proton transfer line would need to be re-examined and some components may need to be replaced with ones of larger aperture.

Radiological Issues

Dramatically increasing the beam intensity has radiological implications for the Linac, Booster, Main Injector enclosure, and the NuMI beam line. In the case of the Linac and Booster, the radiological issues are implicitly dealt with as part of the total proton output capacity, discussed earlier, and there is no need to deal with them further at this time.

In the case of the Main Injector, the primary concerns are above ground radiation and in-tunnel activation. The conditions for above ground radiation limits are well established in terms of occupancy classes and determined by accident conditions laid out in the so-called "Dugan Criteria", and refined later as the "Cossairt Criteria." The Main Injector beam limit was set to 9.6×10^{16} protons per hour as part of the NuMI shielding assessment document. If we examine the situation with 1.4×10^{17} protons per hour, we find that a handful of locations around the ring will either need some additional shielding or to be reclassified as limited occupancy. Unfortunately, the situation for the Recycler is very different. Using the standard rules, the Recycler is treated as a "buried pipe," because it is so close to the ceiling. Such beams are typically assigned an extra two feet of earth shielding when compared to beams in enclosures. This means that with a given amount of shielding, the Recycler would only be allowed to transport about one sixth the amount of beam as the Main Injector. In the past, this was acceptable, because very little beam went through the Recycler; however, in the Stage II scenario, all protons must go through the Recycler. For a throughput of 1.4×10^{17} protons per hour through the Recycler, a majority of the area above the tunnel will either have to have 1 to 2 feet of additional Earth applied or be fenced and reclassified as limited occupancy.

There may be another solution. The Dugan/Cossairt criteria are based on worst-case loss scenarios in the absence of any other monitoring. In the case of the Booster, a scheme of complete "chipmunk" coverage has been implemented to continuously monitor surface exposure. This allows the Booster to run with *almost ten feet less earth shielding* than is prescribed by the Cossairt criteria. However, the monitoring needs are somewhat daunting. In the case of the Booster, there are 48 separate chipmunks positioned near the surface around the ring, plus some additional ones at key locations. If this were scaled up to the circumference of the Recycler, on the order 300 to 400 chipmunks would be required. The system would also be required to provide complete coverage under all possible running conditions.

Yet another possibility would be to implement some type of an "E-berm" system to monitor beam going in and out of the recycler to directly measure loss. Such a system would need to be sensitive to losses on the order of 10-20% to bring them down to a level at which they would satisfy the earth shielding requirement. This does not sound particularly challenging, but such a system would not be able to distinguish between uncontrolled loss and loss in a collimator system, which might be of a similar scale.

So far, the discussion has focused on above ground radiation. As experience with the Booster has shown, in-tunnel activation is also a concern. The accepted standard for high intensity machines is to try to limit uncontrolled beam loss to an average of 1 Watt/meter. At $1.4\text{x}10^{17}$ protons per hour, this would limit the total beam loss to about 6% at 8 GeV, or 0.4% at 120 GeV. The Recycler will only handle 8 GeV beam, but experience with the Main Injector has shown that it is difficult to maintain low loss during slip stacking. It is currently assumed that a collimation system will need to be implemented in the Main Injector in order to go to full slip-stacked intensity to NuMI. If this turns out to be true, then a similar collimation system to slip-stack in the recycler must be presumed. Given the mass of the shielding required in such a collimation system, the height of the Recycler above the floor and the small distance from the ceiling will definitely complicate the design.

IV. Impacts on Experimental Programs

So far, discussions have focused entirely on the protons that can be delivered to the NuMI beam line. It is likely there will be other experiments going on at the lab during this period whose needs will have to be balanced.

In the case of experiments utilizing the 120 GeV program, their use would come directly out of the protons projected for the NuMI line. In the case of fast spills, Main Injector operation could allow for either full or partial Main Injector proton loads to be directed to other users, either Switchyard 120 or, if needed, the Antiproton Source. In the case of slow spill operation of the SY120 program, there would be the additional impact to the time line, which would result in an addition reduction to the NuMI intensity beyond merely the number of protons required. A Tevatron 120 GeV fixed target program would mitigate these issues, as described earlier, though the operational cost could be prohibitive.

In the case of 8 GeV protons, additional Booster capacity could in principle be used for other users without decreasing the total number of protons available to NuMI, in much the same way as the MiniBooNE experiment operates now. However, this would almost certainly require some Booster modifications beyond those included in the Proton Plan. As discussed in Section II, even the baseline proposal requires the Booster to run at about 9 Hz, the limit of the Proton Plan. On the other hand, if proposed modifications were made to allow the Booster to run at a full 15 Hz, the total proton limit based on beam loss would exceed the capacity of the Recycler/Main Injector, and could provide 8 GeV protons at a rate on the order of 4×10^{16} protons per hour (2×10^{20} protons per year). Of course, if the Main Injector cycle time were reduced significantly, it is extremely unlikely that there would be excess protons for an 8 GeV program using only the present Booster synchrotron.

V. Summary

Following the conclusion of the Tevatron Collider program, and assuming the Recycler Ring is no longer used for an antiproton program, this storage ring may be easily, and at relatively modest cost, reconfigured as a proton pre-injection ring for the Main Injector. The Recycler would accept batches directly from the Booster, perform necessary slip stacking maneuvers, and prepare beam for single-turn injection into the Main Injector, all well within the faster 1.5 sec. cycle time, thus upgrading the MI throughput from 400 kW (after completion of the Proton Plan) to over 600 kW. Assuming the Main Injector is able to accept 50 Tp per pulse, a full 12 Booster batches could then be slip-stacked in the Recycler, increasing the throughput to well beyond 700 kW. Table 1 shows the progress of relevant parameters from the present operation, through the Proton Plan, to the implementation of the Recycler option. Here, "Option 0" refers to the use of a shorter MI cycle time (1.5 sec), but with similar intensities (*i.e.*, 9 Booster batches) as projected for the end of the Proton Plan. "Option 1" refers to the implementation of a shorter MI cycle time *and* the use of 12 Booster batches slip-stacked in the Recycler. "Option 2" shows the effect of reducing the cycle time to one second. As discussed in Section II, this last option would have implications for the Proton Source beyond the needs of the existing Proton Plan. Also, reducing the cycle time would require significant modifications to the Main Injector RF system and magnet power supplies, which would perhaps only be done in preparation for a future Proton Driver project, or equivalent.

Table 2 below provides a very rough estimate for the costs of implementing the required upgrades to the Recycler systems and the connecting beam lines. The RF system cost is D. McGinnis' estimate for moving three cavities and support hardware from the Tevatron.[5] The transfer line costs are based on the estimate for a new 600 MeV line from the synchrotron-based proton driver study.[6] The BPM, BLM, and damper costs are based on similar projects in Run II.[7] The collimators are based on the estimate for the Main Injector Collimators in the Proton Plan.[8] Remaining costs are good faith estimates. These costs do not include escalation or contingency.

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[5] D. McGinnis, "A 2 MW Multi-stage Proton Accumulator", Beams-doc-1782 (2005).
[6] W. Foster, *et al.,* "Proton Driver Study II", FNAL-TM-2169 (2002).
[7] See Run II plan, v-3, at http://www-bd.fnal.gov/run2upgrade/ .
[8] See MS Project file at http://www-accel-proj.fnal.gov/Proton_Plan/index.html .

	Present Operation	Proton Plan	Recycler Option 0	Recycler Option 1	Recycler Option 2	
Booster Limits						
<*N*>	4.5	5	5	5	5	Tp/batch
<*R*>	5	8	8	8	14	Hz
<*N·R*>	8	14	14	14	20	10^{16} pph
NuMI Operation						
# batches, *B*	5	9	9	12	12	
B<*N*>	23	45	45	60	60	Tp/cycle
<*T*>	2.2	2.2	1.5	1.5	1.0	sec
B<*N*/*T*>	4	7	11	14	20	10^{16} pph
<*P*>	200	400	580	770	1000	kW

Table 1 – Proton Throughput. In the case of the first four scenarios, the "*Booster Limits*" represent the output limit of the Booster, as projected in the Proton Plan. In Option 2, the "*Booster Limits*" represent the minimum performance necessary to accommodate the capacity of the Recycler/Main Injector. Option 0 uses a shorter cycle time, but no increase in MI intensity beyond the Proton Plan. In Option 1, 12 Booster batches are used and in Option 2, the MI cycle time has been reduced to 1.0 sec. For both, it is assumed that required MI upgrades to allow higher intensities have been performed.

	K$
53 MHz RF system	300
MI-8 mods.	2000
RR/MI xfer mods.	500
RR BPM upgrade	1300
RR BLM upgrade	1000
RR dampers	500
RR LLRF upgrade	200
RR kicker upgrade	400
RR abort mods.	200
RR collimators	500
TOTAL:	6900

Table 2 – *Extremely* Approximate Cost for Recycler Option.

Final Recommendations

Using the Recycler Ring as a pre-injector for the Main Injector synchrotron is the most natural first step toward higher power, at lowest cost, for the Fermilab neutrino program following the conclusion of the Tevatron Collider Run II. With minor changes to the existing infrastructure the proton throughput to the 120 GeV neutrino program can be increased by nearly a factor of two. This is achieved by shortening the cycle time of the Main Injector, as charge is pre-injected into the Recycler Ring from the Booster, and by making available 12 Booster batches to the program once antiproton production is ceased.

To prepare for such an upgrade to take place by the end of the Collider run, expected to occur around 2009, a team should be assembled soon to generate a design document with detailed specifications for the items and modifications required, including the components listed in Table 2 above, along with a corresponding cost estimate.

Using the Recycler Ring for accumulating 9 Booster batches places no new demands on the Main Injector above those anticipated for the present Proton Plan. The full reach of the Recycler option, using 12 Booster batches would deliver approximately 33% more particles per pulse and the MI will need to be able to handle the new beam intensities and conditions. With this in mind, it is also recommended that a Main Injector intensity upgrade program be further developed and reviewed internally on the earliest possible time scale.

Finally, should the community wish to further investigate the use of the Tevatron as a fixed target program stretcher ring, then a short study should be performed to ascertain the extent of accelerator systems modifications that would be required, and to estimate operating costs for such a program.