3.5 Rapid Antiproton Transfers

In Run IIb, antiprotons will be frequently transferred from the Accumulator to the Recycler. The Recycler will have responsibility for accumulating and cooling antiprotons for eventual transfer to the Tevatron. The antiproton source will be configured for maximum stacking rate and will no longer be capable of maintaining an acceptable stacking rate with larger stacks. Transfers of antiprotons from the Accumulator for collider operation in Run IIa occur at approximately 16 hour intervals. The interruption in stacking for the transfers is on the order of 100 minutes. With Accumulator to Recycler transfers in Run IIb expected to occur every 15 minutes or so, the length of the transfer process has to be drastically reduced. To provide enough antiprotons to support Run IIb luminosity goals, transfers would need to be accomplished with only about a 1 minute interruption in stacking.

There are multiple problems with the current antiproton transfers from the Accumulator to the Main Injector. The most serious problems are: the long setup time for beam transfers, beam emittance growth and beam losses related to dipole and quadrupole mismatches and lack of reproducibility of the beamlines. There are a few primary sources for these problems. First, the optics design of the beamlines is inadequate. The beamline lattice has unacceptably large values for the β -functions and a poor dispersion match, which results in increased sensitivity to errors and emittance growth. Second, an incomplete knowledge of the quadrupole fields causes a beam envelope mismatch. Third, the absence of a reliable hysteresis protocol causes irreproducible beam optics and steering errors that lead to additional emittance growth. The lack of reproducibility is aggravated by the fact that the same line is used for both the transport of 120 GeV protons and 8 GeV antiprotons.

Presently one of the largest complications in the process of switching modes from antiproton stacking to transfers is the dual role of the transfer lines. During transfers, 8 GeV antiprotons are transported from the Accumulator to the Main Injector through the combination of the AP3-AP1-P2-P1 transfer lines. However, during antiproton stacking, the P1-P2-AP1 transfer lines are used for sending 120 GeV protons to the antiproton production target. Therefore, the P1-P2-AP1 transfer lines operate at two very different momenta. This large difference in the beam momenta significantly complicates antiproton transfers and requires that the design, measurement and correction of the beamline optics be carefully performed. Alternatively, a new beamline could be installed that would separate 8 GeV and 120 GeV operation.

3.5.1 Beamlines

Initially, the prospect of building a new dedicated beamline to connect the Accumulator to the Recycler was very appealing. The new beamline would be designed specifically for 8 GeV antiproton transfers while the existing P1-P2-AP1 lines would be used for delivering 120 GeV protons to the production target. The new line, usually referred to as the AP5 line, would bring an end to the dual-energy nature of the P1-P2-AP1 lines.

After beginning to examine the implications of constructing the AP5 line, it became less attractive. Assuming that funding could have been found to cover the costs of a project of this magnitude, the impact of civil construction would be very undesirable. Most AP5 scenarios involved new tunnel enclosures to house a relatively direct path from the AP3 line to the Main Injector enclosure. The design and construction of these enclosures would be very time consuming, delaying the benefits of the new line. The tiein of the AP5 line into the AP3 line and Recycler would cause a lengthy interruption to the collider program. An alternative design for the AP5 line that would share the existing tunnels with the P1-P2-AP1 lines had its own share of logistical problems. This version of the new beamline would also cause a major interruption to collider operation.

The perceived problems with building the AP5 line have shifted the focus to improving the existing beamlines and to adopt them for operation in Run IIb. It is believed that the only practical beamline option within the time constraints of Run II is to use existing tunnels and service buildings to house the magnets and power supplies. Changes in quadrupole strength and location as well as aperture improvements could be carried out with a relatively minor interruption in collider operation.

3.5.1.1 Experience from Runs I and IIa

In collider Run I, beamline tuning prior to antiproton transfers went through a number of changes. Protons from the Main Injector were "reverse injected" into the P1-P2-AP1-AP3 transport lines and injected into the Accumulator. By utilizing protons in the tune-up process, adjustments could be made to orbit trajectory and closure without using the stored antiprotons. Initially, Main Ring positions at the extraction point were adjusted to a reference orbit. Then, Secondary Emission Monitors (SEM's) were used to tune beam positions in the AP1 and AP3 lines to a reference (P1 and P2 did not exist prior to the construction of the Main Injector). SEM displays were compared to a paper copy of a reference orbit and dipoles were adjusted until the tuner subjectively determined that they were "close enough". Beam Position Monitors (BPM's) were not used routinely. The transfer efficiency was also used as a figure of merit, normally 100% transfers could be achieved after tuning was completed. Turn-by-turn (TBT) oscillations were minimized using an applications program to calculate and implement corrections. It was found empirically that offsets had to be made to kickers in the Accumulator and Main Ring as well as several AP1 trims to achieve better agreement between the proton and antiproton orbits. TBT oscillations on the antiprotons in the Main Ring were minimized with an applications program during the six transfers.

Over the course of Run I, the beamline tuning became more streamlined to save time. Most notably, beamline steering was no longer done routinely. After positions in the Main Ring were adjusted, overall transmission was checked to ensure it was above a threshold of 80%. In most cases this was the case, and the next step was to minimize TBT oscillations in the Accumulator. The reproducibility of the Main Ring, AP1 and AP3 lines were good enough so that orbits only changed a few millimeters from day to day and did not adversely affect transmission. Trim changes required for TBT corrections were recorded and long term drift was compensated for by occasional changes to the initial magnet settings. The total antiproton source portion of the transfer setup in Run I eventually took less than an hour to execute.

When the Main Injector was built to replace the Main Ring, the beamline configuration became more complicated. The addition of the P1 and P2 lines (P2 mostly consists of the old Main Ring between F0 and F17) nearly doubled the length of the

beamline connected to the Accumulator. P2 is a dual mode line, running at 8 GeV and 120 GeV, P1 operates at these energies plus 150 GeV to transport beam to the Tevatron. The P1 and P2 optics were designed to match the old Main Ring lattice conditions at F17, which should have resulted in similar conditions to those in Run I. This philosophy maintained the high dispersion found in the old Main Ring near F17 plus the design of the P1 line caused the vertical dispersion to not be matched between the Main Injector and Accumulator.

Initial operational experience in Run IIa indicates that the beamlines have a restricted dynamic aperture, particularly in AP1. Since the magnets in P2, AP1 and AP3 are the same as in Run I, some combination of lattice and survey errors seems to be the most likely cause. Failure to adequately cool the core and carefully steer the antiprotons through the beamline results in poor efficiency and large transverse emittances. At present, even small deviations from the reference orbit results in decreased transfer efficiency. Although new software has been implemented so that BPM's can be used to more accurately steer to a reference orbit, the steering appears to be required on a shot by shot basis.

Future transfers between the Accumulator and the Recycler will not require some of the steps used for transfers to the Tevatron. However, the transfer process will need to be greatly simplified to achieve an antiproton transfer to the Recycler that limits the interruption in stacking to only a minute or two. In addition, there will not be time available to cool the antiprotons prior to transfer to the Recycler. The beamlines will need to have a larger dynamic aperture in order to efficiently transfer the antiprotons.

3.5.1.2 Beam Optics

Recently we started making detailed optics measurements of the Antiproton Source transfer lines. Optics measurements were performed using a differential orbits technique. One complete measurement consists of 5 differential orbits excited by 2 horizontal correctors, 2 vertical correctors and an energy change. With the appropriate betatron phase advance between correctors, such a measurement completely characterizes a linear optics transport line. In this case, the x-y coupling is sufficiently small so that only six differential orbits are required. They include, two horizontal responses from two horizontal correctors, two vertical responses from two vertical correctors, and horizontal and vertical displacements related to the energy change (dispersion measurement). To illustrate such measurements, the differential orbits from two correctors (one horizontal and one vertical) are shown in Figure 3.5.1 for the current beamline optics (March-October 2001). On the top plot, the curves are built using results from quadrupole magnetic measurements, while on the bottom plot, the curves are built from the fitted quadrupole strength using all six differential orbits (only two are shown in the figure). As one can see, there are discrepancies for both the betatron amplitude and the betatron phase if the focusing strength of the quadrupoles is not adjusted. To fit the data, several of the quadrupole fields require adjustment. For this particular measurement, the most significant discrepancies are for quadrupoles PQ2 (powered by M:Q202) (-9%) and EQ13 (powered by D:Q913) (+8%). The first discrepancy is related to the fact that the 120 GeV and 8 GeV power supplies for PQ2 have opposite polarities, which have not been correctly taken into account in the optics model.





Figure 3.5.1 Fitting of the optics model to beamline measurements: top – curves are built with design model; bottom – curves are built using updated model, where focusing for a number of quadrupoles was adjusted to get agreement with measurements. Measurements were performed with reverse protons so that the line begins at the Main Injector extraction point and ends at Accumulator injection. Only two of six differential orbits are presented in the figure.

Currently, we do not understand the cause of the second discrepancy. In addition to the obvious disagreement between the model and the data, the current optics have a number of other problems such as large beam sizes at regions with small apertures, large β functions and unmatched dispersion. The most severe problem is related to the large beam size at regions with small apertures. Currently, it causes about a 15-25% loss in antiprotons during transfers to the Main Injector. Large β functions cause an undesired

increase in the sensitivity of optics due to the quadrupole gradient errors. Even in cases where the acceptance of the beamline is adequate, the large β functions should be avoided if possible. Therefore, the β functions should be minimized through the entire transport line. Although the dispersion mismatch does not cause significant emittance growth because of the small energy spread of the antiproton beam, it would also be desirable to match both the vertical and horizontal dispersion. Thus, to improve the Accumulator to Main Injector antiproton beam transport, both well-designed optics and careful corrections based on beam measurements are required.

There are a few practical limitations imposed on the redesign of the optics. The first is related to the fact that many quadrupoles in the AP3 line are combined into groups so that they are powered from a single power supply. Taking into account that reconfiguring power supply connections with magnets can be an involved process, it is desirable to avoid or, at least, minimize it. The second limitation is caused by the fact that different power supplies are used in AP1 for 8 GeV and 120 GeV operation. Presently, both power supplies have the same polarity and using them with different polarities requires significant hardware modifications. Therefore, changing polarity of the AP1 quadrupoles at 8 GeV implies a simultaneous polarity change for the 120 GeV mode. Generally speaking, the goal is to find a solution that would result in reliable transport line operation quickly and with minimum expense.

Two optics solutions have been proposed as possible upgrades. The optics of the first solution is matched for both β functions and dispersion, but to implement requires significant changes to connections of quadrupoles to power supplies. In contrast, the second solution has unmatched vertical dispersion but does not require any power supply reconfiguration. It still requires a change in polarity for seven AP1 quadrupoles, but is a relatively quick and uncomplicated procedure. Figure 3.5.2 presents the dispersion and β functions for both choices and how they compare to the current optics. Efforts to implement the second optics solution have already begun. Final tuning of the new optics is expected to be completed in the first quarter of 2002.



Fri Nov 02 17:43:25 2001 OptiM - MAIN: - C:\Optics\Tevatron\PBar\TransferLines\AP3_P1\PbarToMainInjReconnected.



Fri Nov 02 17:59:26 2001 OptiM - MAIN: - C:\Optics\Tevatron\PBar\TransferLines\AP3_P1\PbarToMainInjOct01.opt

Figure 3.5.2 β functions and dispersion for various optics options for transport from the Main Injector to the Accumulator: top – completely matched optics, middle – optics with no changes to the quadrupole power supply configuration (vertical dispersion is not matched), bottom present optics as it follows from reconstructed measurements.

3.5.1.3 Reproducibility

Reproducibility of the beam optics is another serious issue. In order to limit the emittance growth due to an optics mismatch to a few percent, the reproducibility of the integrated quadrupole strengths should be about 10-20 G. This corresponds to $(3-5)\cdot10^{-4}$ relative to the total gradient. For comparison, note that for 3Q120 quadrupoles (located in the P1 and AP1 lines), the integral strength resulting from the residual field is approximately 2000 G and is about hundred times greater than the necessary accuracy. Thus, reliable transfers require both good regulation in the quadrupole power supplies and reliable hysteresis cycling of the magnets. A comparison of differential orbit measurements performed on different days has been used to measure long term transfer line reproducibility. Figure 3.5.3 presents such results from measurements performed on September 6 and 16, 2001. The top picture shows differential orbits corresponding to the excitation of the I:HT702 corrector in the P1 line. The orbits exhibit a significantly larger difference than orbits corresponding to the other three correctors. In the presented data,

the beam displacement is normalized to the square root of the β function, $x\sqrt{\beta_0/\beta}$ (β_0 =10 m), and the betatron phase advance is used as a longitudinal coordinate. In the variables, the beam motion exhibits a sinusoidal character. One can see that the measurements are approximately the same, but show some discrepancy between the two measurements and between the measurements and theory. The bottom picture shows the difference of differential measurements. One can see that at the beginning of the line the difference is nearly zero, then grows and exhibits a sinusoidal behavior in the second half of the line. The appearance of such a discrepancy is related to differing focusing strength for one or more quadrupoles. Detailed analysis has shown that for this particular case, the irreproducibility is mainly related to the PQ7A&B quadrupoles (powered by M:Q207), which experienced a field change of approximately 300 G. That corresponds to approximately 7% of its integral strength compared to the residual field and to 0.5% of its total focusing strength at 8 GeV. We need about an order of magnitude improvement in the reproducibility of the quadrupoles. The belief is that the improvement can be achieved by introducing hysteresis cycling for all magnets immediately before transfers.



Figure 3.5.3 Comparison of differential orbit measurements performed on September 6 and 16, 2001; top – differential orbits, bottom – difference of differential orbits. Data are presented in normalized coordinates

Lack of reproducibility of the beam orbit (steering) is easier to control and correct. Figure 3.5.4 presents the difference between beam orbits for measurements performed on September 6 and 16, 2001. Solid curves represent the beam orbit for the beam injected with an initial beam offset and angle coming from the Main Injector and with no beam deflection by correctors. This is justified by the fact that the correctors, with the exception of the last two horizontal correctors, were the same for both measurements. One can see that the total difference between the orbits is as much as 5 mm. Most of the error is caused by a trajectory change originating from the Main Injector growth related to the dipole mismatches can be estimated by the following formula:

$$\frac{\Delta\varepsilon}{\varepsilon} = \sqrt{1 + \frac{x_0^2}{\varepsilon\beta} - 1} \approx \frac{x_0^2}{2\varepsilon\beta}$$
(3.5.1)

where x_0 is the maximum beam displacement related to the β function β , and ε is the rms beam emittance



Figure 3.5.4 Difference of horizontal and vertical beam positions for differential orbit measurements performed on September 6 and 16 of 2001

To meet the requirement that emittance growth due to dipole mismatches is below 1%, the maximum beam orbit deviations should not exceed 0.6 mm ($\mathcal{E} = 0.33$ mm mrad, $\beta = 50$ m), which is significantly smaller than the observed long term orbit stability. The requirements for beam transport with no losses are less strict. An orbit within 5 mm of the ideal would still allow transfer efficiencies near 100%. A beam damper could be used to greatly reduce TBT oscillations, it is realistic to expect that the P1-P2-AP1-AP3 beamlines will have adequate reproducibility to efficiently transfer antiprotons.

While differential orbit measurements are well suited for measuring optics properties of a beamline, they are not able to measure the actual beam envelope match for beam transfers. Therefore, it's necessary to use an additional diagnostic for correcting the beam envelope match. A quadrupole pickup is well suited for this role. As with most other optics tuning procedures, the measurements will be performed with reverse protons injected into the Accumulator. The presence of quadrupole oscillations in the beam will indicate an envelope mismatch. Four "orthogonal" quadrupoles in the transport line will be used for the final tuning of the envelope match. It would be desirable to resolve the beam envelope oscillations corresponding to about a 1% growth in emittance. That implies that for a standard pickup with signals coming from two electrodes subtracted from each other, we need to resolve oscillations with an amplitude of 10^{-4} relative to the total plate signal. Knowing that the oscillations occur at double the betatron frequency significantly simplifies the problem. For the case of 10^{10} protons injected into the Accumulator, there should be no problem resolving quadrupole signal from electronics noise. However, there is a challenging problem of rejecting the common mode signal. A quadrupole pickup already exists in the Accumulator. It was used in collider Run I with limited success and has not been used since that time. The plan is to revive it and try to make it a useful diagnostic. If it is found to not be possible to achieve the required common mode rejection for this pickup, a new quadrupole pickup similar to a CERN design could be used. The CERN design does not have a problem with common mode rejection.

3.5.1.4 Suitability of present beamlines

After analyzing the optics and aperture data for the P1-P2-AP1-AP3 lines, all indications are that the present beamlines can be modified for use in Run IIb. At the present time, it is believed that the physical apertures will be adequate for efficient antiproton transport with the anticipated beam emittances. Presently the beamline lattice is not adequate and the transfer efficiency is less than 100%. The lattice will need to be modified to minimize the transverse beam size at locations with small physical apertures and also provide a lattice match. Some AP-1 magnets may still need to be replaced to provide larger aperture if losses remain. Magnets in AP1 will need to be ramped in order to achieve rapid transfers as described in the next section. The existing power supplies will need to have improved regulation in order to operate at both 8 GeV and 120 GeV. Ramp cards will also be installed to provide the appropriate reference for the supplies.

The option of upgrading the existing beamlines is much more manageable in scope to the alternative of building the AP5 line. Most of the upgrades can take place during relatively short periods of machine downtime. Besides the large improvement in program interruption, the cost of implementing the plan is far less. Changes to the lattice will take place over the next year and will provide an immediate benefit to the collider program, both in improved transfer efficiency and emittance preservation.

3.5.2 Frequent, rapid transfers

3.5.2.1 Run IIa sequence

Presently, the process of preparing to transfer antiprotons from the Accumulator to the Tevatron (via the Main Injector) is a lengthy process. The tune-up and preparation for transfers usually takes between 1 and 2 hours. Listed below are the major steps that are undertaken in the setup process. Also listed is the approximate time required for each step (including intermediate or related steps) and an explanation of how the step will be modified or eliminated when making transfers to the Recycler.

- (1) Antiprotons in the Accumulator core are stochastically cooled to reduce the momentum spread and transverse emittances. The core cooling takes place in parallel with the following steps, but takes at least 30 minutes. Some of the following steps are synchronized with transfer preparations in the Tevatron. [30 minutes in parallel with steps below] *No additional time is spent cooling the core, emittance needs to be controlled during stacking. Also, there will be no need to synchronize with activities in the Tevatron.*
- (2) Stacking is halted, beam in the stacktail is swept far enough towards the core so that the core momentum systems can capture the beam. [10 minutes] *Beam left in the stacktail is not swept into the core. Beam in the stacktail is not lost during the extraction process and is swept over when stacking resumes.*
- (3) Main Injector injection energy and last turn positions at the extraction Lambertson magnet are checked and corrected. [10 minutes] *There is no check, with reverse protons, of Main Injector positions. If needed, low field stacking orbits could be correlated to orbits on antiproton transfers allowing corrections between transfers.*
- (4) AP-1 power supplies are switched from 120 GeV to 8 GeV operation. Timers and other devices related to the transfer process are set to nominal. [10 minutes] *Beamlines are ramped, ramps are triggered to play when the transfer is initiated.* No changeover is required for AP-1 and timers are already set for antiproton transfers.
- (5) The beamline orbit is checked with reverse protons between the Main Injector and Accumulator. A steering program is used to make corrections to less than 1 mm from the reference orbit. [15 minutes] *There will be no steering corrections with reverse protons. The beamline will be able to tolerate orbit drift anticipated to be a few millimeters.*
- (6) Turn by turn oscillations in the Accumulator are minimized to ensure the first turn matches the closed orbit to within 0.5 mm. [10 minutes] *There will be no turn by turn corrections with reverse protons. Antiproton oscillations in the Main Injector will be reduced by injection dampers. Additionally, oscillations will be minimized with adjustments based on measurements and made between transfers.*
- (7) RF systems and timing are set up for antiproton transfers. [5 minutes] RF systems will already be on and configured for transfers, awaiting the appropriate trigger.
- (8) The antiproton longitudinal distribution is "squared" so that the nine transfers have approximately the same intensity and to maximize the total flux. [10 minutes] *There will be no need to square the core, the entire core will be removed in single transfers to the Recycler.*
- (9) Antiprotons are transferred in nine separate transfers at approximately 60 seconds apart. Details of the transfer process are listed below. [10 minutes] *Only a single antiproton transfer will be made. Beam is bunched at 2.5 MHz and moved to the extraction orbit in about 10 seconds.*
 - (a) Adiabatic bunching and acceleration from the core to the extraction orbit of about 10% of the original antiproton stack with an h=4 2.5 MHz RF system.

- (b) Bunching with an h=84 53 MHz RF system for synchronous transfer to the Main Injector
- (c) Transfer from the Accumulator to the Main Injector down the AP3, AP1, P2 and P1 lines.
- (d) Acceleration to 150 GeV in the Main Injector and coalescing the antiprotons into four bunches.
- (e) Transfer from the Main Injector to the Tevatron down the A1 line.
- (f) Injection into the Tevatron with beam cogged to the proper longitudinal location.
- (10) The antiproton source is reconfigured for stacking. [15 minutes] *Stacking resumes immediately after the transfer when the appropriate timing events return.*

3.5.2.2 Mechanics of transfers to the Recycler

In the future the transfers from the accumulator to the Recycler will consist of the following steps:

- (1) Stacking is halted and appropriate transfer events are loaded. A small number of devices are switched from stacking to transfer configuration. (10 seconds)
- (2) The stack is adiabatically bunched at 2.5 MHz and accelerated to the extraction orbit. [10 seconds]
- (3) The transport lines will undergo two hysteresis cycles prior to the transfers. P1, P2 and AP1 will ramp, AP3 will be cycled prior to the interruption in stacking. [10 seconds]
- (4) Extraction from the Accumulator and transport to the Main Injector through the AP3, AP1, P2 and P1 lines. [0 seconds]
- (5) Injection into the main injector and synchronous capture into Main Injector RF buckets. [0 seconds]
- (6) Fast damping of the betatron oscillations created by injection errors. [0 seconds]
- (7) The beam energy and frequency are matched to the Recycler. [5 seconds]
- (8) The beam is transferred from the Main Injector to the Recycler. [0 seconds]
- (9) Beam is debunched adiabatically in the Recycler. [10 seconds, but takes place after transfers have been completed]
- (10) Main Injector stacking events return and stacking resumes. [10 seconds]

Intermediate steps will add a small amount of additional time, but the transfer process is expected to take about one minute. To achieve this ambitious goal, the following are prerequisites:

- (1) P1, P2 and AP1 all need to be ramped (P1 and P2 are already ramped). Ramps should be designed so that virtually no time will be needed to switch between stacking transfers. EB6, which is located where AP3 joins the AP-3 line, will also need to be ramped. AP3 power supplies will continue to run DC, but will need to follow a hysteresis protocol prior to each transfer.
- (2) Orbit reproducibility in the transport line has to be better than 5 mm. P1-P2-AP1-AP3 optics and dynamic aperture need to be improved to the point that 5 mm oscillations do not cause beam loss.

- (3) Lack of quadrupole reproducibility should not cause emittance growth.
- (4) Injection oscillations in the Main Injector and Recycler will be minimized by a combination of trim magnet adjustments between transfers and injection dampers in both machines.
- (5) Injection dampers need to suppress injection errors in about 100 turns.
- (6) Reverse proton tune-up will only be used for troubleshooting failures, poor transfers or for operation after longer periods of downtime.
- (7) Settings changes to devices need to be kept at a minimum for the transfer process to be acceptably short. The transfers need to be highly automated, but mostly driven by hardware awaiting appropriate triggers.

It is important to note that the beamline BPM's will not be able to detect the antiproton positions because of the 2.5 MHz RF structure. The BPM's are designed for a 53 MHz RF structure, so SEM's and multiwires will be the only diagnostic available to determine antiproton positions. It is assumed that orbit corrections will be infrequent and will either be based on SEM and multiwire data or BPM data taken with reverse protons.

3.5.3 Reducing injection oscillations

3.5.3.1 Orbit correction and closure

In collider runs I and IIa, reverse protons are used to tune up the P1-P2-AP1-AP3 lines prior to antiproton transfers. Antiprotons have traditionally not been used for beamline tune-up due to their limited supply. Besides being wasteful, typical antiproton transfers do not have enough intensity to provide reliable BPM data. Secondary Emission Monitors (SEM's) can be used to identify gross steering errors, but would not be appropriate for fine adjustments with a steering program. BPM's in the Accumulator are used with the reverse protons to close the injected beam to the closed orbit. In principal, the antiprotons transferred into the Main Injector would follow an identical orbit to the reverse protons and there would be no injection oscillations. In practice, the orbits are only approximately the same and significant TBT oscillations are observed.

Beamline tune-up with reverse protons will not be routinely performed for antiproton transfers to the Recycler. Although this mode of operation is still available for identifying failures and infrequent orbit adjustments, the beamline orbit will generally not be adjusted. Antiproton TBT oscillations in the Main Injector will be reduced using BPM data and a closure program. Closure of the antiprotons into the Main Injector is already performed routinely during collider operation and was also used in Run I. The BPM's are designed for a 53 MHz beam structure so new detectors designed for a 2.5 MHz RF structure will need to be built and installed. A similar system will need to be created for the Recycler, although their BPM system is already designed for 2.5 MHz.

Even with closure tuning between antiproton transfers, residual injection oscillations will still remain. Transverse dampers will be used to minimize the remaining oscillations and preserve transverse emittances. The dampers are a key component of the fast transfer scenario and are needed to ensure small emittance dilution and efficient transfers.

3.5.3.2 Injection dampers

Maintaining orbit stability within 5 mm of the ideal orbit on antiproton transfers should result in transfer efficiencies near 100%. However, to prevent emittance growth in the Main Injector, the plan is to use an injection damper to minimize oscillations. The damper will need to suppress initial betatron oscillations with amplitude of up to 5 mm within 100 turns.

	Horizontal	Vertical	
Momentum [GeV/c]	8.9		
Kicker length [m]	1.0		
Kicker gap [cm]	9.5	9.5	
Amplifier power [kW]	1.6		
Power amplifier bandwidth [MHz]	10-80		
Maximum kick [µrad]	1.8	1.8	
Range [±mm]	5	5	
Beta function [m]	60	60	
Damping time [turns]	90	90	

Table 3.5.1 Main Injector damper parameters

Instead of designing and installing a new damper system, the plan is to enhance the capabilities of the existing Main Injector injection damper. The damper currently is used to damp proton injection oscillations, but is unable to damp an antiproton beam because of the direction of travel. The plan is to add low-level electronics to the existing damper system for the antiproton direction and to use the existing power amplifier and kicker. This not only has the benefit of reducing the cost, but also more importantly will reduce the downtime needed to implement the system. A simplified diagram of the system is presented in Figure 3.5.5 and damper parameters are listed in Table 3.5.1. To achieve $\pi/2$ betatron phase advance between the BPM and kicker, the signals from two BPMs are combined. While the power amplifier has a sufficiently wide bandwidth, the existing system is built to damp only the lowest betatron sideband. This significantly alleviates the sensitivity to noise on the pickup. As will be illustrated below, the existing amplifier has adequate power to prevent emittance growth due to injection errors on the protons and would be suitable for the antiprotons. The system has to be able to damp betatron oscillations of up to 5 mm and to suppress the emittance growth by about 100 times as compared to undamped betatron oscillations.

In the case of strong damping, $g \gg \sqrt{\Delta v^2}$, the emittance growth due to injection errors is determined by the following expression:

$$\frac{\Delta\varepsilon}{\varepsilon} \approx 2\pi^2 \frac{\overline{\Delta v^2}}{g^2} \frac{x_0^2}{2\varepsilon\beta}$$
(3.5.2)

where g is the dimensionless damping decrement, and $\sqrt{\Delta v^2}$ is the rms betatron tune spread related to the beam decoherence time $\tau_{decoh} \approx 1 / \left(f_0 \sqrt{\pi^2 \Delta v^2} \right)$. As one can see

from Table 3.5.1, the damping time is about 90 turns for a 5 mm beam displacement. Then, Eq. (3.5.1) yields that the betatron tune spread has to be below $2.4 \cdot 10^{-4}$, which corresponds to about a 1500 turn decoherence time. The decoherence time of the Main Injector is mainly determined by the lattice chromaticity and is usually in the range of a few hundred to a few thousand turns. Figure 3.5.6 shows a turn-by-turn BPM measurement made with protons showing the damper response time after the beam is "pinged" with a kicker. The diagram illustrates that a beam with 5 mm oscillations can be damped with the existing system. It also shows that the machine can be tuned so that the decoherence time is long enough so that damped injection oscillations will cause only small emittance dilution.



Figure 3.5.5 Simplified schematic of the narrow band feedback system



Figure 3.5.6 *BPM turn by turn of an undamped proton beam (top) and damped proton beam (bottom)*

The orbit length of the accumulator is 1/7 of the orbit length of the Main Injector. This allows the use of a narrow band system, which damps only the lowest betatron side band. The bandwidth of the system has to be narrower than the revolution frequency and wider than the damping decrement. In this case, the betatron oscillations of the injected batch are damped by a low frequency sinusoidal waveform. If the system is appropriately phased, the residual betatron oscillations are below $(\pi/14)^2/2\sim0.025$ of the initial betatron oscillations. The corresponding emittance growth is the square of this number and is negligible in comparison with other effects.

3.5.4 Plan and status

The primary goals of the project are to avoid any beam loss during antiproton transfers to the Recycler and to minimize or eliminate emittance growth. In addition, transfers need to be made in a short period of time, much shorter than the time required presently for transfers to the Tevatron. To address these problems, the plan is as follows:

- (1) Redesign and correct the lattice in the Accumulator to Main Injector transport lines (P1-P2-AP1-AP3).
- (2) Introduce a consistent hysteresis cycling protocol for all quadrupoles, dipoles and trims in the transfer lines into the transfer process.
- (3) Make final lattice adjustments with a diagnostic quadrupole pickup, either the existing device in the Accumulator or a newly designed pickup.
- (4) Modify electronics for AP-1 120 GeV power supplies so that regulation is good enough for 8 GeV operation.
- (5) Add electronics to the Main Injector injection damper for the suppression of dipole injection errors on the antiproton transfers.
- (6) Improve the efficiency of beam steering and optics analysis.

Expenditures related to this project can be grouped into five categories.

- (1) The lattice upgrade for the transport lines will eventually involve some reconfiguration of power supplies and magnet shunts. M&S requirements for installing cables and shunts will be \$40k for FY '02. Labor requirements in this time frame will be 0.2 FTE of technician time for installation and 0.4 FTE of physicist time to commission the new lattice.
- (2) The Main Injector injection damper will be modified for use with antiproton transfers. In FY '02, \$20k of M&S will be spent for upgrades to the low level electronics and instrumentation. Labor requirements will be an engineer at 0.3 FTE and a technician at 0.2 FTE for the design and installation of the electronics. 0.2 FTE of physicist time will also be needed to commission the system with beam.
- (3) Power supplies for the AP1 line will need to be upgraded to have adequate regulation during 8 GeV operation. To support rapid transfers, the AP1 line will need to operate at both energies with a single power supply. The upgrade is expected to take place in FY '03, so there will be no expenditures in FY '02. M&S requirements for FY '03 will be \$300k for the electronics modifications to the supplies. To support the modifications, 1 FTE of engineering and 1.5 FTE of technician time will be required. 0.5 FTE of physicist labor and 1.0 FTE of computer professional labor is included for software related to implementing the rapid antiproton transfers.
- (4) On-line modeling of the transfer lines will be upgraded to improve orbit correction and lattice measurements. No outlay of M&S is expected in FY 02.

Labor will be 0.5 FTE of physicists time and 0.5 FTE of computer professional time.

(5) The diagnostic quadrupole pickup in the Accumulator will be recomissioned and used for lattice corrections. If this device proves inadequate, a new pickup will be required that will require more resources than those estimated here. M&S requirements for FY 02 will be \$20k which will cover electronics upgrades to the existing detector. Labor requirements for the next year will be 0.25 FTE of engineering time and 0.2 FTE of technician time for the design and installation of the electronics and 0.2 FTE of physicist time for commissioning the system.

	Total	M&S	Labor	Phys.	Eng.	Draft	Tech	СР
FY02	380	90	290	1.3	0.5	0.6	0	0.5
FY03	700	300	400	0.5	1	0	1.5	1
FY04	0	0	0	0	0	0	0	0
FY05	0	0	0	0	0	0	0	0
Project	1080	390	690	1.8	1.5	0.6	1.5	1.5

Table 3.5.2 Funding profile for rapid antiproton transfer project

3.5.5 Conclusion

Rapid transfers from the Accumulator to the Recycler can be achieved in Run IIb, but will require a significant change in philosophy from transfers made in the past. Routine beamline orbit corrections with reverse protons will be eliminated, greatly reducing setup time. To be successful in this mode of operation, several changes and improvements will need to be made. The beamlines will need to be far more reproducible than has been experienced in the past. A combination of lattice improvements, ramped power supplies and a consistent hysteresis protocol will be used to make the magnetic fields more reproducible and the beamline more tolerant to errors. The existing beamlines will be utilized for the transfers, avoiding the cost and program interruption that would accompany the construction of a new beamline. To achieve a short interruption to stacking for the transfers, device setting changes will need to be kept to a bare minimum. The transfer process will need to be highly automated, requiring minimal interaction from the Operators.

There are a number of advantages to taking this approach for rapid transfers. Lattice measurements and improvements will take place in the near future and the benefits will improve transfer quality prior to the start of Run IIb. The cost and program interruption associated with the beamline upgrade will be modest compared to what a new beamline will require. Ramped AP-1 power supplies can be tested and implemented prior to Recycler operation. Similarly, pbar injection dampers would improve collider luminosity as soon as they are commissioned. In general, the upgrades and improvements anticipated to support rapid antiproton transfers to the Recycler are incremental. Potentially, they will provide operational improvements to the collider program as they are implemented.