Rapid Antiproton Transfers from the Accumulator

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Introduction

To take full advantage of the increased stacking rate in the Accumulator, it will be necessary to reduce the time needed to transfer pbars from the Accumulator to a the Recycler from hours to the order of minutes. Improvements in beam line control, real time control of emittance growth and steering errors and greater automation of the process are the primary components of the plan to speed the transfer process.

Current Status and Limitations

Currently 'Shot Set Up', for loading pbars into the Tevatron, requires typically 1 hour and 50 minutes to accomplish. Table 1 summarizes the time taken for each Sequencer aggregate to play out from the point where stacking is halted through having the Tevatron loaded. Minimum and Maximum Sums represent ideals rather than the actual minimum and maximum shot set up time achieved to date. Just over thirty minutes is required to wait for the core to cool and switch to the shot lattice, twenty-five minutes to tune up reverse protons, seventeen minutes to complete final preparations and wait for the Tevatron to be ready to accept pbars, and twenty-three minutes to fill the Collider with pbars. Ideally, the load time would be of the order of five minutes to perform nine transfers.

Sequencer Mode	Minimum time	Median time	Maximum time
Start Set-Up	00:04:17	00:07:52	00:38:59
Start Reverse Protons	00:00:42	00:01:36	00:29:02
Switch to Shot Lattice	00:04:58	00:33:04	02:13:17
Finish Reverse Protons	00:02:32	00:24:31	01:54:25
Continue Shot Set Up	00:01:05	00:02:50	00:28:42
Prepare to Load Pbars	00:01:38	00:17:22	00:43:08
Load Collider Pbars	00:13:52	00:23:21	01:40:49
Sum	00:42:59	01:50:36	08:08:22

Table 1 – Shot Set Up aggregate Length
November 2002 - present

The Sequencer allows for reproducible, and where feasible, automatic control of the set up process. Certain steps require human intervention. As the table summarizes, it should be feasible to load the Collider in 43 minutes under ideal conditions. This assumes no problems encountered in the entire complex during shot set up. The primary tasks in shot set up are:

1) Stop stacking, cool the core, orient AP1 and AP3 for 8 GeV operation. A Time Line Generator file is loaded to facilitate set up of all affected accelerators.
2) Switch the Accumulator lattice to the so-called 'shot lattice' once the core is sufficiently cool longitudinally. Main Injector tune-up at 8 GeV occurs in parallel.

3) Check and correct, as needed, the antiproton beam line orbit against a reference orbit. The beam line is actually comprised of four: P1, P2, AP1, and AP3. A minimum of 30 bunches with intensity greater than ~2 X 10^{11} is needed for stable BPM performance.
4) The reverse proton intensity is lowered and turn-by-turn oscillations of the reverse protons injected into the Accumulator are minimized. Cooling of the core in all three planes continues in parallel.
5) With reverse proton tune up complete, the extraction kicker and a handful of correction dipoles are changed to shot specific values based on empiric data. The kicker change is motivated by the difference in how the magnetic and electric fields are summed due to charge and direction reversal.
6) RF curves are loaded for unstacking systems and final checks of timers and RF parameters are made.
7) Pbars are unstacked from the core with an h= 4 system, accelerated to the extraction orbit and transferred to the Main Injector once the Tevatron is loaded with protons and the injection helix opened. The process is repeated nine times, for a total of 36 bunches. Each transfer requires 31 seconds to unstack and transfer to the MI.
8) Turn-by-turn oscillations are monitored at MI injection and corrections made as necessary.
9) The Accumulator lattice is reoriented for stacking and the entire complex set back up for antiproton production.

Further gains in speed can be accomplished, most notably in the reverse proton tune up. The tune up has stabilized to the point that, as was the case late in Run I, the decision to carry out a full reverse proton tune up will be based on the transmission efficiency from the Main Injector to the Accumulator. An efficiency of >85% will be sufficient to continue without a tune up.

A reasonable expectation is to reduce shot set up time to 60 minutes or less. Experience with rapid transfers to the Recycler has succeeded in stacking to stacking times of 60 minutes.

Rapid Transfers Overview

Rapid Transfers will require a fundamental change in how pbar transfers occur. Transfers will be based on stack size and will need to be accomplished as quickly as possible so as to maximize the available time to stack. As such, transfers will have to occur on demand and be based much more on clock events than now. Manual intervention will be virtually non-existent. Several steps in the current scheme can be removed since pbar transfers will be made to the Recycler and the constraints to provide a ‘Collider quality’ beam less rigorous. The removed steps include:

- Core cool-down time
- Switch to the ‘Shot Lattice’
- Waits for downstream machines i.e. Tevatron

In some instances, steps will be carried out only on an as-needed basis during ‘maintenance studies’ periods. Reverse proton tune up, though now routine, will be conducted only when performance is observed to degrade below a pre-determined limit. Where possible, timer changes will be incorporated for all modes of operation. It is expected that one, at most two, transfers will be done, driven by longitudinal emittance constraints and capabilities. Another change is anticipated in support of stack tail cooling upgrades. Playing the unstacking RF curve in reverse will serve to phase displace any pbars not removed from the stack back to their previous momentum so as to preserve the proper distribution for optimum stack tail cooling performance.

The envisioned scheme of events is:

1) Stacking proceeds with a normal stacking time line.
2) As the stack size approaches the pre-determined limit, a rapid transfer sequencer aggregate is invoked.
3) Cursory checks of critical parameters are made.
4) The time line is modified (automatically) to insert an unstacking module and perform any necessary beam line power supply hysteresis.
5) One or more transfers are made, depending on longitudinal emittance constraints.
6) RF phase displacement moves any perturbed beam remaining in the Accumulator to its previous distribution as part of each transfer.
7) Injection oscillations into the Main Injector are minimized with the Injection damper.
8) Stacking resumes with a ‘normal’ stacking timeline once the transfer(s) is complete.

In order to bring Rapid Transfers to realization a number of upgrades are required. These upgrades can be compartmentalized into four main components including:

- Improved beam line magnet control
- New transverse oscillation control/correction scheme
- Sequencer/process changes
- Enhanced/upgraded diagnostics

Embedded in each of these components is new or improved software.

Improved Beam Line Control

As currently envisioned transfers will occur on an on-demand basis by inserting the appropriate Time Line Generator (TLG) module for transfers from the Accumulator to the Recycler via the Main Injector. It will be necessary for all transfer lines to be able to switch operating energy on clock event. The P1 and P2 lines currently operate in this manner. Particularly, the P1 line operates at 8, 120, and 150 GeV to facilitate beam transfers between the Main Injector and the Antiproton source and Tevatron. AP3 operates exclusively at 8 GeV and is turned on and off as needed. The AP1 line magnets are operated in a bi-modal state – at 120 GeV for stacking and at 8 GeV for Pbar transfers and for studies purposes. Except for the correction dipoles, the magnet (strings) are powered by two separate power supplies for 8 and 120 GeV operation respectively to optimize regulation. Although the switch from one supply to another happens in very short order, on the order of a few seconds, it will be necessary to run the magnets using a single supply controlled with a waveform generator card with the magnet current set appropriately on clock event. Such a change will make a switch in beam line operating energy virtually instantaneous and also provide for predictable hysteresis behavior. The following steps will be required to ensure that this is feasible:

- Calculation of the acceptable orbit variation and emittance growth will determine the bound on magnetic field quality. This limit will determine the necessary power supply regulation.
- Studies of both power supply regulation, stability, and beam-based measurements using the current 120 GeV supplies operating at 8 GeV currents will determine what, if any, improvements in regulation will be required.
- It may be possible to begin to operate the AP1 line with only a single set of supplies for routine operation and change settings based on mode of operation.
- In order to efficiently operate AP1 with a single set of supplies it will be necessary to control them with waveform generator (465) control cards so as to have the appropriate setting for the desired mode of operation already in place.

New transverse oscillation control/correction scheme

Currently, shot-to-shot transverse oscillations into the Main Injector are monitored by dedicated strip line BPMs and minimized using the ‘Beam Line Transfer’ (BLT) application. Two correction dipoles in each plane at the end of the P1 line closest to the Main Injector are adjusted, based on empirical behavior, to minimize the oscillations. The operations crews apply suggested changes if the measured RMS amplitude is in excess of 0.5mm in a given plane. The correction is applied to the subsequent transfers. Typically, two or more corrections are made in each plane as the nine transfers are made. Slow feedback is done manually by charting shot-to-shot corrections and applying offsets to the correction dipoles settings between reverse proton and pbar modes.

In the fast scheme, with only one or two transfers, it will be necessary to make corrections in real time. This will require the use of a ‘fast’ injection damper. Slow behavior, such as a consistent offset, will be fed back to correction dipoles in both planes at the downstream end of the P1 line (as pbars travel).

A narrowband transverse damper system already exists in the Main Injector to act on protons. As protons and antiprotons travel in opposite directions in the Main Injector, the addition of load transfer switches to make the damper bi-directional and low level enhancements would make it possible to use this system on pbars. The complete scope of damper changes will require further study.

In order to maintain gross control of the pbar oscillations into the Main Injector a slow feedback loop also needs to be incorporated using signals from the damper pickups and the existing BLT system.

Under study at present is an alternative means of monitoring transverse oscillations in the Accumulator using a set of normal and skew quadrupole pickups located in the A10 low dispersion straight section.

Sequencer/process changes

Although pbar transfers will continue to be driven by the Sequencer, significant modifications will be required to support rapid ones. A re-write of the aggregates and enhancements to sequencer commands, possibly a higher level of decision-making, will be necessary. A fundamental shift in operations mentality is probably the most significant change. Also under consideration is a scheme to drive mode changes using state devices. Such a scheme may provide control or change in settings based on the value of a state device and could potentially provide for rapid switchover to different modes of operation in addition to the modes addressed here. Ideas such as this will undoubtedly evolve.

Additional software support will be required in support of rapid transfers. Much of the effort will be to provide code for user-friendly control of 465 cards for AP1. Other needs will be new applications to measure and change beam line lattice and orbit and new Turn by Turn correction application(s) to name a few.

Enhanced Diagnostics

In support of the changes outlined above, an expanded suite of diagnostics will be required to support rapid transfers. Additional projects will undoubtedly be considered. For now, the two most notable ones in support of beam line performance.

Reproducible magnetic fields will be crucial to the long-term stability and high performance of the P1, P1, AP1, and AP3 lines. Real-time monitoring of the field of each magnet or string will provide the necessary knowledge base. Miniature hall probes are being considered as possible monitors.

Taking the reverse proton tune up step out of the sequence of steps will mean that there will be virtually no information on the beam trajectory. Beam Position Monitors are in place in all of the beam lines in question, designed to sense 53 MHz structure on the beam. Upgrading the electronics to be able to sense the intensity and bunch shape of pbars traversing AP3, AP1, P2, and P1 will be vital to monitor beam line stability. SEM grids and multiwires exist and could conceivably be used, but the available coverage and passive nature of BPMs makes upgrading them a much more attractive alternative.

Schedule

It is foreseen that much of this effort can be staged in parallel. Each component has merit in improving the transfer time and Collider performance. Beam line regulation and control upgrades are expected to take of the order 3 months from preliminary measurements and tests of existing power supplies to implementation of new ramped waveform control of power supplies. This assumes that necessary personnel are available at the 100% level. The Injection damper is estimated to require 18 months of work. Diagnostics upgrades and additions are expected to require a year to realize. Software support will be ongoing throughout all of this and is estimated to consume 17 months of a full-time computer professional’s time in addition to part time physicist and engineer effort. Dedicated study and commissioning time will also be required to bring rapid transfer to full fruition.

Summary

In order to maintain a peak Pbar stacking rate, it will be necessary to transfer antiprotons from the Accumulator to the Recycler as rapidly as possible once the stack has reached its maximum. Modeling of an upgraded stack tail cooling system suggest that with a stacking rate of 40×10^{10} pbars/hour it will be necessary to empty the core every at least every thirty minutes. At this frequency, transfers need to be accomplished in less than one minute. Improvements in beam line control, Main Injector injection dampers, enhanced diagnostics, and virtually complete automation of transfers as outlined above should serve to realize transfers the desired goal in rapid transfers.