X. Modes of operation

The Antiproton source can be configured into several operating modes. In addition to antiproton stacking and transfers, there are modes that utilize 8 GeV protons. Protons provide a readily available source of relatively high intensity beam for tune-up and studies. The antiproton source has also been used to provide beam for experiments housed in the A50 pit. Each mode of operation that has been used to date is summarized below, with the exception of 8 GeV proton transfers from Booster using the decommissioned AP-4 line.

A. Antiproton stacking

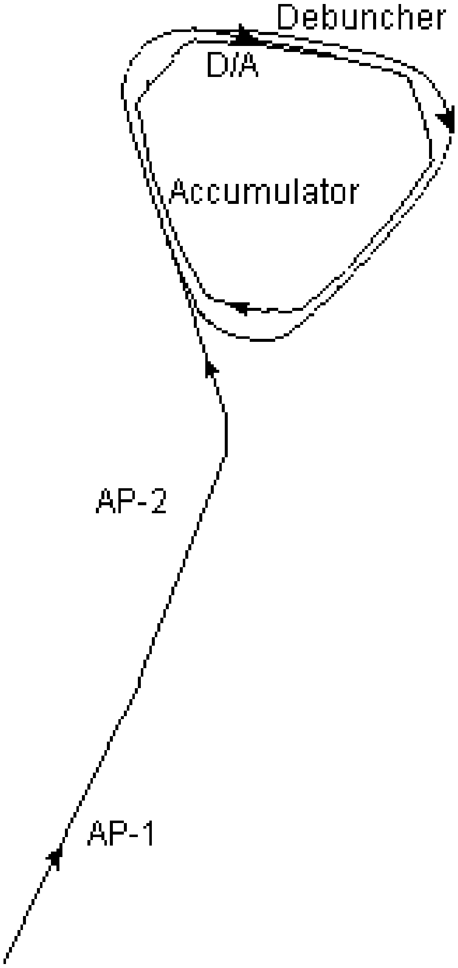

Figure 10.1 Stacking

Two Booster batches are injected into the Main Injector and merged into to a single batch via an RF manipulation called slip-stacking. Slip-stacking provides a higher intensity beam per pulse to pbar. After slip-stacking, the beam is then accelerated in the Main Injector to 120 GeV and bunch rotated. The short bunch length beam is extracted from the Main Injector at MI-52. Beam is transported down the P1 and P2 lines, then directed into the AP-1 line (see figure 10.1). The protons continue down the AP-1 line into the Target Vault where the beam strikes an Inconel target. Downstream of the target, 8 GeV antiprotons, as well as other negative secondaries, are focused with the Lithium Lens and are momentum selected with the Pulsed Magnet. Particles that are off-momentum or positively charged are absorbed in a beam dump. The secondary beam travels to the Debuncher via the AP2 line where most of the non-pbar secondaries decay away. Of the remaining secondaries, most are lost in the first dozen turns in the Debuncher. Only a small fraction of antiprotons with appropriate energy survive to circulate in the Debuncher. For every million protons on target, only about 20 antiprotons make it to the core. After debunching and cooling in the Debuncher, the pbars pass through the D to A line and into the Accumulator. Successive pulses of antiprotons arriving in the Accumulator are 'stacked' into the core by ARF-1 and stochastic cooling. Associated TCLK resets are Booster $14, Main Injector $29 or $23, Debuncher $80 and $81 and Accumulator $90. The Main Injector can provide beam on either a stacking-only cycle ($29 event), or a mixed mode cycle with NuMI ($23 event). Stacking-only cycles are at least 2.2 seconds long and can be extended to improve the stacking rate with larger stacks. When Main Injector is running in mixed mode, beam is provided for both pbar production and NuMI in one cycle. The beam to each area is extracted separately in both location and time. The pbar production beam is extracted first up the P1 line and a couple of milliseconds later the NuMI beam is extracted down the NuMI beamline. Beam to NuMI is also bunch rotated, but extracted with a small momentum spread to minimize losses in their beamline. The mixed mode cycle maximizes beam to both areas and can repeat with a 2.2 second cycle time.

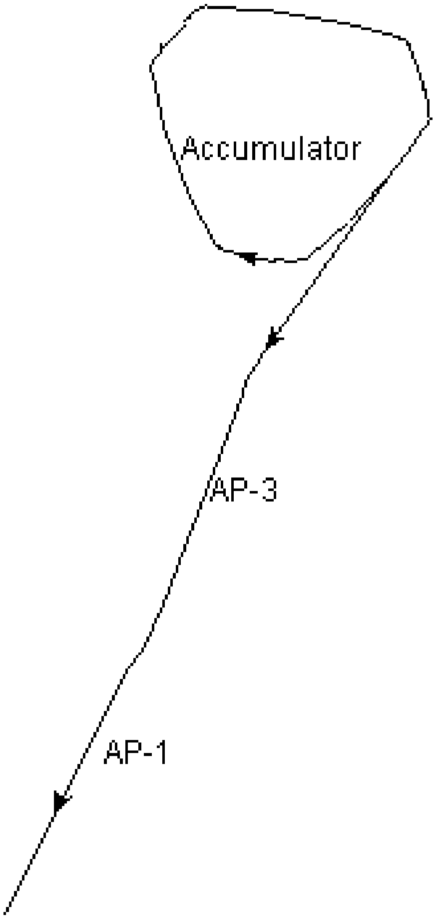

Figure 10.2 Pbar transfers to Main Injector

B. Antiproton transfer

Pbars are unstacked from the Accumulator core with ARF-4 and accelerated to the extraction orbit. The ARF-4 voltage is then increased to narrow the pbar bunches. The Accumulator extraction kicker imparts a horizontal oscillation on the beam so that it passes through the field region of the extraction Lambertson in A30. The beam is bent upward by the Lambertson and a C-magnet into the AP3 line (see figure 10.2). The beam continues down the AP-3 line, skirting the Target Vault, and enters the AP-1 line (running at lower currents for 8 GeV operation). The AP-1 line connects to the P2 line at F17 where a B3 dipole magnet and 2 C-magnets bend the beam upward to the trajectory of the old Main Ring. Beam continues down the P2 and P1 lines and is injected into the Main Injector at MI-52. The pbar beam is destined for the Recycler, where it is stored until needed in the Tevatron. Significant TCLK resets are: Main Injector $2D and Accumulator $90 and $9A.

C. Reverse protons

Protons in the Main Injector are not accelerated, remaining at 8 GeV until being extracted at MI-52. The protons trace the reverse path of the beam in an antiproton transfer (see figure 10.3). The protons enter the P1 line and continue down the P2 line to the F-17 location. The B3 magnet at F-17 functions as a switch, either selecting the AP1 line or the P3 line. If I:F17B3 is powered, then the beam is bent upward into the AP-1 line. Beam is then bent horizontally into the AP-3 line with EB6, powered by D:H926. EB5 and EB6 make up a dogleg that diverts beam along the outside of the Vault. After passing through AP-3, the beam continues through a C-magnet and the field region of the extraction Lambertson (ELAM) which bends the beam upward into the Accumulator at A30. The extraction kicker in A20 deflects the beam horizontally onto the closed orbit of the Accumulator.

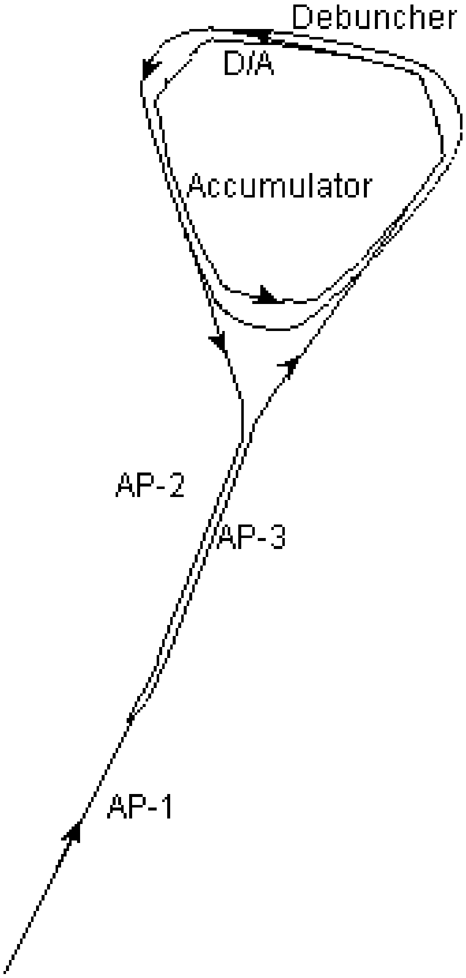

Figure 10.3 Reverse Protons

Reverse proton mode compliments stacking in the sense that the polarity of the Rings and beamlines do not need to be reversed. Reverse protons are used during Collider operation to tune up the beamlines prior to a pbar transfer from the Accumulator to the Main Injector. Reverse proton mode is also used for studies in both Rings and all beamlines. If desired, protons can be extracted from the Accumulator and sent down the D to A line into the Debuncher. Beam can then be injected backwards into the AP-2 line and transported to the Target Vault. Significant TCLK resets on reverse proton cycles are a Booster $16, Main Injector $2D, and Accumulator $93.

D. Forward protons

8 GeV protons are extracted from the Main Injector and continue into the AP-1 line in the same manner as in reverse proton mode. At the end of AP-1, beam is sent to the Target Vault instead of into the AP-3 line (D:H926 is left off). In the Target Vault, the target and Lithium Lens have been pulled out of the beamline and the polarity of the Pulsed Magnet has been reversed. The Rings and beamlines downstream of AP-1 also have their polarities reversed. This way the 8 Gev protons can continue into the AP-2 line, the Debuncher, the D to A line and the Accumulator as required (see figure 10.4). The proton beam could also be injected into the AP-3 line, but it is normally more convenient to use reverse protons.

Forward proton mode can be useful for phasing cooling systems using higher intensity beams and other direction-specific studies in the Antiproton Source. This mode was most commonly used at the beginning of running periods to phase in the Debuncher cooling. In Run II, upgrades to the Debuncher cooling pickups and an increase in pbar intensity has allowed phasing to be accomplished with pbars in a normal stacking configuration. Significant TCLK resets for forward protons are a Booster $16, Main Injector $2D, and a Debuncher $85.

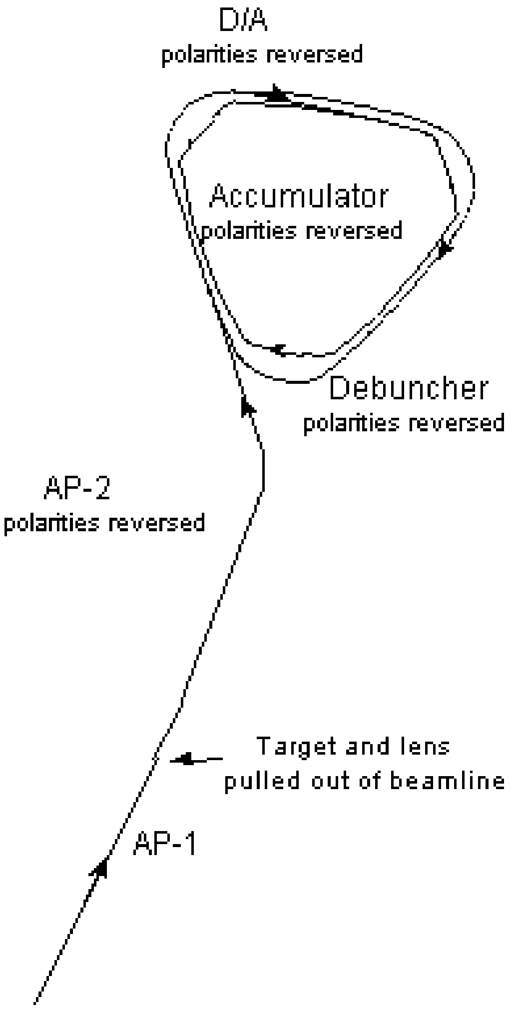

Figure 10.4 Forward Protons

E. Proton stacking

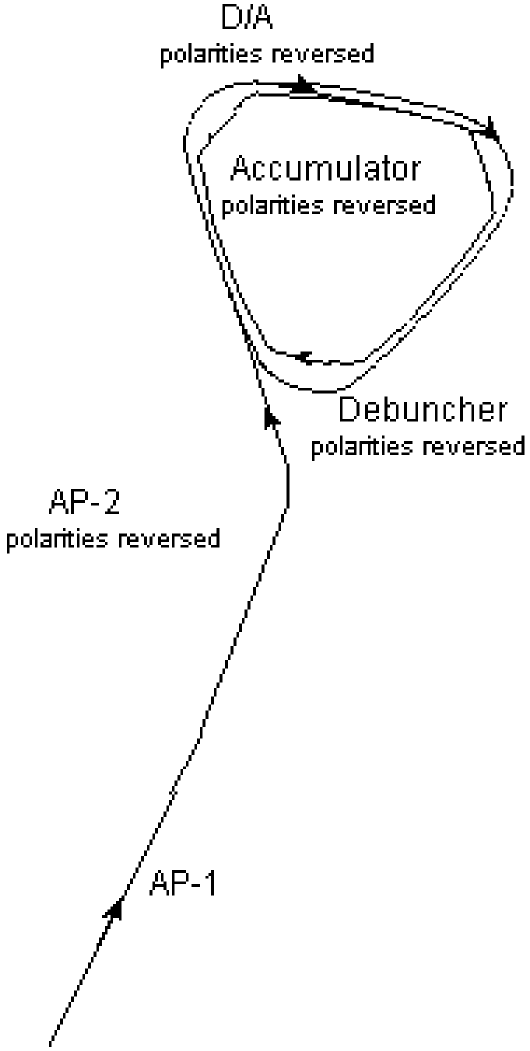

Figure 10.5 Proton Stacking

In proton stacking mode, the beam follows the same path as for antiproton stacking, but proton secondaries are stacked instead of antiprotons (see figure 10.5). To accomplish this, polarities of components downstream of the target are reversed. In the Target Vault, 8 Gev protons are focused and charge and momentum selected with the Lithium Lens and Pulsed Magnet configured for protons. The polarity reversal not only includes the Rings, AP-2 and the D to A line but also the dampers and stochastic cooling systems.

Proton stacking has been used to test the limits of the stacking rate by stacking secondary protons instead of antiprotons. Proton secondary flux to the Debuncher is about six times greater than that achieved with antiprotons due to the production cross section of protons. This is particularly useful for testing cooling systems under conditions simulating increased intensity, most notably the stacktail system. Proton stacking studies at the end of Collider Run 1b attained a peak stacking rate of 12.2 E10/hr (as opposed to 7.3E10/hr for antiproton stacking earlier in the run). Significant TCLK resets are the same as during stacking, a Booster $14, Main Injector $23 or $29, and Accumulator $80 and $81.

F. Deceleration

In 1986, an experimental pit adjacent to Accumulator straight section 50 and a counting room attached to AP50 were constructed. The pit and counting room were built to provide space for experiments interested in using circulating Accumulator antiprotons. Experiment E760 was the first to make use of the new facilities. The goal of the experiment was to measure the mass and width of charmonium states by means of $\overline{p}$ - p collisions. A charmonium state is produced when a charm and anti-charm quark pair are produced and bound together, briefly orbiting each other. The quark pair is very short-lived, decaying in only 10^{-20} seconds. The angular momentum from the spinning quarks contributes to their total energy. There are a number of different charmonium states defined by the rate at which the quarks rotate around each other.

The main components of E760 were a hydrogen gas jet target, which was the source of the protons, a particle detector, and the Accumulator, which provided the antiprotons. The gas jet target provided an interaction region of roughly one cubic centimeter. Circulating antiprotons in the Accumulator pass through the gas jet and some fraction of them interact with the hydrogen.

The Accumulator was modified to serve as a decelerator to reach the necessary energies, the lowest of which is at 3.770 GeV. Some of the desired resonances are located below the transition energy of the Accumulator. To reach these energies beam was decelerated below transition. To accomplish a deceleration, all power supplies and the ARF-3 frequency were ramped down in a very precise fashion. Because the velocity of the beam was reduced during deceleration, the cooling system delays were also lengthened to maintain the proper phasing. Quadrupoles, sextupoles and octupoles were ramped to keep the tunes safely away from resonances. Special code in the pbar front end provided the ramp waveforms necessary for the deceleration.

The beam was kept on the central orbit so that it was centered in the aperture in high dispersion regions. A new set of 2-4 GHz core momentum pickups was added that was sensitive to beam on the central orbit. The pickups used during collider operation are located at the core and not suitable for cooling beam on the central orbit. The 4-8 GHz core momentum pickups were mounted on a motorized stand and could be moved to the central orbit.

The E760 run took place during the 1990 Fixed Target run with the Antiproton Source dedicated to running the experiment. A typical sequence of events was as follows: one or more shifts of stacking to accumulate several

10E10 of pbars with the stacking cycles occurring in the 56 seconds between Tevatron injections. After the appropriate number of antiprotons was stacked, Physicists and Operators in the MCR decelerated the beam using the sequencer program. After the deceleration was completed the experiment would conduct hours or days of data taking after which the cycle would repeat.

Experiment E835 was a progression of E760 and took data during the 1996-97 Fixed Target run. Among the improvements for E835 was an upgraded detector with a liquid Helium cooled calorimeter, which required a stand-alone Helium refrigerator at the AP-50 service building. This prompted the relocation of the A:QT power supply from AP-50 to AP-10 to provide room. Control of the deceleration ramps was integrated into the Pbar front end instead of an auxiliary front end as was done with E760. E835 was primarily interested in improving their statistics on the 1P1 resonance and also attempt to observe the Eta c' resonance which had never been observed.

E862 ran in parallel with E835. The experiment was involved with measuring anti-Hydrogen atoms created by the E835 gas jet. A separate beamline extended into the tunnel aisle downstream of A5B3. The beamline included a table that contained a stripping foil, magnets and a positron detector. Downstream of the table was a pair of dipole magnets and three wire proportional chambers, with the line ending at an antiproton detector.

Not all experiments require a dedicated running period during Fixed Target operation. During collider run 1b, experiment E868 (also known as APEX - AntiProton EXperiment), had a successful run. Their goal was to make a lower estimate of the lifetime of an antiproton. Most of their data-taking time was during interruptions in stacking.