Operational Experience with Tevatron I Antiproton Source

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Introduction

The Fermilab antiproton source consist of five beamlines, a targetting station and two storage rings. (Figure 1).[1] The beam is extracted from the Main Ring at 120 GeV from F-17 and transported up AP-1. At AP-0 they are targetted on a 7cm copper (5cm) target. The antiprotons are collected at 8 GeV with a 15 cm long lithium lens of 1 cm radius operating at 800 T/m gradient.

The secondaries are transported down the AP2 line into the Debuncher ring. The Debuncher ring has a 20π x 20π transverse acceptance and 4% momentum acceptance. The antiprotons are then rotated using 4.2 MV of 53 MHz R.F. to .4% $\Delta p/p$ in 80 turns and the adiabatically debunched to .2% $\Delta p/p$. The antiproton are then stochastically cooled for 2 seconds in the transverse planes with 2-4 GHz cooling systems to 7π x 7π. The antiproton are then extracted from the Debuncher and transported across the D/A line to the Accumulator.

The antiprotons are injected onto the injection closed orbit with a shuttered kicker in a high dispersion region in the Accumulator. The antiprotons are then adiabatically captured in an H = 84 R.F. system and decelerated to the stacking orbit. They are then stochastically stacked using the 1-2 GHz stacktail momentum system until they are captured in the core by the 2-4 GHz core system. They are also cooled transversely by the 2-4 GHz transverse cooling systems at the core orbit.

The antiprotons are unstacked from the core using a broadband suppressed H=2 R.F. system and accelerated to the extraction orbit. The suppressed bunch is then adiabatically compressed with a resonant H=2 system and subsequently bunched in a H=84 R.F. system for bucket to bucket transfer to the Main Ring. The antiprotons are extracted from the Accumulator by a shutter kicker in a high dispersion section and transported down AP-3 to AP-1 and into the Main Ring at F-17. The antiprotons are kicked onto the Main Ring closed orbit at E48.

The AP-4 line is used to bring 8 GeV protons from the Booster when particles are unavailable via the Main Ring.

History

The source groundbreaking was in August of 1983. The first beam extracted from the Main Ring at F17 and brought to the target station occurred in February of 1985. Beam was first circulated in the Debuncher in April of 1985 and beam was subsequently circulated in the Accumulator ring in August of 1985. Antiproton production and stacking took place in August of 1985 approximately two years after the groundbreaking. A short test of the reverse injection into Main Ring and the Tevatron which began in September of 1985 resulted in detected 1600 GeV collisions in the C.D.F. detector at BØ in October of 1985. At this point the Main Ring went down for construction of the DØ Collision Hall and the BØ overpass.

The AP-4 line was installed and commissioned by February of 1986 and studies with primary protons commenced. The thrust of the primary proton studies was the improvement of the Accumulator and Debuncher acceptance. The protons studies were discontinued on May 1 to allow for the Booster Controls conversion. The source was brought back up in August of 1986 with both protons from the Booster and from the Main Ring. Antiproton stacking began on again in November 1986.

Diagnostics

As with all accelerators, diagnostics devices are fundamental to successful operation. The diagnostics for the source are roughly divided between the beamline devices and the storage ring devices.

The primary diagnostic tool used in the beam lines is thirty segmented secondary emission monitors. These monitors provide position and profile information for beams which vary in intensity from 10^{12} particles to 10^{7} particles. These monitors are motorized to allow removal from the beamlines. In beamlines where the intensity is high and the beams have distinct R.F. structures, non intersecting beam position electrodes are used to measure the center of mass of the particle beam. This is especially important in the reverse injection of pbars, where emittance dilution due to the SEM grids is highly undesireable.

All the beam lines are equipped with current toroids and gated 50Ω integrators for measuring the beam intensity. These devices are useful for beam intensities of 10^{9} particles or more. Also all beamlines are equipped with loss monitors which in general are the Fermilab "paint can" style.[2] These consist of a paint can filled with liquid scintillator and viewed via a phototube. These signals are integrated and sampled to measure beam loss.

The AP2 line has some unique diagnostics as it transports secondary beams from the target to the Debuncher. This line has five moveable collimators to allow variable collimators of beams in x, x', y, y' and momentum. It is also equipped with three ion chambers which measure the particle intensity along the AP2 beamline. Since the dominant particle in the AP2 beamline is the π-, the beamline is equipped with a Cerenkov counter which allows the direct measurement of the pion to antiproton ratio. Coupled with the ion chambers and a knowledge of the pion decay lifetime this permits a reconstruction of the antiproton intensity along the beamline and a prediction for the antiproton yield in the Debuncher.

The Debuncher and Accumulator have many diagnostic systems in common. Both machines have resonant schottky pickups for horizontal, vertical, and longitudinal beam information. Figure 2, shows the signal from the longitudinal schottky pickup in the Accumulator with a antiproton stack of 2×10^{11} pbars. The longitudinal schottky's are used in both

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rings to provide yield and efficiency numbers for various operations as well as core density. Yield measurements can be made to the level of 10^4 particles which these devices. Figure 3 is the Debuncher schottky signal analyzed by a fast Fourier transform device to provide bunch rotation efficiency. The transverse schottky's are used in both rings to measure tunes, coupling, and chromaticity, as well as, core emittance and transverse instabilities in the Accumulator.

Each ring is equipped with a beam position system and a direct current transformer. The D.D.C.T.'s have a noise level of a few 10^7 particles and a maximum range of 10^{12} particles. The Debuncher has 120 beam position pickups and the Accumulator 90 beam position electrodes. The system can provide closed orbits, first turn or turn by turn information. Each ring is also equipped with a resistive wall pickup, a distributed loss monitor system and three beam scrapers. Figure 4 is a readout of prebunched antiprotons prior to a transfer on the resistive wall pickup using a mountain range system. The beam scrapers horizontal, vertical, and momentum are invaluable for measuring ring acceptances and providing narrow momentum spread primary beams for stochastic cooling studies.

The Debuncher contains two residual ion profile monitors to give a real time non destructive transverse cooling display and the Accumulator contains addition systems which allow diagnosis of transverse and longitudinal instabilities from the 1-g betatron sideband up to four gigahertz.

Final Startup 1985 Run

The initial startup of the source began in January of 1985 and ran through October of 1985. This encompassed the first beams extracted from the Main Ring toward the source to observe collisions at 1600 GeV in the CDF Detector in the Tevatron. Initial turn on was fraught with the normal problems associated with the turn on of a new machine. Initial problems with controls, data base, power supply settings, and timing were numerous.

During the initial attempt to circulate beam in the Debuncher, it was found that an RF cavity placed between the injection septum and injection kicker reduced the injection aperture to zero. After removal of the RF beam stop, beam particles were circulated in the Debuncher.

Initial attempts to circulate beam in the Accumulator were stymied by a cardboard pizza pan which had been used by the welders as part of the welding purge. This twelve inch piece of cardboard in a high dispersion pipe resulted in a sixty turn lifetime in the Accumulator and was quite difficult to find.

Additional problems were encountered later in the Accumulator. After the initial vacuum bake the Accumulator aperture disappeared and beam could only be circulated by a rather gross distortion of the closed orbit. It was ascertained that some of the bellows in a high dispersion region which were buried under bakeout jackets had collapsed. These had to be replaced by bellows with fewer convolutions and the sector then rebaked.

During the early part of the run the lithium lens transformer failed. This necessitated inserting a lens of an earlier design with a new transformer and limited the lens field to 600 T/m. The target to lens distance however was matched to a 1000 T/m lens and thus this change had an adverse affect on the net antiproton flux.

In addition, the time dedicated to the gain and phase adjustment of the stochastic cooling system was limited. This is very important especially in the stacktail momentum system. This system covers a board range of momentum. Thus crossovers between subsystems must be carefully adjusted in both phase and gain to provide the appropriate stack profile with no bottlenecks. None the less, collisions were observed at 1600 GeV, at the end of this run.

At the end of the 1985 run, all the systems had been commissioned, but the source performance was far from the design goal.

The maximum stacking rate was 10^9/hr and the maximum stack of antiprotons was 1×10^{10}.

Besides many small problems, the major problems were found to be due to acceptance problems in the two rings, and target station reduced flux due to a reduced lithium lens gradient.

Improvements After 1985 Run

After the 1985 run the Main Ring was shutdown for nine months to construct the DØ Collision Hall and the BØ overpass. During this period the antiproton source undertook an improvement program.

In the early part of the shutdown, primary 8 GeV proton beam was available from the booster via the AP-4 line. The beam was utilized to understand acceptance problems in the Accumulator and Debuncher.

Initially all small aperture devices were removed from the rings and the orbits were adjusted to maximize the acceptance.

The small aperture devices were retrofitted with motorized moveable stands and reinserted into the machines. These devices were then centered on the established closed orbit.

Additionally twelve dipoles in the Accumulator were motorized to enable the dipole to be rolled remotely. This gave twelve additional vertical trim elements in high dispersion regions where there is no space for additional trim magnets.

With these additions, the Debuncher aperture was increased from 8π x 12π vertically and horizontally to the design goal of 20π in both planes. The Accumulator was improved from 7π in both planes to 8π x 12π vertically and horizontally. The Accumulator design is 10π in both planes. The vertical discrepancy is believed to be the result of cocked chambers in the large dipoles. These chambers are not securely fixed by the dipole due to the addition of heaters, insulation and cooling jackets for bakeout. A plan to solve this problem by rolling the dipoles from end to end is under consideration.

During the 1985 run it was noted that the octupole magnets in the Accumulator were not strong enough to suppress the quadratic tune variation.

Thus during the long shutdown the multipole magnets were removed and the octupole windings were replaced by water cooled windings capable of twice the current. This allows for a correction of the tune vs. momentum across the Accumulator aperture of ±.006.

Due to the problems encountered during the initial bakeout, all of the high dispersion bellows were replaced by a series of shorter bellows. These short bellows were welded together with stiffeners in between to make long bellows which wouldn't collapse. Some have been baked three times now and no additional failures have occurred.

A new Lithium Lens and target module were designed and built. With the new target module the antiproton collection has been optimized for an 800 T/m lens gradient with no significant reduction in antiproton flux. To date the system has run for almost seven months with no Lens failures.

During the long shutdown and during the early part of the present run, extensive measurements of stochastic cooling systems were done. A stacking rate of $4x10^{10}$ particles per hour was achieved with primary protons. This represents forty percent of the design rate. Also a total stacking excess of $2x10^{11}$ antiproton has been achieved and represents fifty percent of the design goal.

Early in the present run a strong betatron heating of the core due to the stacktail momentum system was noted. This is due to assymmetries in the longitudinal kickers and thus produce transverse kicks. Since the stacktail momentum schottky band overlaps the core betatron sidebands, significant core transverse heating can be done by the high power longitudinal systems. To counteract this problem, four of the stacktail longitudinal kickers were converted to transverse kickers. They are spaced ninety degrees apart in betatron space for each plane. These kickers were then used to dead reckon out the transverse heating terms.

Present State of the Antiproton Source

The overall performance of the Antiproton Source has been extremely reliable, especially the Accumulator Ring. The major source of failures in the Antiproton Source have been the fast kicker cables (RG220) and the pulsed septum magnets. Neither of these types of failures have resulted in loss of stored antiprotons. However, additional stacking of antiprotons is delayed until these problems are remedied. An aggressive program to improve the reliability of these devices is underway. Figure 5 shows antiproton beam current in the Accumulator during a typical week of stacking and unstacking.

The operation of the Accumulator as a storage ring is of utmost importance to the successful operation of the Antiproton Source. At present some antiprotons have circulated in the Accumulator for a period of fourteen days. Approximately two days of continuous stacking is required to achieve the present goal of $2x10^{11}$ antiprotons for unstacking and after each antiproton transfer a period of ten to twelve hours of stacking is required to achieve the level of $2x10^{11}$ antiproton. For this reason the reliability of the Accumulator is extremely important. To date only one failure of an Accumulator ring quadrupole supply has caused a loss of a stack. Almost all other stack losses can be traced to human error or deliberate shutdowns.

The present average vacuum in the Accumulator is approximately $1.5x10^{-10}$ torr. With this pressure and the core cooling, the beam lifetime is in excess of eight days. Even at the present stacking rate of $.8x10^{10}$ antiprotons per hour the stack should reach the design Z/n limit of $100x10^{10}$ particles, if the only limitation was beam lifetime due to vacuum.

The tunes in the Accumulator have been adjusted to 6.611 .006 ν_x and 8.611 .006 ν_y over the entire momentum aperture. Thus during the entire stacking cycle, resonances up to order 13 are avoided. Figure 6 is a plot of Accumulator tune vs. momentum. In addition the sextupole driving term for the $2Q_y+Q_x=24$ resonance, which was viewed as the most troublesome systematic resonance, has be minimized by two sets of six quadrature sextupoles in zero dispersion.

The coherent transverse instabilities in the Accumulator have been reduced via two active transverse dampers. A recent failure of one of the dampers provided graphic evidence of the necessity of the damper system.[4]

Up to this point no ion instabilities or macro particle instability have been observed in the Accumulator ring. Because of the CERN experience with these problems, an extensive ion clearing system was installed in the Accumulator and special care to eliminate potential wells was incorporated in the vacuum system design.

Table 1 categorizes the performance of the source at the present time. As can be seen, all cooling and rf systems are working close to the design goals.[7,8,9] At present the stacktail system is not stressed to its design limit due to the reduced flux of antiprotons. Independent studies with proton have shown that the system will presently stack at 50% of the design goals and betatron heating of the core by the stacktail momentum is presently limiting the stack intensity to 50% of the design goal.[3]

The major missing factor exclusive of the Main Ring is item two. At present the reduced yield in the target station to Debuncher is believed to be due to a misestimate of the antiproton production cross section. Present studies with both the Cerenkov counter and the collimaters in AP-2 show the yield to be between a factor of 2 to 2 1/2 lower than design book number. If this proves to be true, with the addition of a tungsten target the source itself has a recoverable missing factor of only 1.7. Thus the antiproton source is working very close to its capability with the present design.

Table 1
$\bar{p}$ Source Stacking Rate

Stage	Design Report	Feb 87	Missing Factor Feb 87	Missing Factor Goal 87
MR Intensity on target	$2x10^{12}$	$1.2x10^{12}$	1.7	1.33
$\bar{p}$ production collection to Debuncher	$7x10^{7}$	$12.4x10^{6}$	3.4*	2.5

$\bar{p}$'s after bunch rotation in 0.2% δp/p	$7x10^7$	$10.3x10^6$	1.2	1.1
$\bar{p}$'s in Accumulator on injection orbit	$7x10^{10}$	$8.6x10^6$	1.2	1.1
$\bar{p}$'s on stacking orbit	$7x10^7$	$7.8x10^6$	1.1	1.1
$\bar{p}$'s in core	$6x10^7$	$6.7x10^6$	1.0	1.0
Cycles/hr	1800	1200	1.5	1.5
Stacking rate	$10.8x10^{10}$/hr	$0.8x10^{10}$/hr	13.5	6.7

*Includes factor of 1.25 due to use of copper target.

Acknowledgements

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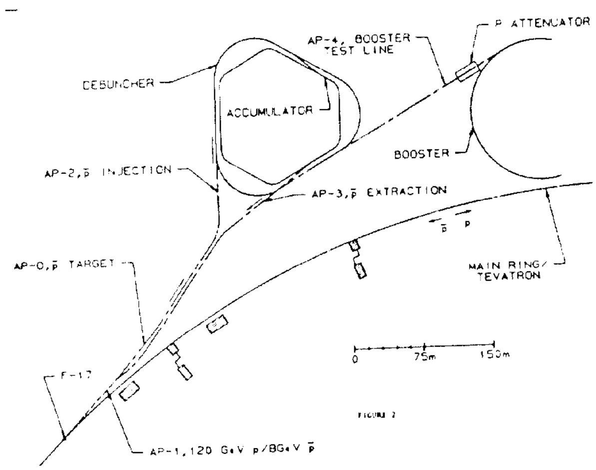

Figure 1. Antiproton Source Layout

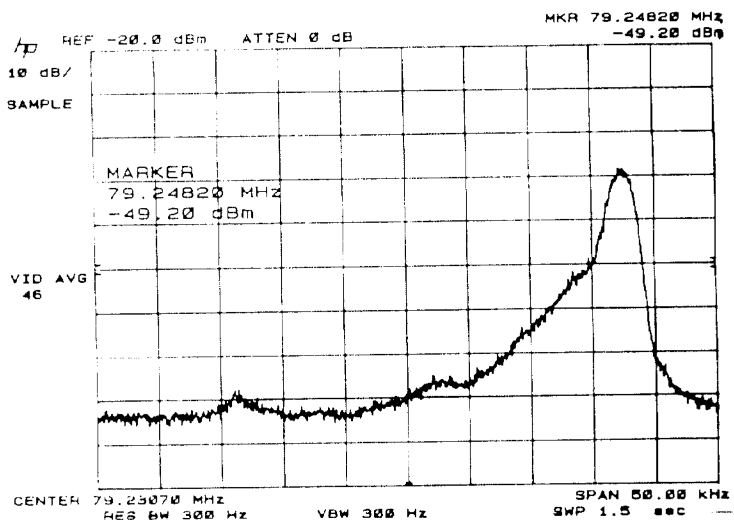

Figure 2. Accumulator Stack on Longitudinal Schottky

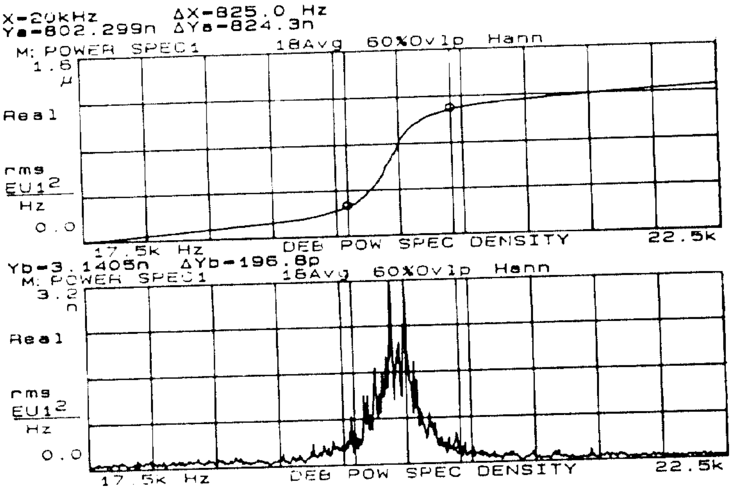

Figure 3. Debuncher Bunch Rotation Momentum Spread Display From Longitudinal Schottky.

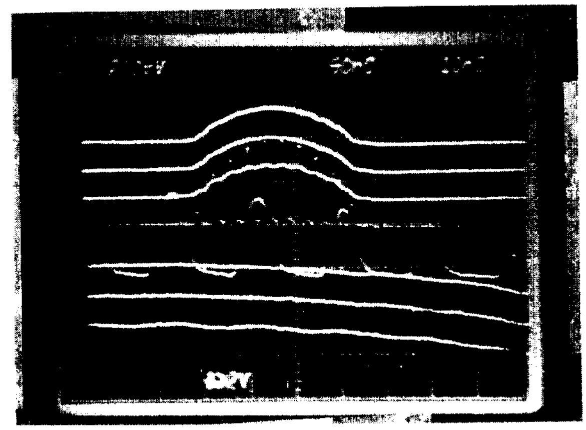

Figure 4. Prebunched Antiproton Beam Prior to Reverse Injection into the Main Ring.

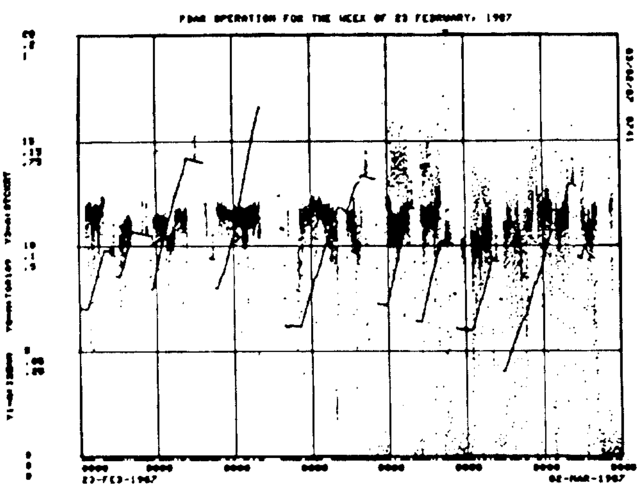

Figure 5. Antiproton Stacking Week Long Display

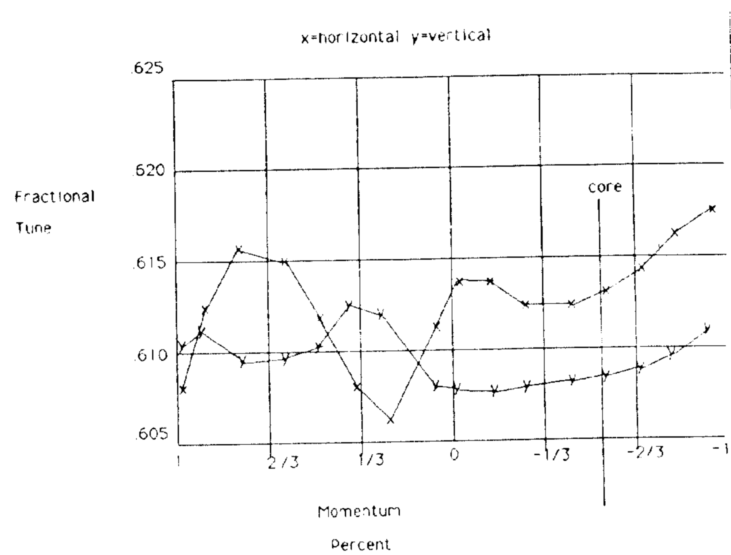

Figure 6. Tunes in Accumulator vs. Momentum