Antiproton Source Rookie Book

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The original Pbar Rookie Book was written by Jim Morgan in 1997 and used by operators for nearly ten years to familiarize themselves with hardware and operations of the Antiproton Source.

Due to numerous changes a new version was written by Jim Morgan, Brian Drendel, and Stan Johnson and presented to Operations in January of 2009.

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1 Introduction

High-energy physics is a branch of science that is concerned with the constituents of matter and their interactions. The particle accelerator is a tool that is used to help the high-energy physicist probe the structure of matter. An accelerator provides a high-energy beam of particles that can be used to unlock short-lived subatomic particles. For a number of years, the method of choice used by accelerator laboratories was to direct the beam of particles onto a stationary, or "fixed" target. In the 1970's a new method of creating the collisions was developed, colliding a beam with its antimatter counterpart in the same accelerator. By colliding beams of particles head-on, the center of mass energy of the collisions was doubled.

The first generation of colliders accelerated electrons and positrons. It wasn't until the early 1980's that CERN (The European particle accelerator laboratory Conseil Européan pour la Recherche Nucléaire, or "European Organization for Nuclear Research") first collided protons with antiprotons. Since the proton is much more massive than the electron, higher energy collisions could be achieved (although electron-positron collisions have the advantage of being much "cleaner"). The SPS accelerator at CERN was used as their first collider. The center of mass energy of the collisions was initially 540 GeV (270 GeV on 270 GeV), and then was later increased to 630 GeV (315 GeV on 315 GeV). With the switch to colliding beams, the SPS became the highest energy accelerator, surpassing Fermilab's Main Ring, which was then a 400, GeV fixed target machine. CERN wouldn't possess the highest energy accelerator for very long, installation work for the Tevatron was being completed back at Fermilab.

The Tevatron began operation as an 800 GeV fixed target machine in 1984, but the eventual goal was to use it as a proton-antiproton collider. Building on the CERN innovations and experiences, Fermilab began construction of its own antiproton source. The first colliding beams in the Tevatron were established late in 1985 during a study period following a Fixed Target Run. The Antiproton Source completed commissioning and the first Collider Run began in late 1986. With a center of mass energy that grew from 1.80 TeV (900 GeV on 900 GeV) to 1.96 TeV (980 GeV on 980 GeV), the world's highest energy accelerator was again found at Fermilab. CERN has since built and operated the LEP (Large Electron Positron) accelerator and has finished its successor, the LHC (Large Hadron Collider). The LHC, a proton-proton collider with an eventual center of mass energy of 14.0 TeV (7.0 TeV on 7.0 TeV), has ended the Tevatron's 20-year reign as the world's most powerful accelerator.

Luminosity is a measure of the rate of collisions at an experiment. Through a series of improvements to Fermilab's accelerators, there has been a steady increase in the Tevatron's luminosity since 1986. During the 1988-89 Collider Run, the design luminosity of $1.0\text{x}10^{30}\text{cm}^{-2}\text{sec}^{-1}$ was achieved. Since that time the luminosity has increased by a factor of nearly 300, surpassing $3.0\text{x}10^{32}\text{cm}^{-2}\text{sec}^{-1}$.

The largest bottleneck in a proton-antiproton collider is the time required to accumulate an adequate number of antiprotons. The process is inherently inefficient, typically for every 10^5 protons striking a target, only about 2 antiprotons are captured and stored. Considerable time and money has been spent improving the accumulation rate. Between the first Collider Run and Collider Run 1b, the peak stacking rate improved by an order of magnitude. Between Run 1b and Run II, there has been another factor of 3 increase in the peak stacking rate (and a factor of 5 increase in the average stacking rate with the use of the Recycler). Despite the improvements, it still takes hours to build up a suitable stack to use for a colliding beams store. The performance of the Antiproton Source and Recycler greatly affects the quality and duration of stores in the Tevatron.

The FNAL Antiproton Source is comprised of a target station, two rings called the Debuncher and Accumulator and the transport lines between those rings and the Main Injector. The following sequence of events is repeated to accumulate enough antiprotons for a proton-antiproton colliding beams store.

- Every 2.2 seconds or so, a "slip-stacked" single batch of protons with an intensity of $8\text{x}10^{12}$ or more is accelerated to 120 GeV in the Main Injector. The Main Injector cycle is usually shared with NuMI

- At Main Injector flattop, the 82 or so bunches contained within the batch are rotated 90° in longitudinal phase space. The rotated bunches are extracted from the Main Injector and travel down the P1, P2 and AP-1 line

- Quadrupoles at the end of AP-1 focus the beam to a very small spot as it enters the Target Vault. The beam strikes the Inconel production target in the Target Vault and produces a shower of secondary particles

- The resulting cone of secondary particles is focused and rendered parallel by means of a lithium lens. The bunch structure of the beam coming off of the target is the same as that of the primary proton beam

- A pulsed dipole magnet bends all negatively-charged particles that have a kinetic energy of approximately 8 GeV into the AP2 line. Most of the other particles are absorbed within a beam dump

- Particles that survive the journey down the AP2 line are injected into the Debuncher, where the momentum spread of the 8 GeV antiprotons is reduced through bunch rotation and adiabatic debunching. Both betatron (transverse) stochastic cooling and momentum (longitudinal) cooling is applied to reduce the beam size and momentum spread

- Just before the next pulse arrives from the target, the antiprotons are extracted from the Debuncher and injected into the Accumulator via the D to A line. Successive pulses of antiprotons are stacked into the Accumulator 'core' by means of RF deceleration and stochastic momentum cooling. The antiprotons in the core are maintained there by betatron and momentum stochastic cooling systems

- Periodically, enough antiprotons have been accumulated to initiate a transfer via the Main Injector to the Recycler. Groups of 4 bunches of antiprotons are unstacked from the densest portion of the stack known as the core. The pbar bunches are extracted from the Accumulator, and transported to the Main Injector via the AP3, AP1, P2 and P1 lines. After a small energy adjustment in the Main Injector, the antiprotons are transferred to the Recycler.

2 Antiproton Production

Main Injector's role

Bombarding a production target with a high energy proton beam produces antiprotons. The pbar production rate is dependent on the incident proton beam energy, the desired pbar energy, the type and length of target material and, to a much lesser extent, momentum spread. The collection efficiency is dependent on the beam spot size on the target, the gradient of the Lithium Lens and the acceptance of the beamline. The beam spot size affects the apparent size of the area from which the secondaries emanate from the target. A smaller proton beam spot results in the cone of pbars being more densely packed together.

An increase in the proton beam energy will result in an increase in yield, but by a diminishing amount after a certain energy threshold is passed. The Antiproton Source was designed for a pbar beam kinetic energy of 8 GeV, since that is the peak Booster energy and was the injection energy for the old Main Ring. Also, the peak in pbar production from a 120 GeV proton beam is close to 8 GeV. A higher energy proton beam will increase pbar yield, but a beam energy of 120 GeV is the best compromise between targeting efficiency, cycle time, and design constraints for the transport line. Prior to its decommissioning, the Main Ring was capable of delivering 120 GeV protons with up to a 2 second cycle time. The Main Injector was built, in part, to reduce the cycle time. Unfortunately, stochastic cooling limitations kept the Antiproton Source from taking advantage of the shorter cycle times. The Main Injector Design Report called for an intensity of 5×10^{12} protons per stacking cycle with a 1.5 second cycle time. With the implementation of "slip stacking," the Main Injector has been able to deliver 8E12 or more protons per stacking cycle. Running the Main Injector in "mixed-mode", where beam to NuMI and Pbar are accelerated together, now limits the cycle time to no shorter than 2.2 seconds.

A single Booster batch comprised of 84 53 MHz bunches (there are actually fewer bunches due to the Booster extraction process) is accelerated in the Main Injector on stacking cycles. Two Booster batches are slipped in time in the Main Injector to effectively double the number of injected protons. Radio Frequency (RF) manipulations are performed on the beam at 120 GeV, just prior to extraction from the Main Injector, in a procedure known as bunch rotation. This process, described below and shown in figure 2.1, narrows the bunches in time at the expense of increasing the momentum spread (Δp/p). The Δp/p of the antiprotons is minimally affected by the Δp/p of the protons hitting the target. By narrowing the bunches prior to extracting them from the Main Injector, the phase space density of the antiprotons is maximized, resulting in a smaller Δp/p in the Debuncher ring after bunch rotation and momentum cooling.

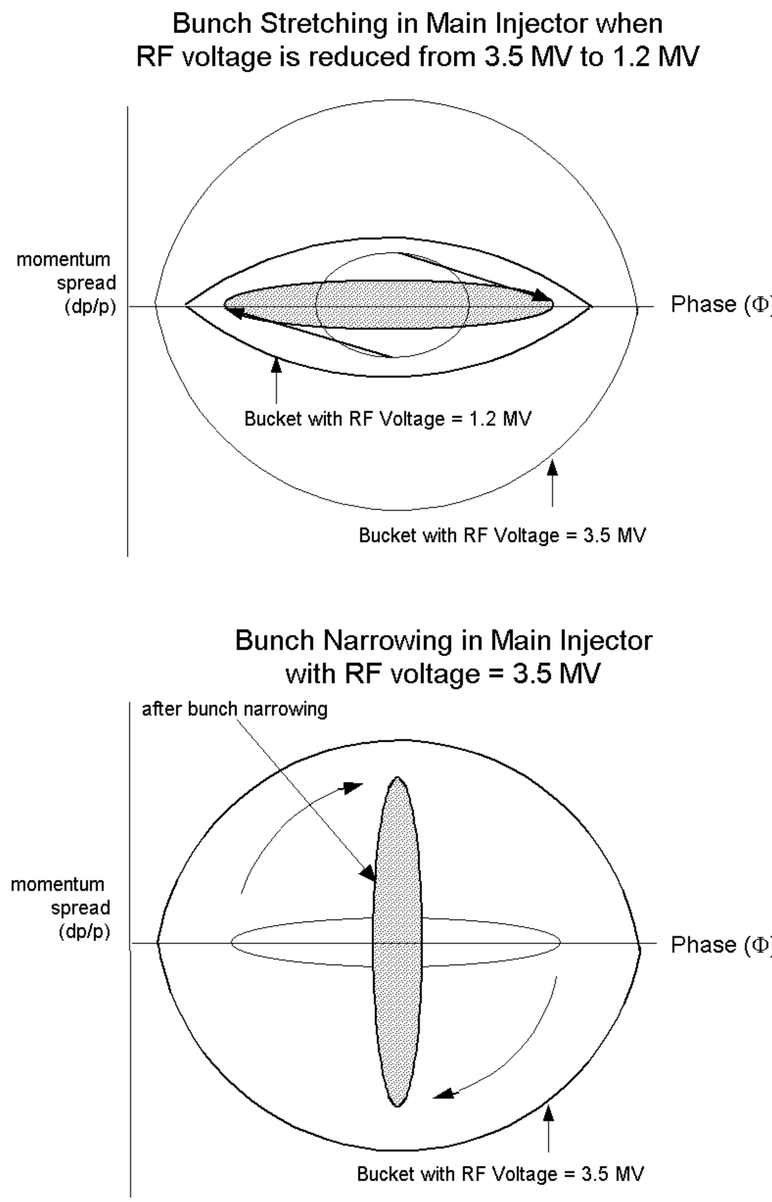

Figure 2.1: Main Injector Bunch Rotation

Once the beam reaches flattop in the Main Injector, the RF voltage is quickly lowered to 1.2 MV from its normal value of 3.5 MV by turning off 12 of the 18 RF stations. The RF is left at 1.2 MV for about 1.9 milliseconds while each bunch stretches in time, occupying a large time spread and small momentum spread. The RF is then quickly increased back to 3.5 MV. One quarter of a synchrotron oscillation or approximately 1.2 milliseconds later, the bunch has rotated 90° in phase space, reversing the time and momentum spread.

After bunch rotation, the beam is extracted from the Main Injector towards the pbar production target. The proton bunches have a small time spread and a large momentum spread. The extraction process is completed in a single turn by a fast rise time kicker located at MI-52, which kicks beam into the field region of a set of three Lambertson magnets. The extracted beam travels down the P1 line, continuing into the P2 line in the Tevatron enclosure at F0, and then follows the path of the decommissioned Main Ring to F17. At F17 a B3 magnet and a pair of C-magnets bends the beam upward into the AP-1 line. The AP-1 line exits the Tevatron enclosure at F18 and continues through the Pre-Target and Pre-Vault enclosures before reaching the production target in the Target Vault. A pair of "Sweeping Magnets" are located in AP-1 at the end of the Pre-Vault enclosure and are used to minimize peak heating in the production target. A toroid, M:TOR109, is located in the AP-1 line in the narrow space between the Sweeping Magnets and the Target Vault wall to provide a measure of beam intensity at the production target.

Target Station

The actual production and collection of antiprotons occur in a specially designed vault located 17 feet below the floor of the AP0 service building. The Target Station components are hung from 6-foot high steel modules that are suspended into the Vault. This arrangement allows easy removal and replacement of faulty components and the steel provides radiation shielding. The major components as seen by the incoming proton beam are:

Upstream sweep magnets

This system is actually located just upstream of the Target Vault, in the Pre-Vault enclosure. It was included here because it is functionally part of the Target Station and was designed to have components in the Vault itself. The Sweeping System has magnets that produce a rotating dipole field that deflects the proton beam in a roughly circular pattern on the target to minimize local heating. Antiproton yield increases with a smaller spot size down to a beam σ of about 0.13 mm, but increases the peak heating on the target. A proton beam intensity of 5E12 or more causes the loss of target material around the outside circumference of the target. The Sweeping System only moves the beam a few σ's, enough to reduce the local heating by about a factor of 2-3. Use of the Sweeping System only slows the rate of target deterioration, which is caused by a complex combination of oxidation, thermal and mechanical effects. The original Sweeping System design included a downstream Sweeping Magnet to create a closed orbit bump through the target vault. It was to be located immediately downstream of the Lithium Lens. The downstream Sweeping Magnet has not been used operationally because of the complexity and reliability related to running the two systems synchronously. Use of the upstream system alone was found to have a minimal negative impact on the stacking rate.

Target SEM grid

The Target SEM (Secondary Emission Monitor) is used to measure the beam position and size near the target. Central wires in the SEM are only 0.125 mm apart to provide good resolution measurements of the spot size. The SEM has motion control to move the wires out of the beam path during normal operation. Beam intensity of more than about 4×10^{12} could melt the SEM wires. Even when the target SEM is in the "out" position, the beam is only about 5mm from the wires, so grossly missteered, high intensity beam could still damage the wires. The SEM is under vacuum with a small, dedicated ion pump providing the pumping.

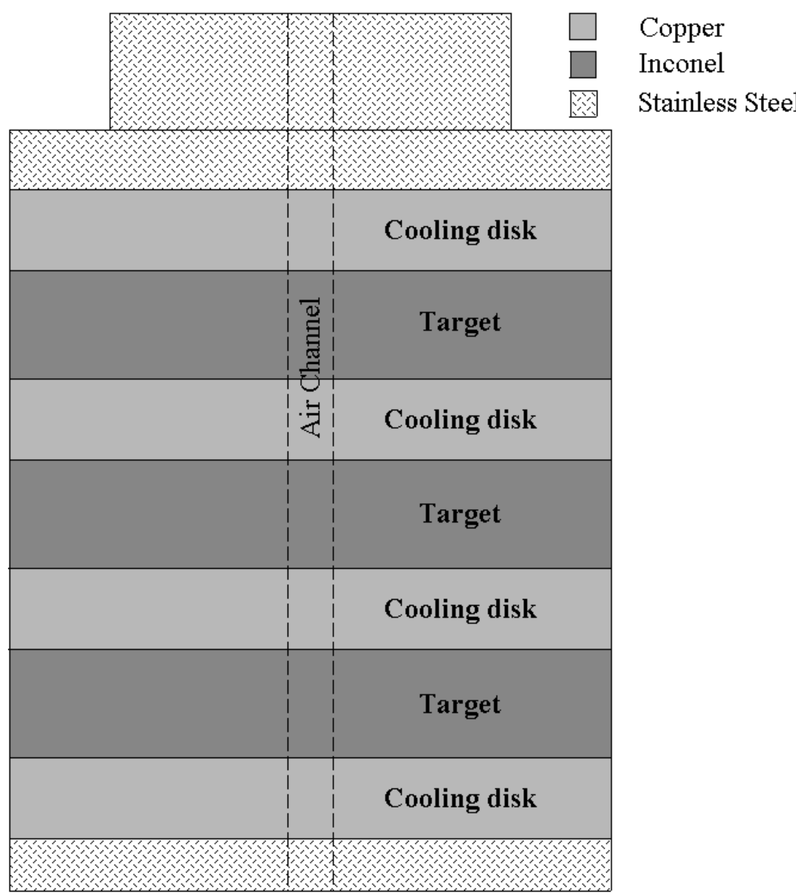

Figure 2.2: Pbar Production Target

Target assembly

The Target design has had a number of improvements over the years and has recently gone through another revision. The old design was made up of a stack of metal target disks, separated by copper cooling disks that had air blowing through them to provide heat removal from the targets. In the past, the target has almost always incorporated alternating target and cooling disks. Tungsten targets were used in the early years of pbar operation, followed by targets of copper, nickel and eventually Inconel (a nickel-iron alloy). Inconel was chosen as the best choice of target material because it can withstand higher stresses caused by the rapid beam heating. Figure 2.2 shows the cross section of the old target assembly used after 2006, but prior to the new design. The new target design is made of a single cylinder of Inconel, with air blowing through a heat exchanger incorporated into the center shaft. A shell of beryllium provides a cover for the Inconel target, to reduce target oxidation and damage. Since the target design is still evolving, an illustration won't be available until the design is finalized.

Horizontal Target Position

The horizontal target position is adjustable (D:TRX) so that the amount of target material the beam passes through can be varied. This distance, known as the target length, is one of the parameters that determine the antiproton yield. The target assembly is rotated so that target damage is minimized – depletion of the material is distributed more uniformly through the entire target. The rotation rate can be varied, but typically takes less than a minute to complete a revolution. Vertical motion control (D:TRY) makes it possible to adjust where beam hits the target or change the target disk in use. The position of the target in the z axis (D:TRZ), the distance between the target and lens, can be adjusted to match the diverging cone of secondary particles to the focal length of the Lithium Lens.

Lithium Lens

Immediately downstream of the target module is the Lithium Lens module. The lens is designed to focus a portion of the 8 GeV pbars coming off of the target, greatly reducing their angular component (as illustrated in figure 2.3). Electric current passing through the cylindrical lithium conductor produces a magnetic field that has strength approximately linear with radius that focuses the 8 GeV pbars. The Lithium Lens has the advantage over conventional quadrupoles in that it focuses in both transverse planes and produces an extremely strong magnetic field. The main disadvantage of the lens is that beam passes through the beryllium end windows and lithium conductor, resulting in about 18% of the antiprotons being absorbed. The beryllium and lithium also cause some scattering of the pbar beam, increasing the beam size. Lithium was chosen because it is the least-dense solid conductor, which in turn minimizes the scattering and absorption.

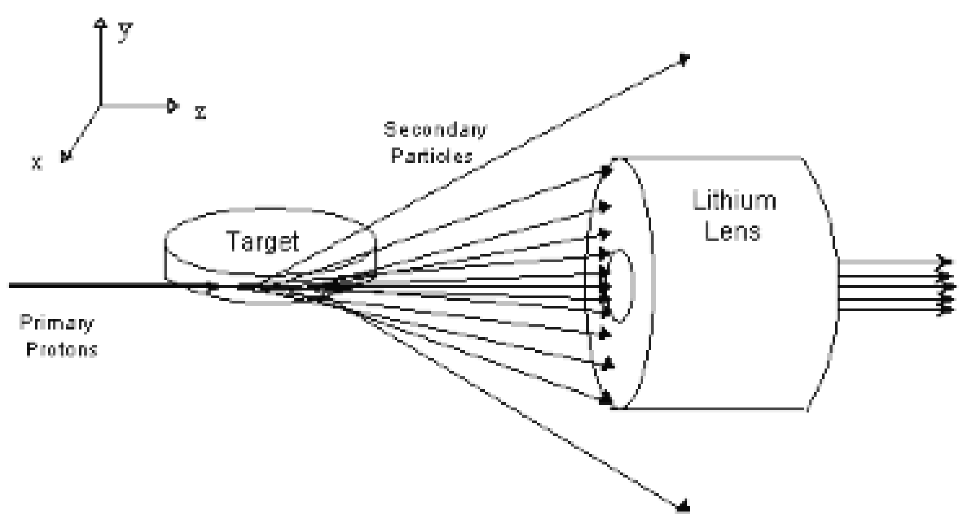

Figure 2.3 Pbar Lithium Lens

The lens is contained within a toroidal transformer and is designed to operate at a peak current of 650,000A for a gradient of 1,000 Tesla/meter (operationally lenses are run at a lower gradient to prolong their life). The transformer is used to step up the current received from the power supply (D:LNV) by a factor of 8 in order to achieve the current required. The lithium conductor is 15 cm long and

2 cm in diameter. The lens and transformer are cooled with a closed loop cooling system. Low Conductivity Water (LCW) from the closed system is heat exchanged with chilled water. A pair of eccentric shafts, which can be used to vary the position and angle of the Lithium Lens, provides horizontal motion control. The entire lens assembly can also be moved vertically.

Collimator

This device is used to reduce heating and radiation damage to the Pulsed Magnet, which is located immediately downstream of the Collimator. The Collimator is cylindrical in shape and made of copper, with a hole in the middle for the beam to pass through. Water cooling lines are located on the outside of the Collimator to remove heat and are connected to the Pulsed Magnet water system. Use of the Collimator, designed and implemented during Run II, was in response to reduced Pulsed Magnet survival rate as the intensity of the primary beam increased.

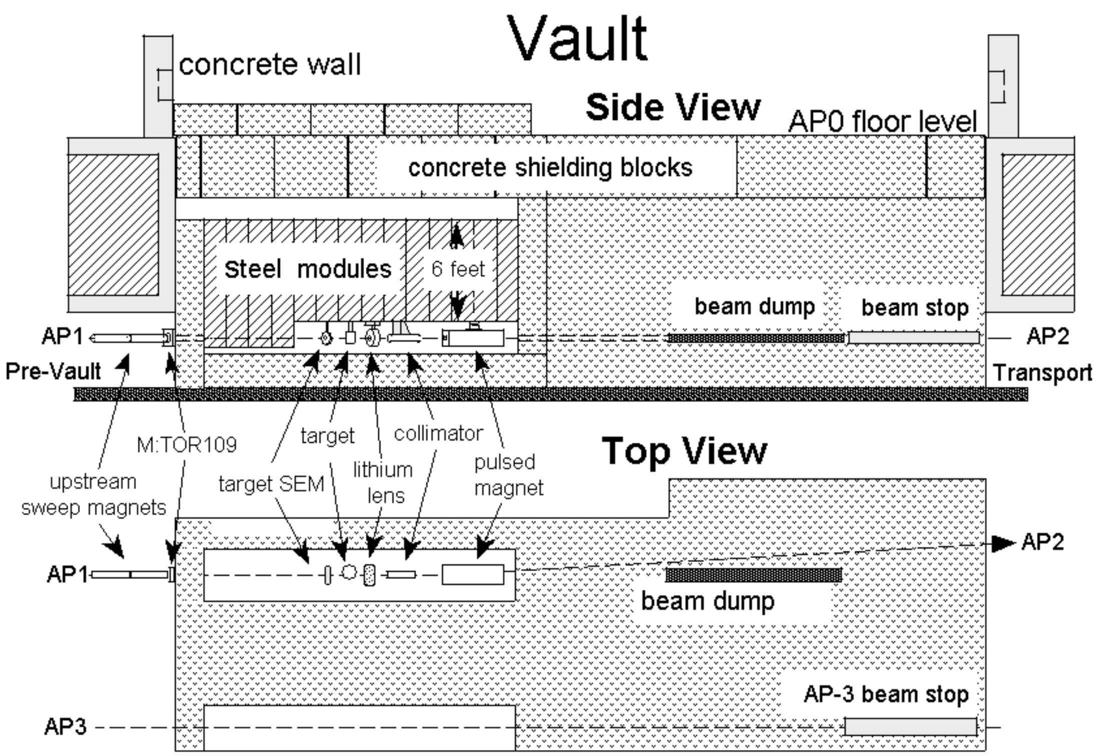

Figure 2.4, Target Vault Layout

Pulsed Magnet

Figure 2.4 shows the location of the Pulsed Magnet and other devices located in the Target Vault. The Pulsed Magnet is a 3-degree pulsed dipole that is located downstream of the Collimator. Its purpose is to select 8 GeV negatively-charged secondaries and bend them into the AP-2 line. The dipole was designed specifically for the Target Vault and is a single-turn, radiation-hardened, water-cooled, 1.07 m long magnet with an aperture measuring 5.1 cm horizontally by 3.5 cm vertically. Radiation hardening is achieved by using ceramic insulation between the magnet steel and the single conductor bars as well as using Torlon as the insulating material on the bolts that hold the magnet together. The pulsed magnet achieves a field of 1.5 Tesla.

Beam dump

Most of the particles not momentum and charge-selected by the Pulsed Magnet are absorbed in the Beam Dump. The dump is modeled after the Tevatron abort dump, with stacked steel and concrete and a water-cooled dump core in the beam path. The graphite core is encased in an aluminum shell that contains water cooling passages. A channel through the steel shield provides an exit for the 8 GeV negative beam and allows it to pass into the AP-2 line. The downstream end of the dump also contains a beam stop for the AP-3 line (D:BSC925) that is a safety system critical device and is remotely operable. The AP-2 beam stop (D:BSC700) was originally located in the dump, but was relocated to the Transport enclosure to improve aperture in the channel through the dump steel.

3 Debuncher

Function

The purpose of the Debuncher is to accept pulses of antiprotons from the AP-2 line and to reduce their momentum and transverse phase space for efficient transfer to the Accumulator. The momentum spread is initially reduced by RF bunch rotation and adiabatic debunching and further reduced by stochastic cooling. Horizontal and vertical betatron stochastic cooling systems reduce the transverse beam size. Without bunch rotation and the cooling systems, transfer efficiency between the Debuncher and Accumulator would be very poor. Also, ARF-1 and the stacktail momentum cooling system in the Accumulator are more efficient when the pbars have a small momentum spread. The cooling systems use the time between Main Injector extractions to cool the beam.

Lattice

The Debuncher 'ring' is a rounded triangle and is divided into 6 sectors numbered 10-60. Each sector contains 19 quadrupoles and 11 dipoles. Other magnetic devices include correction dipoles and sextupoles. There are three straight sections – 10, 30, and 50, which are located directly beneath service buildings AP10, 30 and 50 respectively. The straight sections are regions of low dispersion while the arcs are dispersive regions. A typical cell in the arcs is comprised of an F-quadrupole with similarly oriented sextupoles on either side followed by a dipole or drift region, then a D-quadrupole also surrounded by sextupoles of the same convention and another dipole or drift region (Figure 3.1). This is referred to as a “FODO” lattice. As is the case with straight sections in other Fermilab accelerator rings, the Debuncher straight sections contain an assortment of specialized components. The following devices populate straight section 10: the extraction septum for the D/A line, a gap monitor, the longitudinal Schottky, the DCCT, damper pickups and kickers and stochastic cooling pickup tanks. Stochastic cooling kickers and the IPMs are found in the 30 region. The 50 area is home to the AP2 line injection devices and to all of the Debuncher's RF cavities.

The numbering scheme has a pattern, but not an obvious one at first glance. For example, D10Q is the first quadrupole in sector 10 (it is located in

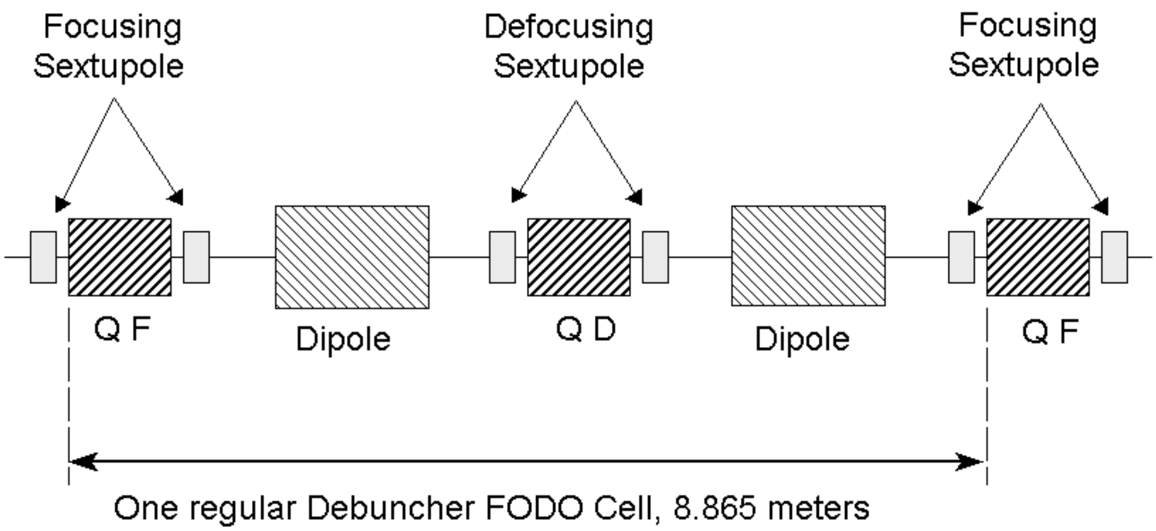

Figure 3.1: Debuncher lattice in the Arcs

the middle of straight section 10) and is followed by D1Q2 and D1Q3. Dipoles are numbered similarly – D1B16 is the dipole following D1Q16. Correction dipoles are labeled according to the quadrupole they precede. Things get tricky in the even-numbered sections due to the mirror symmetry of the Debuncher lattice. The final quadrupole in D10 is D1Q19, and the next quad is D20Q (located in the center of the arc), followed by D2Q19, D2Q18, etc. Thus, in the direction of an antiproton beam, numbers increase in odd-numbered sectors and decrease in even-numbered sectors. The same general numbering scheme also holds true for the Accumulator, although there are fewer elements.

Power supplies

There are six major magnet strings in the Debuncher. Three supplies located in AP10, D:QD, D:QF, and D:QSS power the three quadrupole strings. D:QD powers all of the defocusing quads from DnQ6 to DnQ6 (with the exception of D6Q6, which has its own power supply). Recalling that the Debuncher lattice is FODO, D:QF powers the focusing quadrupoles outside of the straight sections, from DnQ7 to DnQ7. D:QSS is the power supply for the Debuncher quads in the straight sections, DnQ5 to DnQ5 (see figure 3.2), with the exception of D2Q5, D4Q4 and D4Q5 (which have their own power supplies). All of the 3 location quadrupoles on the QSS bus are individually controlled by means of shunts. There are also a number of other quadrupoles, located at various locations, which have shunts. These shunts are used for measurements and lattice adjustments. The Debuncher tunes are changed by adjusting the main quadrupole power supplies in predetermined ratios (mults).

All of the main dipoles are in series and powered by D:IB, the Debuncher bend bus power supply. This supply is a very large PEI located in AP50 just inside of the west entrance. Three special quadrupoles are also powered by D:IB in conjunction with individual smaller power supplies. These are the large quads at D2Q5, D4Q5, and D6Q6. These locations need a quadrupole in the lattice, but the small quadrupoles normally at these locations don't have a large enough aperture to accommodate both the ring and injection or extraction beampipes. The solution was to install a large quadrupole with two beam pipes through the available aperture. The centered beam pipe is for circulating beam. The offset pipe is for injected/extracted beam, which receives a substantial steering kick because of the beam's displacement. In addition to being powered by D:IB, each of these magnets also has its own trim supply named D:QT205, D:QT405, and D:QT606 respectively. The large quadrupoles require significantly more current to produce the same field as a small quadrupole. Whereas D:QF and D:QD deliver about 240A of current, the combination of D:IB and the quadrupole trim supplies produces about 1,500A.

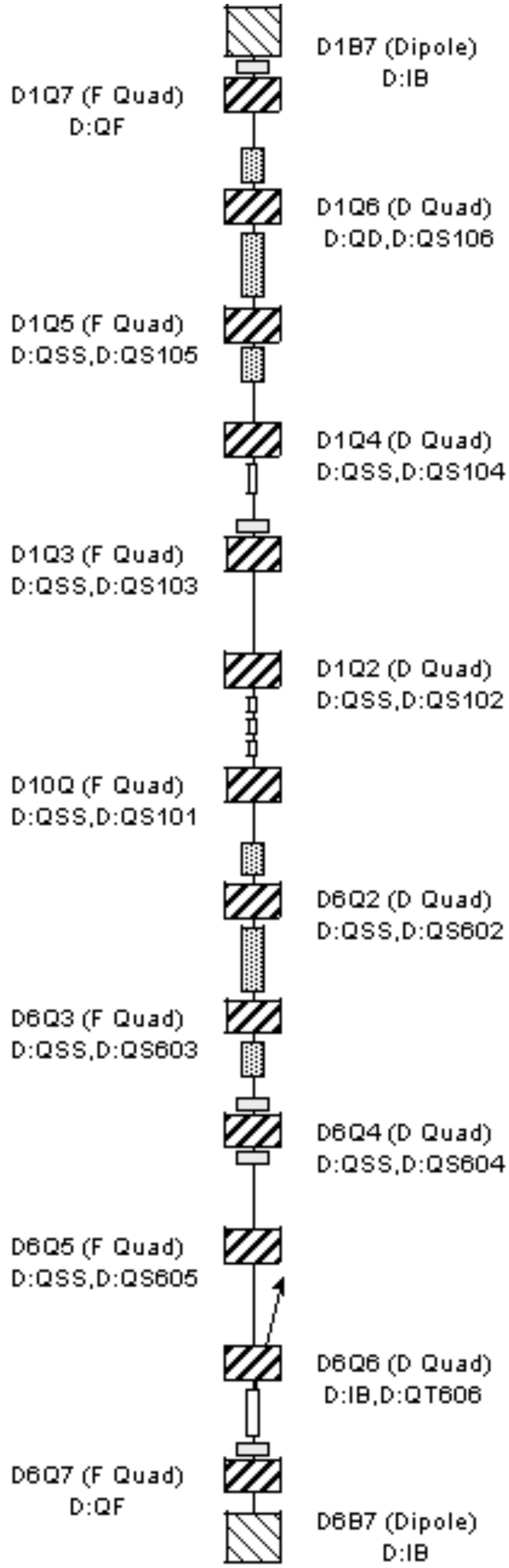

Figure 3.2 D10 straight section

Additional shunts were added to many of the quadrupoles in the dispersive arcs in 1995. These shunts, in combination with the shunts in the straight sections, were originally intended to be used as a "Γ_T jump". The plan was to ramp the shunts so that the lattice (specifically the beam parameter “eta”) could be altered to switch between a lattice conducive to bunch rotation to one that improves the performance of the stochastic cooling. During development it was found that power supply regulation problems resulted in tune excursions and excessive beam loss. Since potential gains from this scheme were expected to be modest anyway, it was abandoned. However, after considerable rearrangement and appropriation of these shunts, they were later used to create a modified lattice that improves the aperture of the Debuncher. Arc quadrupoles at the DxQ8,10,11 and 14 locations currently have shunts.

Sextupoles are included in the Debuncher lattice to provide chromaticity control. All of the sextupoles are powered in series on two separate buses by four supplies. Sextupoles on either side of an 'F' quad are powered by D:SEXFI and D:SEXFV. Neither supply has sufficient voltage to drive the entire string on its own, so the two supplies are powered in series to provide the necessary voltage. The D:SEXFI supply handles the current regulation. D:SEXDI and D:SEXDV do the same thing for the 'D' sextupoles.

Correction dipoles have been placed around the Debuncher to provide fine orbit control of the beam. These elements are powered by 25 Amp bipolar supplies and have been strategically placed to provide position and angle control at the extraction and injection points of the Debuncher, stochastic cooling pick-ups and locations with tight apertures.

There isn't enough room in the lattice to place correction dipoles at every location that they are needed. In addition, some correctors had to be removed when larger stochastic cooling tanks were installed at the beginning of Run II. Motorized quadrupole stands were installed to provide orbit control through quad-steering. Dozens of the motorized stands are distributed throughout the Debuncher and can be used independently or in combination with trims to adjust the orbit in either plane. There is also a single bend shunt, D:BS608, attached to the D6B8 main dipole magnet. Shunting current around the dipole has the effect of a horizontal trim and was formerly used to provide orbit control at the extraction septum

RF systems

Three radio frequency (RF) systems are employed in the Debuncher: DRF-1, DRF-2 and DRF-3. Table 3-1 summarizes the RF frequency, harmonic number, peak voltage and low level inputs for each system. Note that the same frequency Digital to Analog Converter (DAC) is common to all three systems.

System	Freq.	Harm.	Peak Voltage	Amplitude	Frequency
DRF-1	53.1 MHz	h=90	5.1 MV	DAC (D:R1LLDA) 164 card (D:R164AM)	DAC (D:R1LLFR) Lock to MI LLRF
DRF-2	2.36 MHz	h=4	500 V	DAC (D:R2LLAM)	DAC (D:R1LLFR)
DRF-3	2.36 MHz	h=4	800 V	DAC (D:R3LLAM) 164 card (D:R364AM)	DAC (D:R1LLFR)

Table 3.1: Debuncher RF systems

DRF-1

DRF-1 is a 53.1 MHz system (h=90) used for bunch rotation and adiabatic debunching of antiproton pulses injected into the Debuncher. Recall that bunch rotation in the Main Injector shortens the proton bunches in time. This bunch structure is maintained by the pbars created in the target station. DRF-1 accepts the short (in time) pbar bunches coming from the target, then rotates them in phase space, resulting in bunches of antiprotons with a large time spread and a small momentum spread. The beam is then adiabatically debunched over 4 milliseconds by lowering the RF voltage.

There are a total of eight DRF-1 cavities of two varieties: six so-called 'Rotators' and two 'Adiabatic' cavities. The six rotator RF cavities are able to operate at a peak voltage of approximately 750 - 950 kV each. In order to rapidly reduce their voltage, the RF drive signal is inverted just long enough for the fields in the cavity to be forced to zero (drive down). This rapid reduction in voltage is necessary in order for the cavities to quickly pass through the range where they may multipactor, or spark. As the voltage on the six main cavities is reduced, the voltage on the other two cavities is slowly lowered from 100 kV to achieve debunching. These adiabatic cavities are of a somewhat different design to prevent multipactoring. The modifications consist mainly of a ceramic accelerating gap to isolate the beam pipe vacuum from the air in the cavity. This ceramic limits the peak voltage across the gap to about 150 kV. Figure 3.3 shows the total DRF-1 voltage during the debunching process. Note the vertical scale, the voltage is briefly increased by a factor of 50 when the rotator cavities pulse.

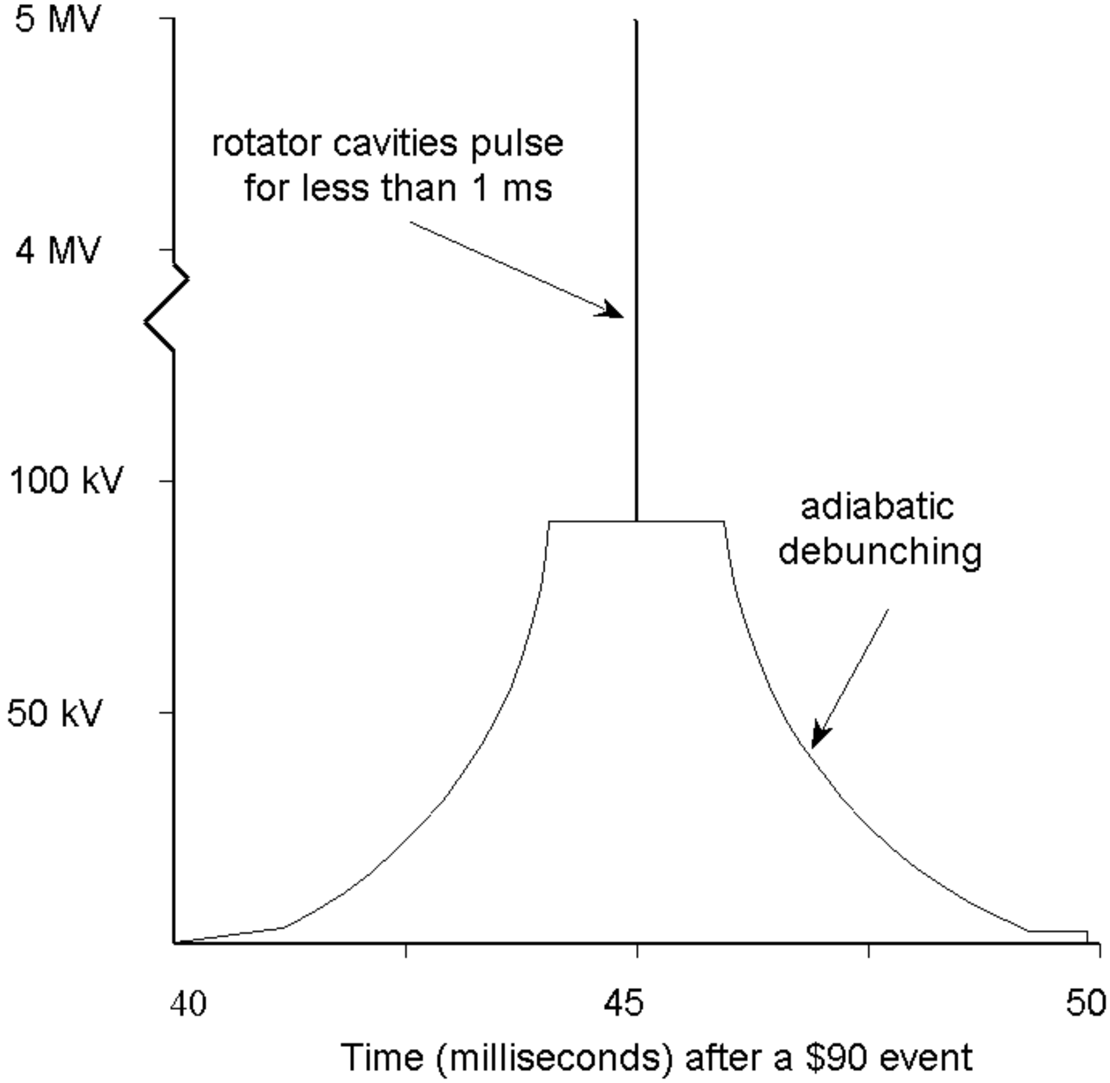

Figure 3.3: DRF-1 cavity voltage during bunch rotation

DRF1 is initially phase-locked to MIRF to provide for a bucket-to-bucket transfer. The 8 GeV secondary particles created at the target retain the same bunch structure as the 120 GeV protons. The DRF1 rotator cavities are powered just before beam arrives in the Debuncher. When timed correctly the RF will reach peak voltage at the time beam is injected, then they are rapidly turned off during drive down. The large bucket area creates a mismatch, as the bucket is much larger than the phase space area of the beam. The rotator cavities only pulse for approximately 200 µs (.2 ms) compared with the 10 ms that the adiabatics are on. The adiabatics are also pulsed briefly towards the end of the stacking cycle for diagnostic purposes. The beam is bunched so that Debuncher BPMs can measure beam intensity.

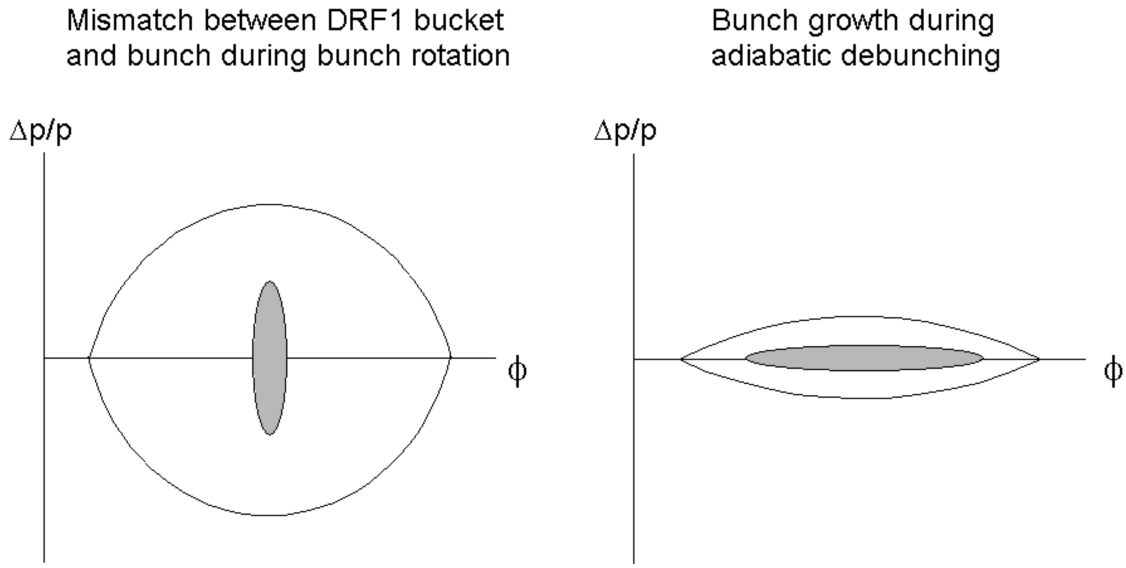

Figure 3.4 Bunch rotation in the Debuncher

Because of the mismatch at injection between the beam and the RF bucket, the bunches rotate as illustrated in figure 3.4. The bunches continue to rotate during rotator cavity drive down and have rotated about 45° in phase space by the time the rotators have turned off. The bunches rotate the final 45° during the adiabatic debunching process. Note that the rotator cavities pulse for only 200 μs but put out a collective 5.0 MV. The two adiabatic cavities are on for about 5 ms after injection, but only put out a combined 100 kV before the voltage is gradually lowered.

The RF amplitude for DRF1 is divided into separate control for the rotator and adiabatic cavities. The adiabatics are normally controlled by a waveform generator (CAMAC 164) card but can also be run Continuous Wave (CW) with a DAC. The RF amplitude that the rotator cavities are pulsed to is controlled by a series of 6 DACs, one for each cavity. Normally, the rotator cavities are tuned to put out as much voltage as possible to maximize bunch rotation efficiency.

The frequency reference comes from a Voltage Controlled Oscillator (VCO). During stacking, the VCO is initially phase-locked to the Main Injector RF and stays at a fixed frequency. This frequency is generally set at the beginning of a running period and remains unchanged. At this writing, the DAC is set to 53.101625 MHz. Since DRF1 is an H=90 system, this corresponds to a revolution frequency of 590,018 Hz. It is important that the beam injected into the Debuncher from the Main Injector has this revolution frequency as DRF1 and the momentum cooling will not work as well if the frequencies vary significantly.

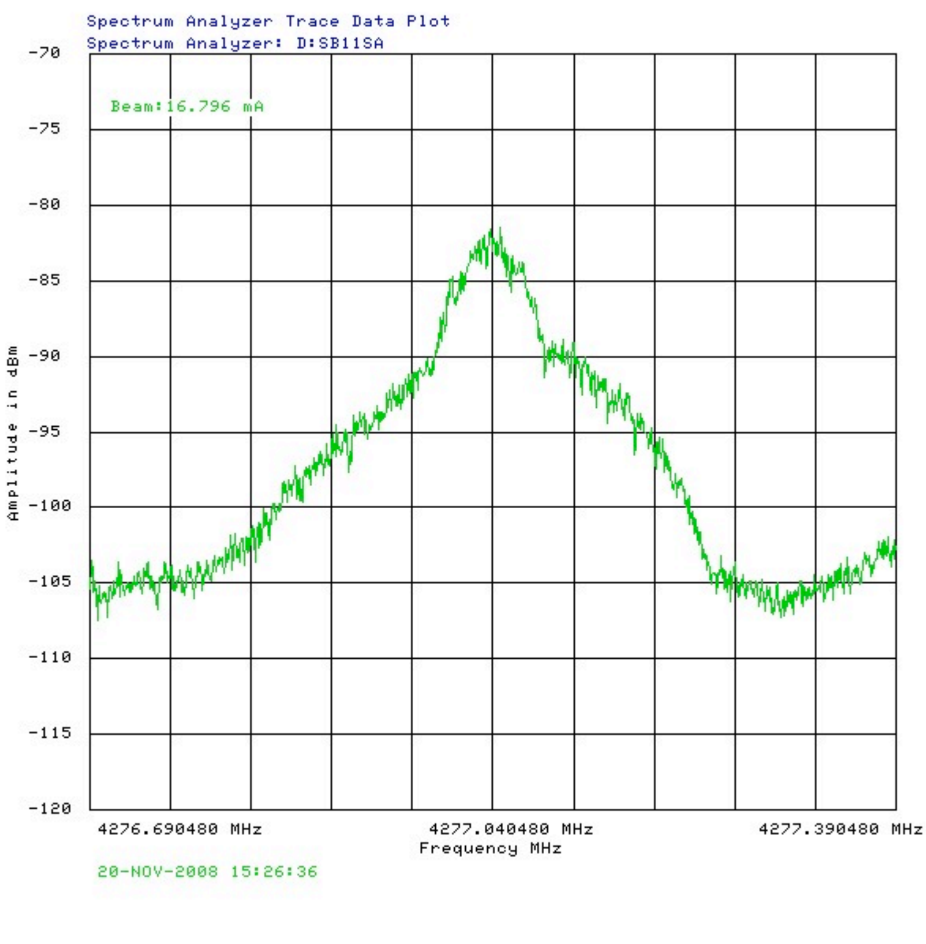

Figure 3.5: Debuncher bunch rotation spectrum analyzer display

There presently isn't a good quantitative way to determine how efficient the bunch rotation process is. Figure 3.5 shows a typical spectrum analyzer display of the frequency distribution of the Debuncher beam. The signal comes from a cooling pickup, so the frequencies displayed are harmonics of the revolution frequency in the microwave range. This display can be used as a qualitative measure of how well the bunch rotation process is working. Two DRF-1 parameters can be tuned to maximize the bunch rotation efficiency. D:R1LLPS is the phase offset between the Main Injector and Debuncher low level RF and is tuned to optimize bucket to bucket transfer. D:R1LLMT is the master trigger time and controls when the DRF-1 rotator cavities are pulsed. By synchronizing the peak RF voltage (and bucket area) to the arrival of the beam, capture can be maximized. A narrower distribution on the spectrum analyzer display, available on Cable Television (CATV) Pbar channel 20, indicates more efficient bunch rotation. Beam quality in the Main Injector is also important. A program called the “Proton Torpedo” on page P194 is used to check Main Injector longitudinal beam quality.

DRF-2

The Debuncher circumference is larger than that of the Accumulator (and the Booster) by 7.1%. The Debuncher 53 MHz harmonic number is 90, while the Accumulator's is 84. Maintaining a gap in the Debuncher beam optimizes Debuncher to Accumulator transfer efficiency. This is so that upon transfer, the beam just fits around the circumference of the Accumulator. When properly timed, the Debuncher extraction kicker rises in the gap. The 200 nanosecond gap (compared to the revolution frequency of 1.69 μs) is preserved by DRF-2, which forms a 'barrier bucket' that excludes particles from its interior. DRF-2 is timed to preserve the gap between the leading and trailing pbar bunches entering the Debuncher.

The period of the applied RF wave is one quarter of the Debuncher rotation period, making it an h=4 system. The nominal frequency is thus 2.36 MHz. The gap electrodes are phased apart for one RF cycle during each revolution, then phased together for the remaining 3/4 revolution for zero effective voltage. The fact that the accelerating field is suppressed for part of each revolution is the reason this type of radio frequency system is known as a 'suppressed bucket' RF system.

Referring to figure 3.6, a normal RF bucket keeps the particles within the bucket by accelerating low momentum particles and decelerating high momentum particles. In the barrier bucket example, the phase of the RF wave is shifted 180° to push beam out of the bucket. Higher momentum particles are accelerated upon entering the barrier bucket region and lower momentum particles are decelerated, which effectively excludes beam from the barrier bucket.

DRF-2 has a DAC that provides the amplitude program (D:LLR2AM). DRF-2's maximum voltage is approximately 500 V although it normally runs in the 200 - 300V range. The same VCO used by DRF-1 is also used by DRF-2 (and DRF-3). The DRF-2 frequency (2.36 MHz instead of 53.1 MHz) is derived by dividing the output of the VCO by 22.5.

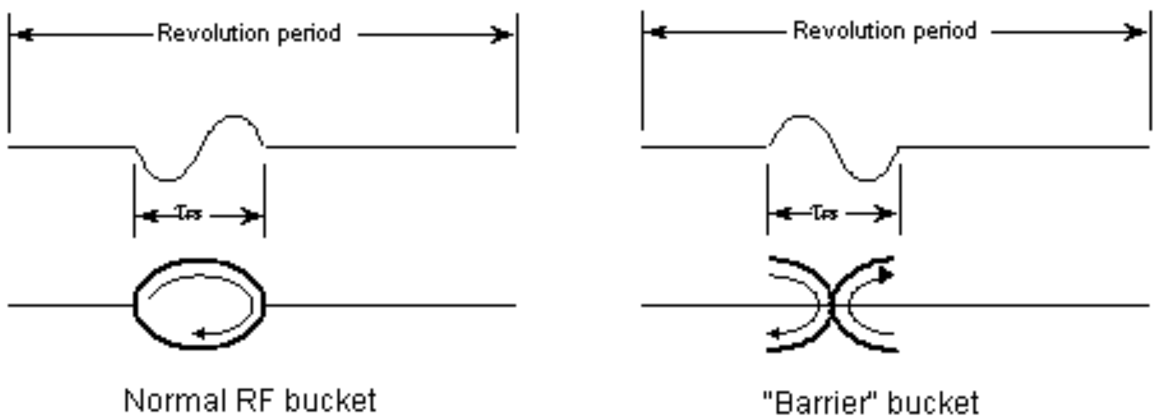

Figure 3.6: DRF-2 barrier bucket

DRF-3

The third and final RF system found in the Debuncher is also an h=4 system. In this case, however, no buckets are suppressed. DRF-3 is not run operationally and is only used during studies. It is primarily used to move the beam to permit full exploration of the Debuncher momentum aperture. It operates at up to 800 Volts.

Either a DAC or a 164 card provides amplitude control for DRF-3, although the latter is rarely used. Frequency control is provided by the same VCO as DRF-1 and DRF-2. As with DRF-2 the frequency from the VCO is divided by 22.5 to change the RF frequency from 53.1 MHz to 2.36 MHz.

4 Accumulator

Function

The purpose of the Accumulator, as its name implies, is to accumulate antiprotons. This is accomplished by momentum stacking successive pulses of antiprotons from the Debuncher over several or many hours. Both RF and stochastic cooling systems are used in the momentum stacking process. The RF decelerates the recently injected pulses of antiprotons from the injection energy to the edge of the stacktail. The stacktail momentum cooling system sweeps the beam deposited by the RF away from the edge of the tail and decelerates it towards the dense portion of the stack, known as the core. Additional cooling systems keep the pbars in the core at the desired momentum and minimize the transverse beam size.

What follows is a chronological sequence of events that takes place in the Accumulator:

1. Unbunched 8 GeV antiprotons are extracted from the Debuncher, transferred down the Debuncher to Accumulator (D/A) line, and injected into the Accumulator in the A10 straight section. The beam is transferred in the horizontal plane by means of a kicker and pulsed magnetic septum combination in each machine (in order: D:EKIK, D:ESEPV, A:ISEP2V, A:ISEP1V and A:IKIK). Extraction from the Debuncher occurs just before another antiproton pulse arrives.
2. The Accumulator injection kicker puts the injected antiproton pulse onto the injection closed orbit which, at the injection kicker, is roughly 80 mm to the outside of the central orbit. The kicker is located in a high dispersion region so the higher energy injected beam is displaced to the outside of the Accumulator. The Accumulator injection and extraction kickers have “shutters” which can move into the aperture between the injection/extraction orbit and the circulating stacktail and stack (See Figure 4.1). If the shutter is closed when the kicker fires, it can shield the circulating antiprotons already in the Accumulator from fringe fields created when the kicker fires. After beam is on the injection orbit, the shutter can be opened again to allow an unobstructed

path from the injection orbit to the deposition orbit. Operationally

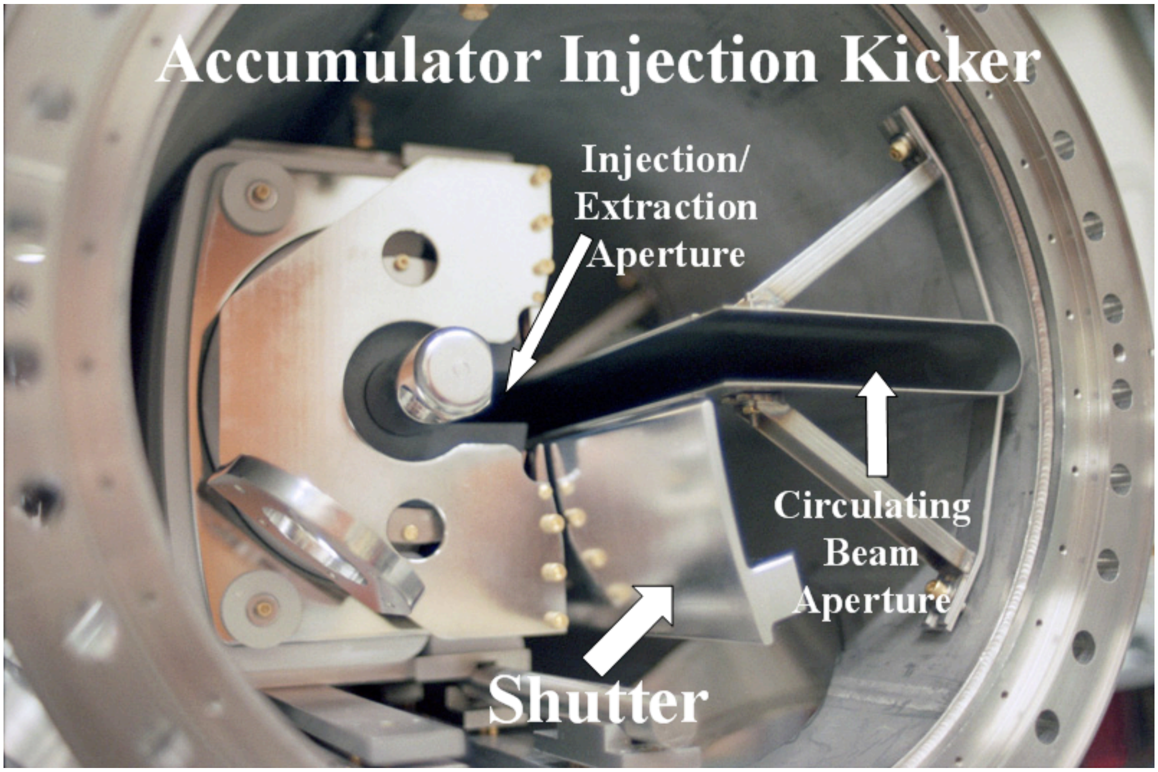

Figure 4.1: Accumulator Injection Kicker

it was found that there was no significant impact on the core when the kickers were fired with the shutters left open. Therefore, the shutters are normally left open during stacking. Figure 4.2 shows a spectrum analyzer display of the Accumulator longitudinal beam distribution in terms of a harmonic of the revolution frequency. The figure, among other things, shows the relative location of the shutters in revolution frequency (which relates to the horizontal position in a high dispersion straight section).

3. After the injected pbars have been kicked onto the injection closed orbit, a 53 MHz RF system known as ARF-1 captures the beam in 84 bunches. ARF-1 then decelerates the beam by approximately 60 MeV to the edge of the stacktail, beyond the space occupied by the kicker shutter. The RF is slowly turned off at the edge of the stacktail, adiabatically debunching the beam.

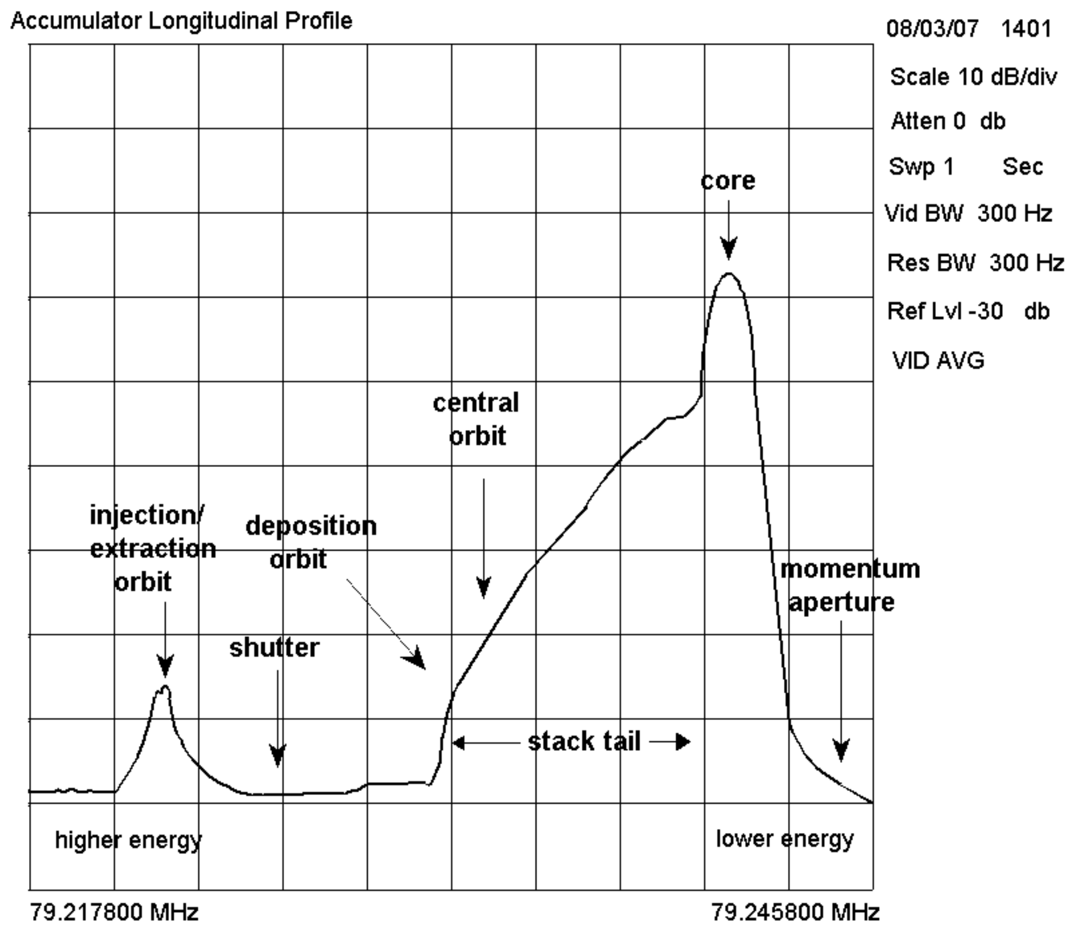

Figure 4.2: Accumulator stack profile

4. The stacktail momentum cooling system now acts on the pbars. This system decelerates the beam towards the core, which is approximately -150 MeV from the injection orbit (or ~70 mm to the inside of the Accumulator central orbit in a high dispersion straight).
5. After approximately 20 minutes, the antiprotons in the stacktail have been decelerated into the domain of the core cooling systems. Eight stochastic cooling systems act on beam in the core during stacking. The 2-4 GHz and 4-8 GHz core momentum systems control the momentum spread and keep the pbars from hitting the low momentum aperture. The 4-8 GHz core horizontal and vertical betatron cooling systems (separated into three systems in each plane) keep the transverse emittances minimized.

6. This process continues for tens of minutes or hours as the stack grows in size until the desired Accumulator intensity is reached for transfers to the Recycler.
7. When a transfer of pbars to the Recycler (via the Main Injector) is desired, an RF system known as ARF-4 is used to move beam from the core to the extraction orbit. ARF-4 has a harmonic number of h=4 and is energized at a very low amplitude at a frequency corresponding to that of the core. The RF voltage is slowly increased and a portion of the beam in the core is captured into four buckets and is slowly moved through the stack beyond the space occupied by the shutter, and onto the extraction orbit (which is the same as the injection orbit).
8. Once the unstacked pbar bunches are on the extraction orbit, the ARF-4 voltage is increased. The additional voltage acts to shrink each bunch longitudinally, creating more room between the bunches for the kicker to rise through.
9. Next, the Accumulator extraction kicker is fired to begin the extraction process. As was already mentioned, although the extraction kicker has a shutter to shield the remaining stack from fringe fields, it is not used operationally. The deflection imparted by the kicker translates to a horizontal displacement at the Lambertson magnet near straight section 30. Beam enters the field region of the Lambertson, which bends beam up and out of the Accumulator into the AP3 line.

Lattice

The Accumulator "ring" actually resembles a triangle with flattened corners. The lattice has been designed with the following constraints in mind.

- The Accumulator must be capable of storing an antiproton beam over many hours with a good beam lifetime.
- There must be several long straight sections, with lengths up to 16 m, to accommodate stochastic cooling pickups and kickers. Some of these straight sections must have low dispersion, while others need to have a dispersion of up to 9 m (high dispersion).
- Betatron cooling pick-ups and kickers must be an odd multiple of $\pi/2$ apart in betatron phase (i.e. the number of betatron

oscillations) and far enough apart physically so that a chord drawn across the ring will be significantly shorter than the arc. Cooling pickup signals must arrive at the kickers on the same turn in order to act on the particles that created the signal.

- The lattice must have room for devices to inject and extract beam from the Accumulator, RF cavities and diagnostic devices.

The end result is that the Accumulator has an unconventional triangular shape that includes 6 straight sections with alternately low and high dispersion. This shape was considered most efficient as compared to other designs, which were up to 10-sided.

It is worth commenting on why there is a need for high and low dispersion sections in the Pbar rings. The dispersion function (often written η_x and η_y for the horizontal and vertical planes) describes the contribution to the transverse size of a particle beam from its momentum spread. Dispersion is caused by bending magnets, but modified by quadrupoles. Particles with different momenta are bent at different angles as a function of the momentum. In a low dispersion area, the beam size is almost entirely defined by the β function and the transverse emittance of the beam. In a high dispersion region, the beam size is defined by the β function and transverse emittance as well as the dispersion function. In the case of the high dispersion straights in the Accumulator, the horizontal beam size is very large and dominated by the effects of dispersion. The beam size is very small in both planes in the low dispersion areas. There is very little vertical dispersion in the Accumulator due to the fact that the only vertical bending magnets are small trim dipoles. Normalized emittance, often written as ε_n, describes the transverse size of the beam independent of the beam energy, β function and dispersion function.

Cooling systems can use low dispersion regions to sense a beam position error due to transverse oscillations only. In a similar vein, position errors in a high dispersion section can in large part be attributed to off-momentum beam. In the case of the Accumulator, betatron cooling system pickups are best placed in low dispersion straights while momentum cooling pickups are found in one of the high dispersion straight sections.

The lattice of the Accumulator, shown in figure 4.3, is much different from the Debuncher. There are special arrangements of quadrupoles approaching

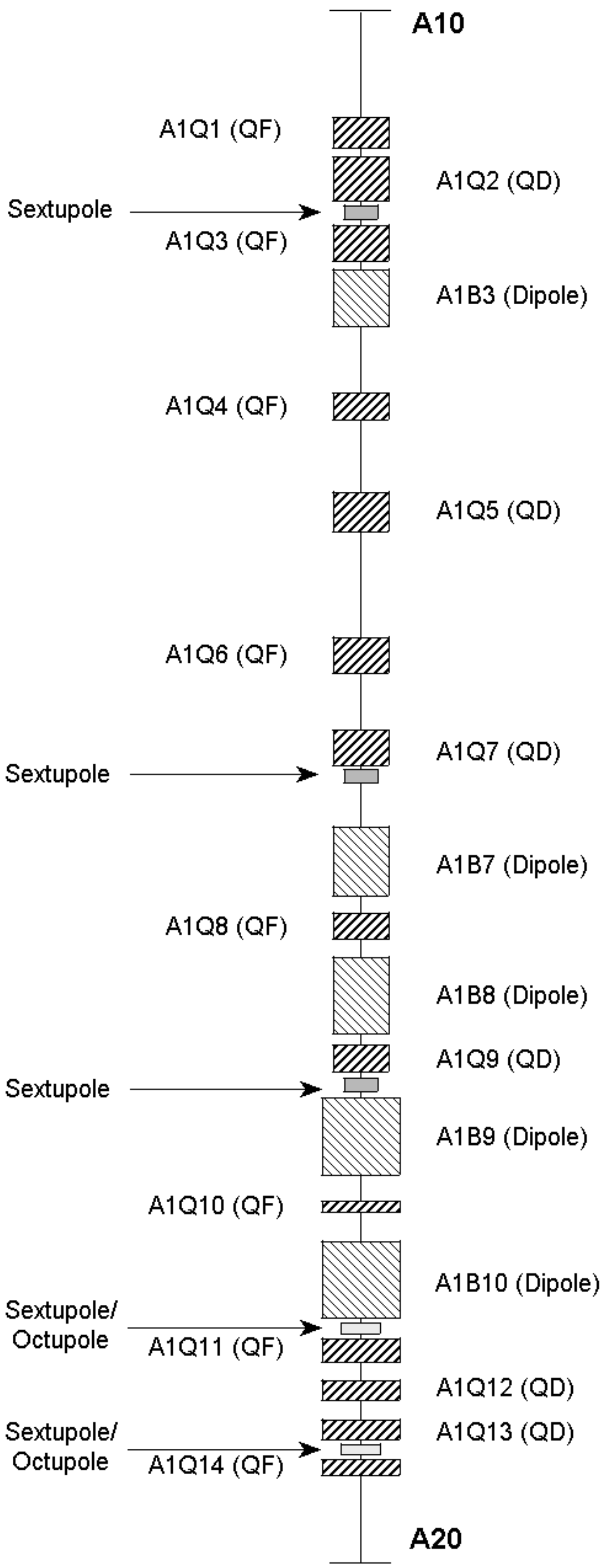

Figure 4.3: Accumulator lattice

the straight sections in order to achieve the desired dispersion. Like the Debuncher, the Accumulator has mirror symmetry about the straight sections. The magnet numbering scheme increases as one travels in the pbar direction in the odd-numbered sectors, and decreases in the even sectors. Like the Debuncher, the Accumulator straight sections are full of specialized devices. A10 contains core betatron cooling pickup tanks, Schottky and other diagnostic pickups, damper pickups and kickers as well as the beam current transformer for measuring the circulating beam intensity. The injection and extraction kickers are found in straight section 20 as are the pickup arrays for the 4-8 GHz core momentum cooling system. In A30 reside the extraction Lambertson, the stacktail momentum, 2-4 GHz core momentum, and core betatron cooling kickers. The vertical scraper and low dispersion flying wires (no longer used) are found outside of the 30 straight section, at the 307 location. Straight section 40 contains a momentum beam scraper and a set of flying wires that are no longer used. A50 contains the horizontal scraper, the kicker tank for the 4-8 GHz core momentum system, a resistive wall current monitor and various

Accumulator RF cavities. An experimental pit is also found in A50. Straight section 60 contains all of the stochastic cooling pickups for the stacktail momentum system and the 2-4 GHz core Δp cooling pickups.

Power supplies

Four different power supplies power the main dipoles and quadrupoles in the Accumulator, A:QT is located in AP10 and the others are located at AP50. All of the dipoles are powered in series by A:IB, a large 12-phase PEI supply. Like D:IB, it has a separate 13.8 kV transformer outside of the AP50 service building. There is a reference dipole magnet with an NMR probe in the A40 stub room that is attached to the main A:IB bus. The NMR probe readback (A:NMR50) can be used to precisely track changes in the Accumulator bend field, which mostly occur because of thermal effects. It is important to follow the prescribed procedure when adjusting the bend field of both the Debuncher and Accumulator, to avoid an energy mismatch.

The 'large' quadrupoles, the ones found on either side of the high dispersion straight sections numbered 10 through 14, are all powered by A:LQ. Each 10, 11 and 14 location quad has a 50A shunt for individual control to make lattice adjustments or beam measurements. Quadrupoles adjacent to the low dispersion straight sections, the 1 through 3 location quads in a sector, as well as the 6 location quads, are connected to the A:QT bus. Each 3 location A:QT quadrupole (i.e. A2Q3, A3Q3, etc…) has a 50A shunt, and each 6 location A:QT quadrupole (i.e. A2Q6, A3Q6, etc…) has a 25A shunt for individual control. In addition there are 25A shunts on the 401 and 501 quads. Outside of the straight sections, one finds alternately focusing and defocusing quadrupoles. With the exception of the 6 location, these are all powered by a single supply, A:QDF. Current is delivered to each type of quad after passing through one of two shunts on the output of this supply. A:QSF1 shunts current from the focusing quads (4 and 8 locations), A:QSD is the shunt for the defocusing quadrupoles (5, 7, and 9 locations). Each 8 location quad (i.e. A2Q8, A3Q8, etc…) has a 25 amp shunt for individual control. In addition, there are also shunts on the 104, 105, 204, 205 and 307 quads, usually only used for studies. The current delivered to the focusing and defocusing quadrupoles on A:QDF differs by less than a percent.

The Accumulator tunes are adjusted by changing the main QDF shunts A:QSF1 and A:QSD. The horizontal tune is more affected by changing

A:QSF1, and the vertical tune by changing A:QSD. In both cases, increasing the D/A value on the shunt decreases that plane's tune value, while increasing the tune in the opposite plane by a smaller amount. There is a sign flip between the setting (positive) and the readback (negative) on all shunts in pbar. The default core tune values in the Accumulator are currently $\nu_x = 6.683$ and $\nu_y = 8.681$ and are normally kept within 0.0005 of these values. The integer portion of the tune is normally assumed and not reported. Figure 4.4 shows the location of the default core tune in relation to the various resonance lines below 13th order. The red lines are the sum resonances and the green lines are the difference resonances. The lines that intersect $\nu_x = .66$ and $\nu_y = .66$ are 3rd, 6th or 9th order resonance lines; the lines the intersect $\nu_x = .7$ and $\nu_y = .7$ are 10th order resonances lines; the lines that intersect $\nu_x = .714$ and $\nu_y = .714$ are 7th order resonances. By far the strongest of the resonance lines, the main 2/3rd resonances are shown in bold.

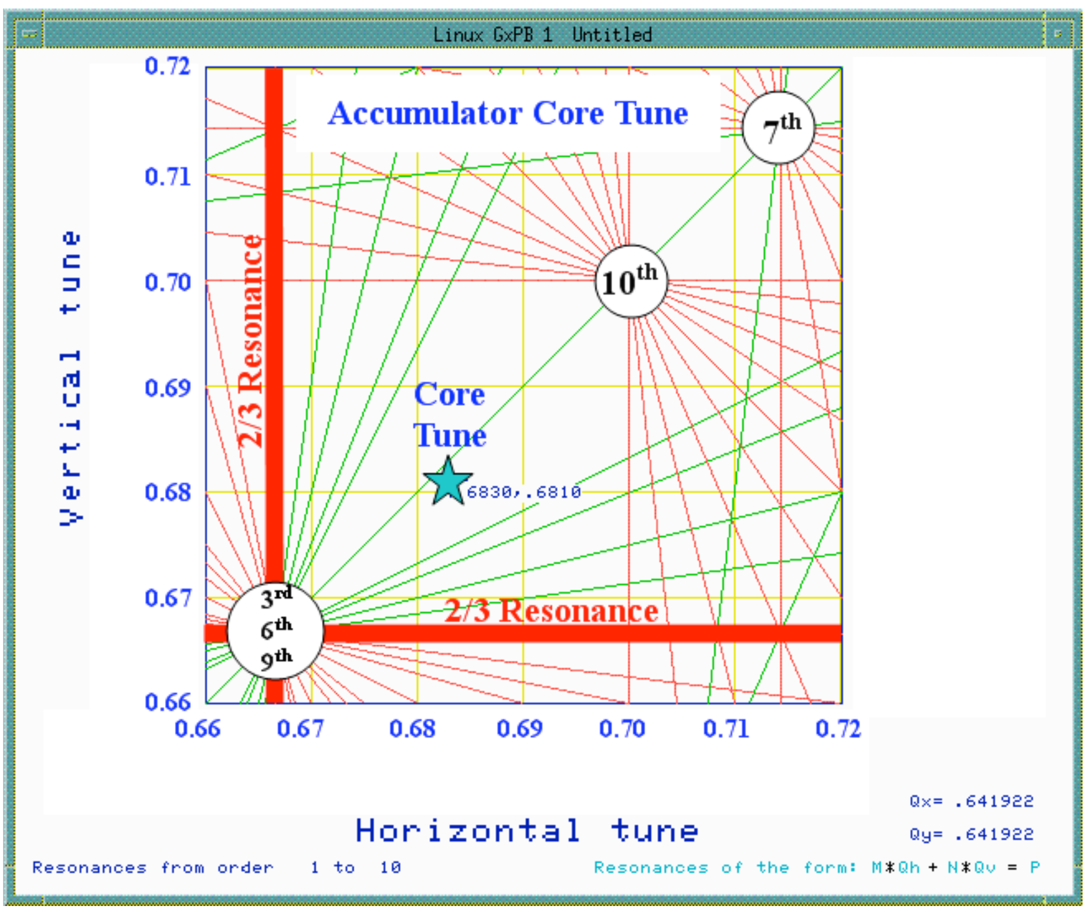

Figure 4.4: Nominal Accumulator tune

It is important to realize that when we quote the Accumulator tunes, we are generally quoting their values for beam at the core. The tune values are not uniform across the Accumulator momentum aperture.

We can see in Figure 4.5 that the tunes traverse through a number of weak resonance lines as they travel from the injection orbit to the core. Keep in mind that the beam does not spend equal amounts of times at each location on the curve. Beam moves from the injection orbit to the deposition orbit in less than a second, but spends increasing time as it moves across the stacktail to the core. Since Accumulator pbars spend a majority of their time in the core (and there's more of them), we are usually mostly concerned about the tune vales at the core. Sextupole and Octupole circuits (A:SEX10, A:SEX12, A:OCT10 and A:OCT12) can be used to modify how the tunes behave across the momentum aperture. Sextupoles change the slope of tunes across the momentum aperture while octupoles produce a parabolic tune change.

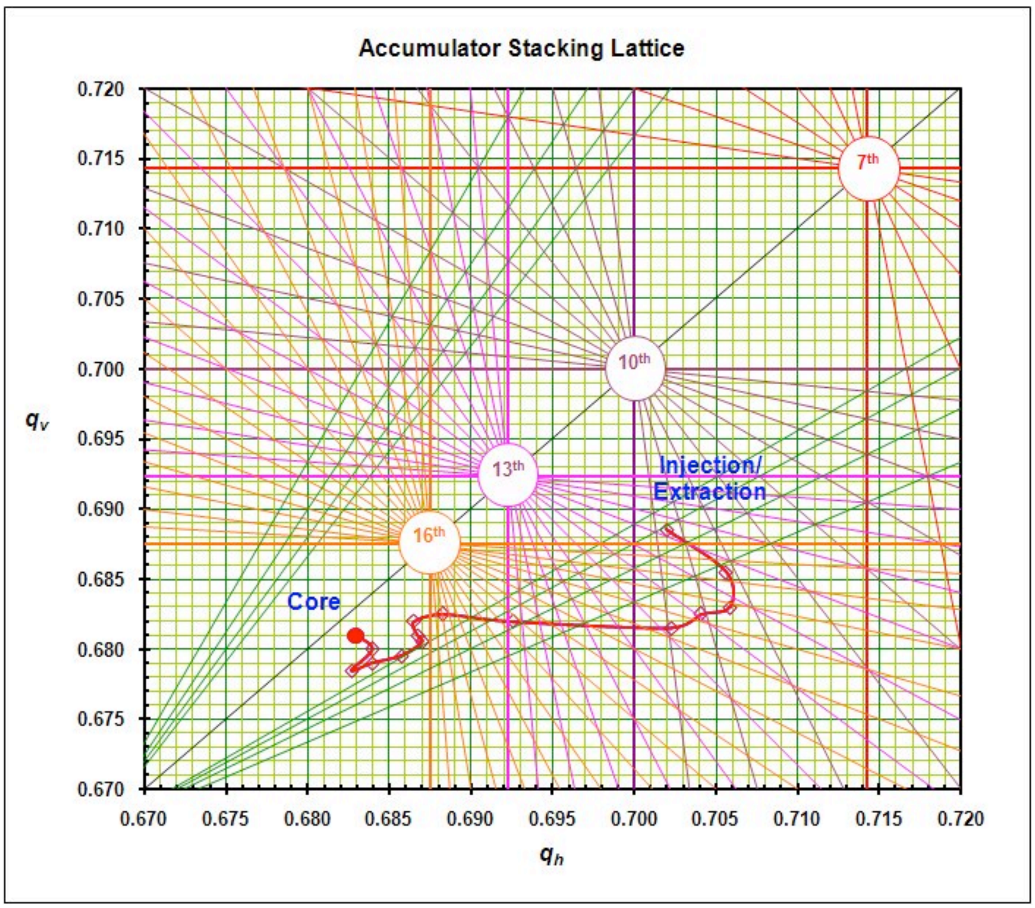

Figure 4.5: Accumulator tunes across the momentum aperture

As an economy measure, the Accumulator magnets were built to provide fields for particles with a kinetic energy no greater than 8 GeV. As a consequence, the magnets are run close to or at magnetic saturation at 8 GeV. When making changes to the Accumulator bend and quad buses, hysteresis effects may be significant. To provide for reproducible tunes and orbits, the major supplies are "cycled" or ramped from nominal to zero current three times following any period when the supplies have been turned off (e.g. for an access).

In addition to dipoles, quadrupoles and trims, higher order correction element strings can be found in the Accumulator. Five sextupole supplies known as A:SEX3, A:SEX7, A:SEX9, A:SEX10, and A:SEX12 power sextupole magnets located adjacent to the third, seventh, ninth, tenth and twelfth quadrupoles in each cell. During normal operations, A:SEX3, A:SEX7 and A:SEX9 are not used. Octupoles are found near the tenth and twelfth quads and are powered respectively by A:OCT10 and A:OCT12. The sextupole and octupole magnets in the '10' and '12' locations are wound on the same frame, the fields being formed by the shape and location of the windings rather than the number of poles.

Decoupling of the horizontal and vertical tunes is possible by means of skew quadrupole magnets powered by A:SQ100 and A:SQ607. Both supplies power a single magnet, and have reversing switches that make it possible to reverse the polarity of either magnet. The supply A:SQ607 originally powered the skew quad at the 607 location, but now powers a skew quad at the 107 location to improve the phase relationship with SQ100. There are also two skew sextupole magnets powered by A:SS106 and A:SS406, which are used to correct coupling as a function of momentum. The skew sextupoles are relatively recent additions to the Accumulator and were added due to field imperfections in the LQ quads, especially the newer LQFs at the 14 locations. Because of the LQF field problems, wedges were added to force the pole faces slightly further apart to distort the magnetic field so as to partially compensate. The skew sextupole circuits provide the final correction.

Finally, there is the extraction Lambertson magnet powered by D:ELAM. This supply is kept on during normal Collider operation despite the fact that it is needed only during reverse injection of protons and transfers of antiprotons. The higher order fields produced by the Lambertson are sufficiently strong in the 'field-free region' so as to cause noticeable tune and coupling differences when on versus off.

Fine control of the Accumulator orbit is possible by means of a combination of trim dipoles, dipole shunts and motorized dipoles. Each main dipole in the Accumulator has a shunt, permitting individual control of the current passing through each, providing horizontal orbit control. The shunts can be used in combination with other shunts or horizontal trims to produce local bumps. Due to space limitations, the AxB8 and AxB10 dipole magnets have stepping motors on their magnet stands allowing them to be rolled slightly. Rolling the dipole imparts a vertical deflection on the beam and can be used in place of a vertical trim magnet. Both horizontal and vertical trims are located near beam transfer points. Vertical trims are also located in the arcs.

System	Freq.	Harm.	Peak Voltage	Amplitude	Frequency
ARF-1	52.8 MHz	h=84	40 kV	DAC (A:R1LLAM) 164 card (A:R164AM)	DAC (A:R1LLFR) 164 card (A:R164FR)
ARF-2	1.26 MHz	h=2	200 V	DAC (A:R2LLAM) 164 card (A:R264AM)	DDS (A:R2DDS1) 468 card (A:R268FF)
ARF-3	1.26 MHz	h=2	2,000 V	DAC (A:R3LLAM) 164 card (A:R364AM)	DDS (A:RLLFS0) 468 card (A:R268FF)
ARF-4	2.5 MHz	h=4	1,500 V	DAC (A:R4LLAM)	DDS (A:RLLFS1)

Table 4.1: Accumulator RF systems

RF systems

ARF-1

The Accumulator has four RF systems, ARF-1, ARF-2, ARF-3 and ARF-4. Table 4.1 summarizes attributes of the various Accumulator RF systems. When stacking, ARF-1 is used to move beam from the injection orbit across the kicker shutter region to the high energy edge of the stacktail (deposition orbit). This process takes about 600 milliseconds. As beam from the Debuncher enters the Accumulator, it is a nearly continuous stream with a small momentum spread and no bunch structure. In order to efficiently capture the beam, ARF-1 bunches the beam adiabatically. The phase is then shifted ~0.7 degree and the frequency increased by ~5.8 kHz to decelerate the beam to the edge of the stacktail. Next, the beam is debunched by adiabatically reducing the RF voltage. The antiprotons experience an energy reduction of 0.7% between the injection orbit and deposition orbit of the stacktail. Figure 4.6 shows how the RF voltage and frequency change during a stacking cycle.

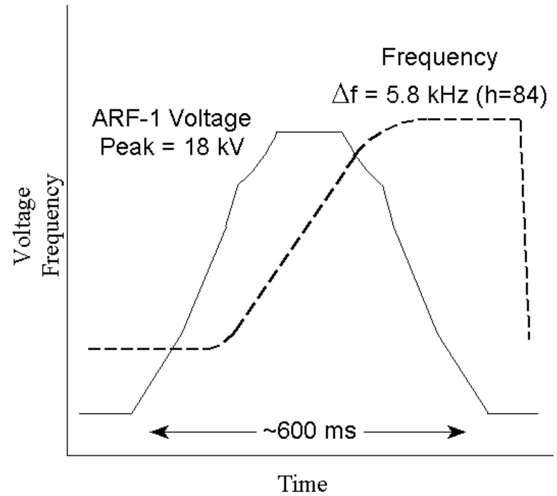

Figure 4.6: ARF-1 voltage and frequency waveforms

The amplitude reference for ARF-1 can be switched to either a DAC (A:R1LLAM) or a 164 card (A:R164AM). The frequency inputs also are provided by a DAC (A:R1LLFR) or a 164 card (A:R164FR).

ARF-2

ARF-2 was originally used to unstack beam from the core during collider operation, a single bunch at a time. ARF-4 has been used for unstacking pbars since the beginning of Run II. ARF-2 is now exclusively used for providing "stabilizing RF", which dislodges trapped positive ions that can lead to emittance growth. Approximately 25 Volts of RF is applied at or near the core revolution frequency to weakly bunch the beam. The bunching of the beam acts to dislodge the ions from their potential wells. ARF-2 is an h=2, 1.26 MHz system that has one of the two buckets suppressed in a manner similar to DRF-2, but not using a barrier bucket (see figure 4.7). This is accomplished by a module, which suppresses every other RF cycle and sends the resultant waveform to the high level.

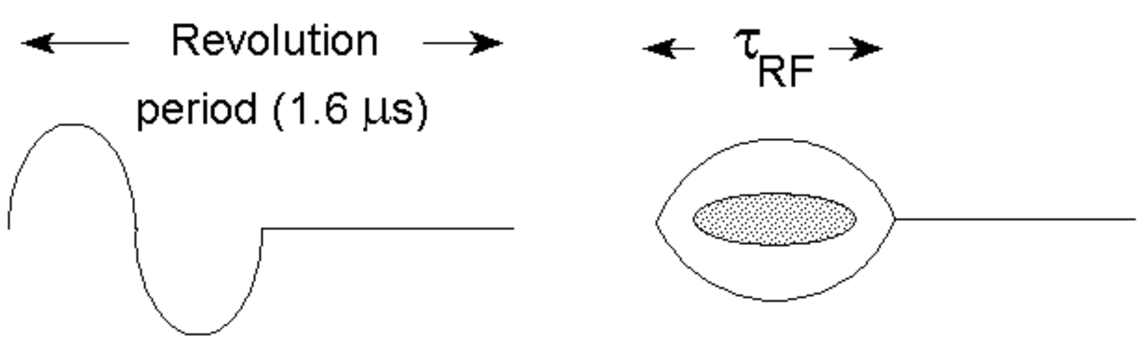

Figure 4.7: ARF-2 structure

Amplitude control of ARF-2 can be switched to either a DAC (A:R2LLAM) or a 164 card (A:R264AM). The frequency inputs are provided by a DDS that can be set to a DC level or ramped (A:R2DDS1).

ARF-3

ARF-3, prior to Run II, was used for to narrow unstacked pbar bunches on the extraction orbit. With the advent of ARF-4 and 4-bunch extraction, ARF-3 is no longer used in the extraction process. ARF-3 operates at 1.26 MHz and h=2, it does not have a suppressed bucket like ARF-2 (see figure 4.8).

Currently, the primary function of ARF3 is for use in beam studies. The ARF3 voltage can be ramped to adiabatically capture beam and the frequency changed to move beam in the momentum aperture. Examples of ARF3 studies are moving pbar beam directly over a stacktail leg pickup for measurements and measuring the tunes across the Accumulator momentum aperture with protons or pbars.

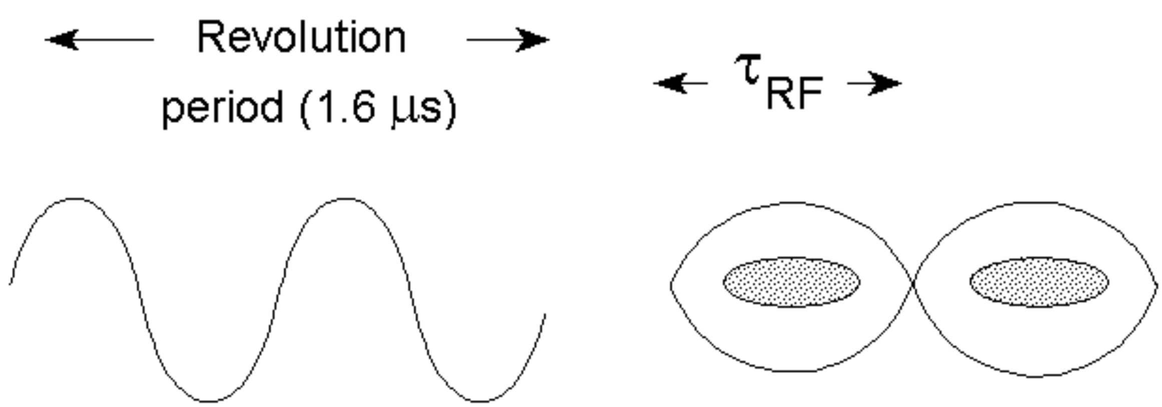

Figure 4.8: ARF-3 structure

ARF-3 was originally connected to two identical cavities, ARF3-1 and ARF3-2. While ARF3-2 is still connected to the ARF-3 amplifiers, ARF3-1 has been modified and connected to the ARF-4 system instead of the original ARF-4 cavity.

The low level amplitude input to ARF-3 comes from either a DAC (A:R3LLAM) or a 164 card (A:R364AM). As with ARF-2, the frequency inputs are provided by a DDS, which can be set to a DC level or ramped (A:RLLFS0).

ARF-4

ARF-4 is a 2.52 MHz h=4 system that captures 4 antiproton bunches for transfers to the Recycler (via the Main Injector). When removing antiprotons from the core, the ARF-4 voltage is slowly increased to adiabatically capture a portion of the core. The voltage amplitude, as defined by the bucket size, can be changed to bunch more or less beam. As the frequency curve plays, the synchronous phase angle of the RF is changed until the bunches are accelerated out of the core to the extraction orbit. The phase angle returns to zero once beam reaches the extraction orbit, and the voltage is increased from 500V to about 1,500V to narrow the bunches in time (leaving a larger gap for the extraction kicker to rise through). ARF-4 phase locks to the Main Injector shortly before beam is extracted. The entire process of unstacking pbars takes approximately 15 seconds (see Figure 4.9).

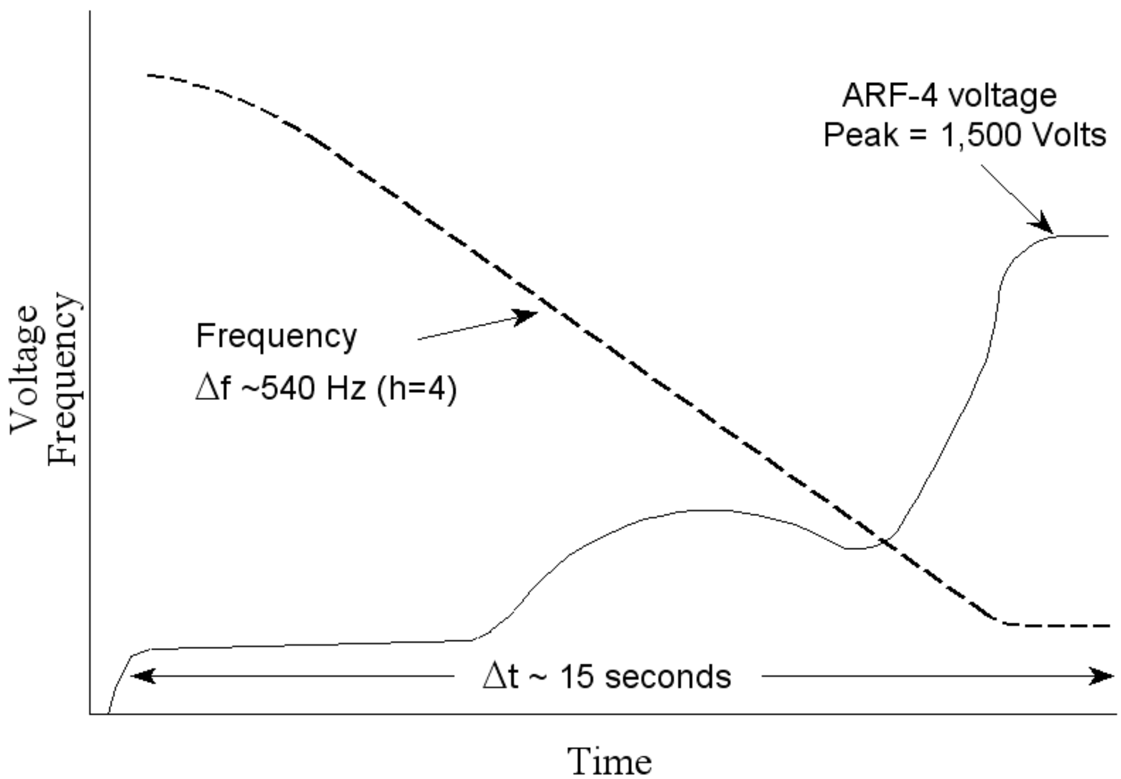

Figure 4.9: ARF-4 waveforms during extraction

Earlier in Run II, when Tevatron shots were made from the Accumulator, a typical transfer involved 9 extractions, for a total of 36 bunches sent to the Tevatron. With the commissioning of the Recycler as the source of antiprotons for Tevatron shots, pbars are no longer sent from the Accumulator to the Tevatron via the Main Injector. Pbar transfers to the Recycler are typically made in pairs at hourly intervals.

The low level amplitude input to ARF-4 is controlled by a DAC, A:R4LLAM, which is part of the VME system known as ACCLLRF. Enabling the curves with A:R4CPAM passes control of the DAC to a program running in the processor. Frequency control is through A:RLLFS1, which is an H=1 value and the actual H=4 frequency value is read at A:RFDDS3. The LLRF can be configured to connect to either the original ARF4 cavity or the ARF3-1 cavity that is presently used.

Notes:

5 Stochastic cooling

Introduction/Overview

Beam cooling is a technique whereby the transverse size and energy spread of a particle beam circulating in a storage ring is reduced without any accompanying beam loss. The goal is to compress the same number of particles into a beam of smaller size and energy spread, i.e. to increase the particle density. Phase space density can be used as a figure of merit for a particle beam, and cooling increases the density. On the surface, it would appear that stochastic cooling violates Liouville's Theorem, which states that phase space volume is conserved. However, Liouville's Theorem only applies to "conservative" systems and stochastic cooling, by definition, is not a conservative process. The cooling electronics act on the beam through a feedback loop to alter the beam's momentum or transverse oscillations.

Two types of beam cooling have been demonstrated and used at various laboratories, including Fermilab: electron cooling, which was pioneered by G. I. Budker and associates at Novosibirsk, and stochastic cooling, developed by Simon van der Meer of CERN. Electron cooling gets its name from the fact that an electron beam is used to cool the particles by removing energy. Stochastic cooling is so named because of the stochastic nature of the beam – i.e., particles move at random with respect to one another.

Theoretically, electron cooling works on the principle of a heat exchanger. Two beams travel a certain distance parallel to each other: a 'warm' beam of protons, antiprotons, or heavy ions with relatively large variation in transverse or longitudinal kinetic energy and a 'cold' beam of electrons having much less variation in kinetic energy. Both beams are tuned to travel at approximately the same velocity, and as the beams interact, the kinetic energy of the warmer beam is transferred to the electron beam. The electron beam can then be collected at the end of the cooling section, or recirculated. Note here that electron cooling is more effective longitudinally than transversely due to the limited transverse size of the electron beam.

Electron cooling was demonstrated at Fermilab in the early 1980's in a small storage ring known as the Cooling Ring that was located in a blue plywood racetrack-shaped building west of the Linac and Booster. It was on this machine, too, that stochastic cooling was first achieved at Fermilab.

During the design of the Fermilab Antiproton Source, electron cooling was not used because of the lack of proven high current relativistic electron sources. Since then, the technology has improved to the point that electron cooling is a viable alternative for future medium-energy storage rings. For that reason, electron cooling was developed for use in the Recycler Ring. Since the Antiproton Source only employs stochastic cooling at this time, the remainder of this chapter will concentrate on this technique for beam cooling. The stochastic cooling systems used in the Antiproton Source are either betatron or momentum. Betatron, βtron and transverse all refer to systems that reduce betatron oscillations in the horizontal and vertical transverse planes. Similarly, momentum, longitudinal, dp, and Δp are used interchangeably to describe systems that reduce the momentum spread of the beam.

Fundamentals

The terms beam temperature and beam cooling have been borrowed from the kinetic theory of gases. Imagine a beam of particles circulating in a storage ring. Particles will oscillate around the beam center in much the same way that particles of a hot gas bounce back and forth between the walls of a container. The larger the amplitude of these oscillations in a beam, the larger the beam size will be. The mean square velocity spread is used to define the beam temperature in analogy to the temperature of the gas. Beam cooling is desirable for applications such as:

- Providing a low emittance beam to a collider ring in order to maximize collision rate (luminosity).
- Accumulation of rare particles – cooling to make space available so that more beam can be stacked into the same storage ring (e.g. the Accumulator).
- Preservation of beam quality – cooling to compensate for various mechanisms leading to growth of beam size and/or loss of stored particles. Stochastic cooling was attempted (unsuccessfully) in the Tevatron for this reason and was known as “Bunched Beam Cooling”.
- To provide a particle beam with an extremely small energy spread for precision experiments. The E760 and E835 experiments had

successful runs in the 1990's, using the Accumulator to collide antiprotons with hydrogen atoms from a gas jet.

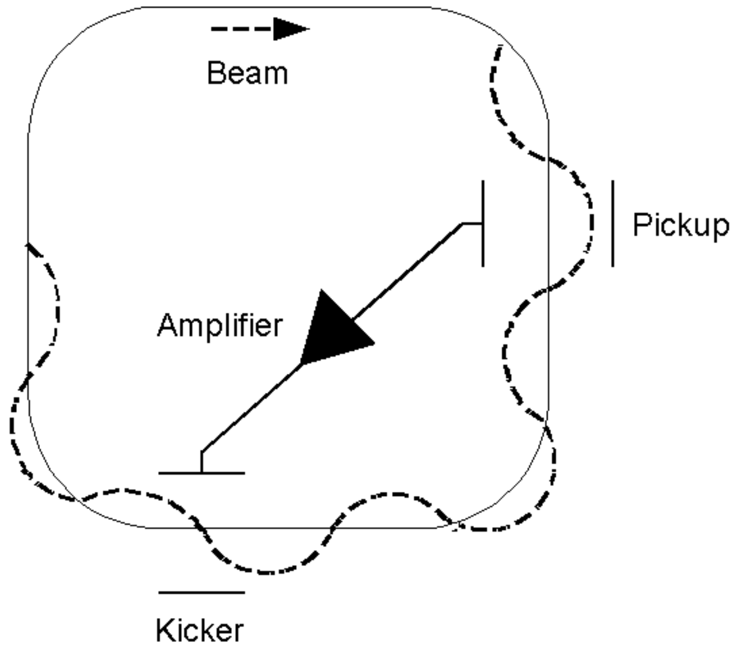

Figure 5.1: Single-particle model for a transverse stochastic cooling system

Consider a single particle circulating in a storage ring as shown in the single particle model depicted in figure 5.1. Assume that the particle has been injected with some error in position and angle with respect to the ideal orbit (the center of the beam pipe). As the focusing system tries to restore the resultant deviation, the particle oscillates around the ideal orbit. These betatron oscillations can be approximated by a purely sinusoidal oscillation. The cooling system is designed to damp the amplitude of this oscillation. A pick-up electrode senses the position of the particle on each revolution. The error signal is ideally a short bipolar pulse that has an amplitude proportional to the particle's deviation from the central orbit at the pick-up. The signal is amplified and applied to kickers that deflect the particle by an angle proportional to its error.

Specifically, consider a horizontal beam pick-up that consists of two plates (usually parallel) and is sensitive to either horizontal motion or equivalently a dipole oscillation. The pick-up is centered on the middle of the beam pipe, with one plate to the left of center and the other to the right. If the particle passes through the pick-up off-center, the plate which the particle passes closest to will have a greater current induced on it. If the signals are combined by measuring the difference between them in a so-called 'delta' or Δ mode, the output will be a measure of the relative particle position with respect to the center of the beam pipe. Generally, the output of several sets of electrodes is combined in phase to provide a signal of usable amplitude compared to the thermal noise floor. This signal is then amplified and applied with the most optimal averaged phase (timing) to the kickers. The kicker, like the pick-up, is an arrangement of plates on which a transverse electromagnetic field is created which can deflect the particle.

Since the pick-up detects a position error and the kicker provides a corrective angular kick, their distance apart is chosen to correspond to a quarter of a betatron oscillation (plus a multiple of π wavelengths if more distance is necessary). As shown in figure 5.2, a particle passing the pick-up at the crest of its oscillation will then cross the kicker with zero position error

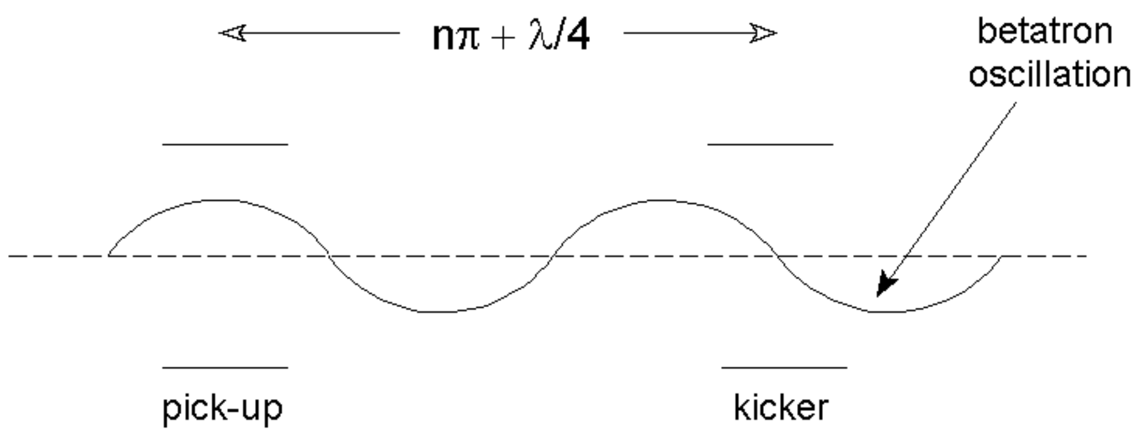

Figure 5.2: Optimum spacing between pick-up and kicker

but with an angular deviation that is proportional to the displacement at the pick-up. Given a perfect kicker response and perfect betatron phasing, the trajectory of the particle would be corrected to that of the central orbit. A particle not crossing the pick-up at the crest of its oscillation would receive only a partial correction and require additional passages to eliminate the oscillation. Cooling systems, in fact, require many beam revolutions to cool the beam due to the large number of particles involved and the finite bandwidth of the hardware.

There is another important aspect of stochastic cooling that this model can illustrate: the correction signal has to arrive at the kicker at the same time as the particle for optimum cooling. Since the signal is delayed in the cables and the amplifier, whereas the particle is moving at close to the speed of light, the path of the correction signal has to take a shortcut across the ring to reach the kicker at the correct time. For reasons explained below, applying the correction signal later than on the same revolution that it was created will lead to less efficient cooling or even heating.

Particle beams, of course, are not composed of just a single particle. Rather, a beam is a distribution of particles around the circumference of the storage ring. Each particle oscillates with a unique amplitude and random initial phase and in this model the cooling system acts on a sample of particles within the beam rather than on a single particle. The number of particles in a sample, N_S, is given by:

$$N_s = \frac{N}{(2WT)}$$

where N is the number of particles in the beam, W is the bandwidth of the cooling system, and T is the beam's transit time around the ring. Using one of the Debuncher systems as an example with N = 1.8 X 10^8 particles, W = 1 GHz (Debuncher systems operate between 4 and 8 GHz, separated into 4 bands), and T = 1.695 μs, the number of particles $N_S \approx$ 53,000 within each equally spaced sample. Making the bandwidth sufficiently large would, in principal, permit the single particle model above to be valid. However, designing the pick-ups and kickers to accomplish this is not practical.

The cooling process can be looked at as competition between two terms: (a) the coherent term, which is generated by the single particle, and, (b) the incoherent term, which results from disturbances to the single particle from its fellow sample members through the feedback loop. The coherent signal's contribution to the cooling process is linearly proportional to the system gain, while the incoherent heating term is proportional to the square of the system gain. If one plots these two terms as in figure 5.3, it is clear that there is some point at which the cooling term is

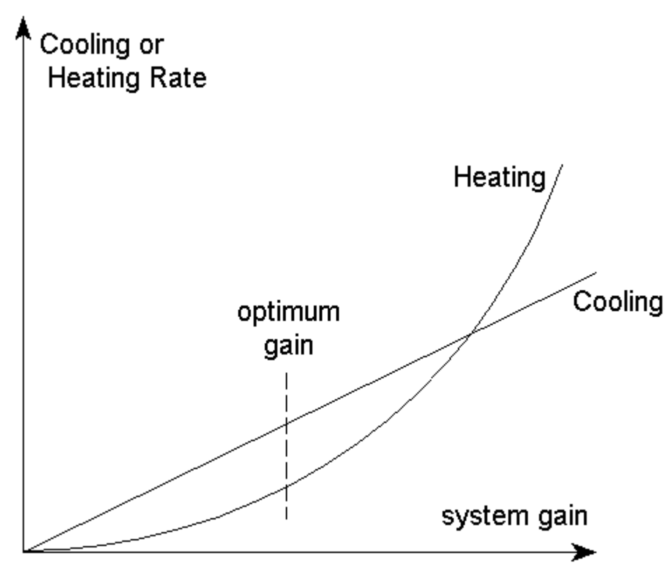

Figure 5.3: Heating and cooling terms as a function of system gain

maximized against the heating term. This is known as the optimum gain of the system. Note that this is usually different from the maximum gain of the system.

Mixing is a term used to represent how completely particles change position with respect to each other. Particles of different momenta "shear" away from each other due to path length differences as they traverse the ring. The stochastic cooling rate is maximized if an independent set of particles constitutes each sample upon each revolution. This is sometimes referred to as "good" mixing. The term "stochastic cooling" is derived from the need for a random or stochastic sample of particles passing through the pick-up upon each revolution for cooling to work effectively. Partially random samples are produced because each particle is on a slightly different orbit due to the momentum spread of the beam. The lattice parameter known as the "slip factor," defined as $\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$ where γ is the Lorentz factor ($\gamma = \frac{1}{\sqrt{1^2 + \frac{v^2}{c^2}}}$) and γ_τ is the Lorentz factor at transition, also contributes to the rate at which the particle samples are mixed from turn to turn. If the samples contain mostly the same particles on successive turns, then the cooling rate is decreased.

Although mixing of particles sampled at the pick-up is beneficial, no mixing is desired between the pick-up and the kicker. This is because the signal obtained at the pick-up should be applied at the kicker to the sample of beam creating the signal. Mixing between the pick-up and kicker is sometimes referred to as "bad" mixing. An ideal cooling system would have no mixing between the pick-up and kicker while having complete mixing between the kicker and the pick-up. In reality, the mixing factor present in an accelerator is somewhat less than ideal. The lattice of the storage ring and the momentum spread of the beam determine the mixing factor. It is for this reason that the spacing of pick-ups to kickers should be as small as reasonably achievable while maintaining adequate time for signal amplification and conditioning.

These factors can be written as an equation for the rate, $^1/_{\text{cooling time}}$ or $^1/_{\tau_{x^2}}$ (where τ is the cooling time constant), at which a beam is cooled:

$$\frac{1}{\tau_{x^2}} = \frac{2W}{N}\left[2g\left(1 - \tilde{M}^{-2}\right) - g^2\left(M + U\right)\right]$$

where W is the bandwidth of the cooling system, N is the number of particles in the ring, g is the system "gain", or more accurately the number of particles multiplied by the electronic gain, $\tilde{M}$ is the 'wanted' mixing factor, M is the 'unwanted' mixing factor, and U accounts for random noise.

A list of selected references is included at the end of this chapter which forms the basis for this text and which can provide much more information to the reader on the theoretical aspects of stochastic cooling.

Betatron cooling

Betatron or transverse cooling is applied to a beam to reduce its transverse size, i.e. to reduce its horizontal or vertical emittance. The single particle model of cooling described above was that of a simple betatron cooling system. Betatron cooling systems use pick-ups in difference mode to generate the beam's error signal. In the case of the Antiproton Source, both pick-ups and kickers are located in areas of low dispersion. This is so that any particles passing through the pick-ups off-center will have that position shift due only to transverse oscillations. In a high dispersion region, a particle's position could also be due to differences in momentum, and the resulting kicks could lead to unwanted momentum heating of the beam. The kickers apply a transverse field to the particles by applying the error signal to the kicker electrodes in "push-pull" fashion (one kicker plate has the same charge to push the beam, the opposing kicker plate has the opposite charge to pull the beam). Details of the specific transverse systems in the Antiproton Source are given below.

Momentum cooling

Momentum cooling systems reduce the longitudinal energy spread of a beam by accelerating or decelerating particles in the beam distribution towards a central momentum. In a momentum cooling system, the pick-up signals are combined in sum mode and similarly, the signal to the kicker electrodes is also applied in sum mode, providing longitudinal fields to accelerate or decelerate the passing particles.

Momentum cooling is used for several reasons in the Pbar source. Its function in the Debuncher is to further reduce the momentum spread of the beam (bunch rotation is the other mechanism used to reduce the momentum spread in the Debuncher). The stacktail momentum cooling system is used to cool the antiprotons deposited by ARF-1 at the edge of the stacktail by decelerating the antiprotons towards the core. The function of the core momentum systems is to maintain a small momentum spread on the particles in the core. This is desirable for two reasons, first to keep particles from being lost on the Accumulator momentum aperture and second to allow a denser bunch of antiprotons to be extracted during transfers. Accumulator momentum pick-ups are located in high dispersion areas and are positioned over the beam that is to be cooled (stacktail pick-ups over the stacktail, core pick-ups over the core). More details on each Δp system can be found in the following sections.

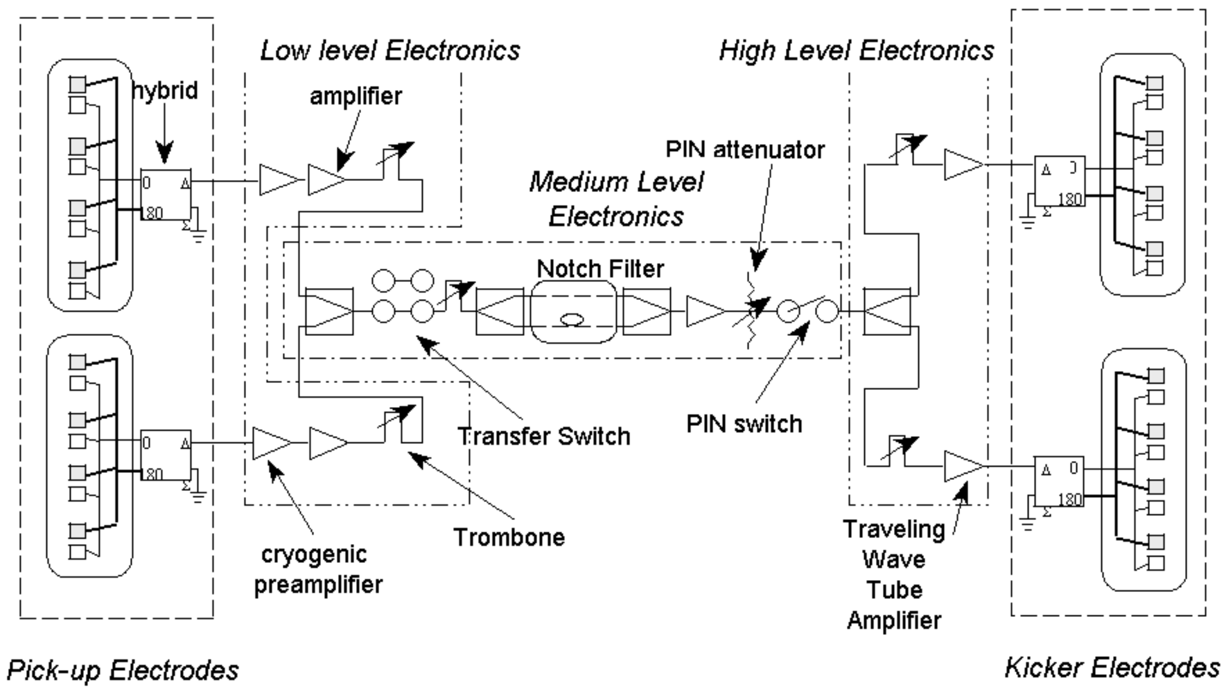

Figure 5.4: Basic stochastic cooling system layout

Specific systems

The stochastic cooling systems in the Debuncher and Accumulator are described below (use figure 5.4 as a reference). While each of the stochastic cooling systems perform different functions, they each have similar components, which will be subdivided into six basic parts for this discussion:

Beam pick-up electrodes or slotted waveguides:
There are two different kinds of pick-ups used to sample the beam. The stacktail momentum and core momentum systems use beam pick-up electrodes. All Debuncher cooling as well as the Accumulator core transverse systems use slotted waveguide pick-ups. Both systems provide the same basic functionality, to provide a beam error signal to be processed by the cooling system.

Beam pick-up electrodes
Beam pick-up electrodes are quarter-wave loop (directional coupler) pick-ups that are contained within a tank assembly, which is kept under vacuum. The pick-up electrodes are striplines, with a terminating resistor on the adjacent grounded walls of the tank. Figure 5.5 illustrates the electric field lines generated by the passage of charged particles. More accurately, each antiproton generates a short pulse in the stripline as it traverses the gaps.

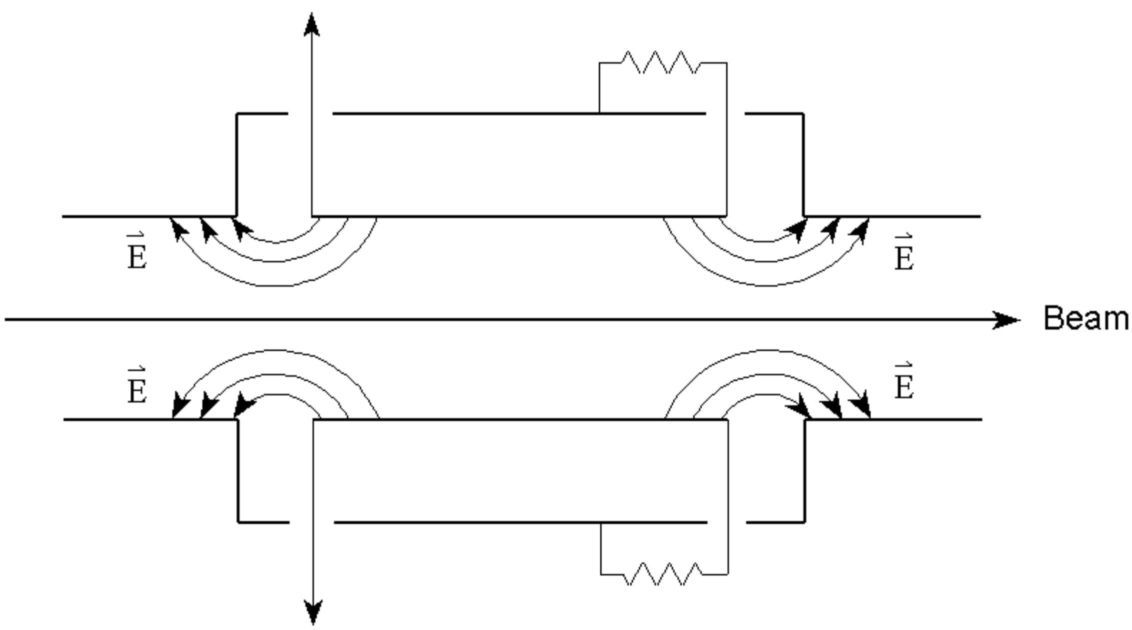

Figure 5.5: Stripline Pick-up

The pick-up plates form transmission lines that have a characteristic impedance. A series of pick-up electrodes are housed in a pick-up tank. Opposing electrodes (top and bottom or left and right, depending on the application) are combined in phase by combiner boards. Adding or subtracting signals between plates found on opposite sides of the vacuum chamber creates sum and difference signals. Difference signals are used for betatron cooling; sum for momentum cooling. Passive devices known as hybrids create the sum and difference signals.

The Slotted Waveguide

The Slotted waveguide “slow wave” structure is shown in Figure 5.6, with the outline of a quarter at the bottom to provide a sense of scale. The rectangular beam pipe (blue box) is coupled to two rectangular waveguides (magenta boxes) by a series of slots. The transverse signal is derived from the difference of the two waveguides and the momentum signal is derived from the sum of the two waveguides. Beam traveling through the accelerator leaves a charged image current on the wall of the conductive beam pipe. The slots interrupt the image current and the electromagnetic waves are excited in the slots, which in turn excite traveling waveguide modes in the side waveguides and beam pipe.

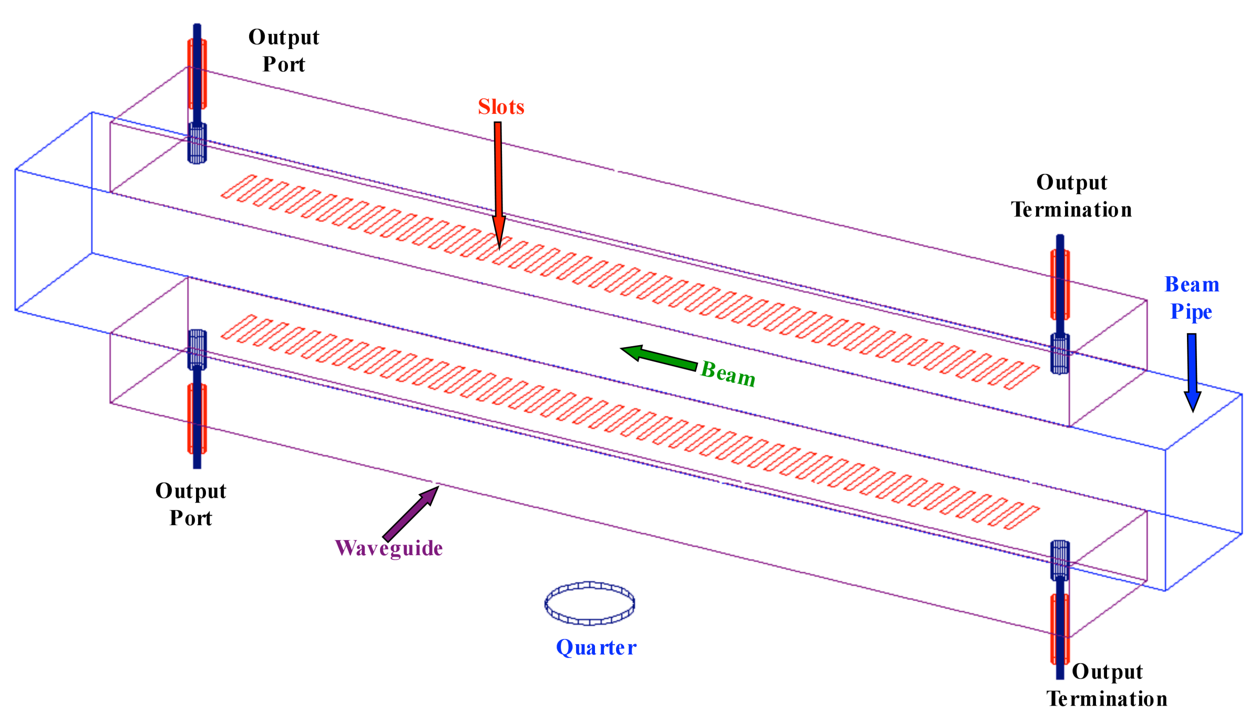

Figure 5.6: Slotted waveguide

The phase velocity is the rate at which the phase of the electromagnetic wave propagates through the waveguide. If there were no slots in the waveguide, the phase velocity would actually be faster than the speed of light. This does not violate relativity, since the speed at which energy is transported in the waveguide, called the group velocity, is not greater than the speed of light. This is similar to how water waves on a lake shore can appear to move much faster (phase velocity) than the actual movement of the water (group velocity). Back to our waveguides, the slots actually "slow down" the waveguide phase velocity modes by creating multiple reflections. The reduction in phase velocity is a function of the slot length and width and the spacing between the slots, and the coupling of the slots to the beam is proportional to the slot length. When the reduced phase velocity of the waveguide exactly matches the beam velocity, the coupling of the slots will add constructively. As a result, the output signal actually grows over the length of the slots like an "Electromagnetic whistle." The gain of the array is proportional to the number of waveguide slots and the length of the array; however, the bandwidth is inversely proportional to the length of the array.

The pick-up assemblies are cryogenically cooled with liquid helium to a temperature of about 4.5° Kelvin for the pick-up and 10° Kelvin for the amplifier. The signals are amplified with low noise cryogenic preamps, and narrow band filters reject signals outside of the desired frequency. Unlike the electrode pick-up systems that operate in the 2-4 GHz range, the slotted waveguide system is designed to operate in the 4-8 GHz range. This system provides a stronger response than the older pick-up electrode system, but the response is over a narrower bandwidth. As a result, slotted waveguide systems are divided into multiple bands. The Debuncher cooling systems have eight bands in each plane for the pick-ups (four bands each divided into upper and lower bands) This was done by making longer, narrower, band arrays that have higher sensitivity and also reduced by a factor of 2 the number of cold to warm feed through transitions in the pick-ups (for heat load considerations). The Debuncher kickers have four bands, as the fan-out system utilizes many TWTs to limit power dissipation at individual power feed-throughs. The Accumulator core transverse systems have three bands each. There is one pick-up array per sub-band per plane.

Low level electronics

Low level electronics: the resultant sum and difference signal is amplified and added in phase with signals from other cooling tanks, if necessary, by means of mechanical delay lines known as trombones. The first stage of amplification is accomplished by GaAsFET preamplifiers, which in most cases are cryogenically cooled to reduce thermal noise. The Debuncher preamplifiers are cooled to liquid helium temperature, stacktail preamplifiers are cooled to liquid nitrogen temperature. Core systems do not require cryogenic cooling because there is a stronger signal from the beam. The 2-4 GHz core momentum system is the exception, the preamplifiers are cooled to liquid nitrogen temperature. Since the pick-up tank is located in A60 along with the stacktail pick-up tanks, there was little additional expense required to provide liquid nitrogen to preamplifiers. Ultimately, an amplified signal with a good signal to noise ratio is the input to the next level of the system.

Medium level electronics

Medium level electronics: more amplification is applied and the signal is sent towards the kickers on a single coaxial cable known as a trunk line. Trombones are again used to ensure that the corrective signal arrives at the kickers at the appropriate time. Also included in the medium level electronics are variable PIN (P type, Intrinsic, N type semiconductor) attenuators, which permit the gain of the system to be adjusted. Increasing the attenuation (expressed in units of dB's) will lower the power output of the system.

Another kind of component found in the medium level is two varieties of switches. Coaxial mechanical transfer switches break the continuity between the pick- up and kicker in order to make open loop transfer function measurements. The beam is a feedback element in this measurement. PIN diode switches are an additional means of opening and closing the circuit. PIN switches are used because they are solid state devices that do not have mechanical fatigue problems from frequent cycling. Most PIN switches have gating capability: the switch can be turned on (the circuit is closed), off (the circuit is open), or gated (the switch can be automatically turned on and off via timers). The core systems, for example, are gated during beam transfers so that the cooling is turned off when unstacking occurs and is turned back on after the transfer has been completed.

An important component of many of the system's medium level circuitry are notch filters. Notch filters act to remove undesired components of the signal from the pick-up before being applied to the kicker (in the case of the Accumulator stacktail and Debuncher betatron systems) or to shape the gain profile (as in the case of the Debuncher momentum system). Specific examples will be provided with the description of each cooling system below. Notch filters built for the cooling systems are of the correlator type, which use the constructive and destructive interference of the same signal transmitted over two transmission lines – like an interferometer. The basic components of the filters are a splitter, trombones, a delay element equivalent to a one turn delay and a hybrid. The splitter splits the medium level signal between two legs - a 'short' leg which is a straight ahead path for the incoming signal and a 'long' leg which consists of a Bulk Acoustic Wave (BAW) delay line, fiber optic link, or superconducting coaxial delay cable. The difference between the two paths is precisely equal to an integer number of revolution delays. Momentum cooling uses a one turn delay. Debuncher cooling systems utilize a delay that is switched mid cycle between one turn and the next. Debuncher transverse cooling utilizes two turn delays. Trombones are used to maintain the proper delay between the two legs and a 180-degree hybrid combines the two legs.

High level electronics

High level electronics: The signal from the medium level is fanned out to all of the kicker tanks and unraveled in time as appropriate by means of splitters and trombones. Prior to being applied to the kicker electrodes or slotted waveguides, the signals are further amplified at microwave frequencies through devices known as Traveling Wave Tubes or TWTs. Although part of the high level, the TWTs are treated separately here.

Traveling Wave Tube

Traveling Wave Tube: The TWT is a linear beam tube amplifier that provides 30-60 db of gain over octave bandwidths at microwave frequencies. Power levels of a few watts to thousands of watts are attainable. The TWTs used in the Antiproton Source for stochastic cooling operate over octave bandwidths of 2-4 GHz and 4-8 GHz. Each has a saturated power level of 200 watts and 40-50 db of gain, although they are normally run at 100 watts or less. Refer to figure 5.7, which diagrams a typical TWT, as you read the description that follows.

An electron beam is accelerated down the center of a helical 50 Ω transmission line, with the helix power supply providing the source of acceleration voltage. The kinetic energy of the electron beam is typically 3-10 keV and beam currents in the 200-500 mA range are produced from the TWTs used in the Antiproton Source. The microwave signal to be amplified is applied to the helical transmission line. Due to the relatively slow velocity of the electron beam, the helical transmission line acts as a "slow wave" structure forcing the propagating microwave signal to match the velocity of the electron beam. Adjustment of the helix supply is necessary to properly match the velocities and optimize tube performance. Propagating in "sync" causes a velocity modulation or bunching of the electron beam resulting in the electron beam imparting some of its energy to the latter part of the slow wave transmission line structure (i.e. gain).

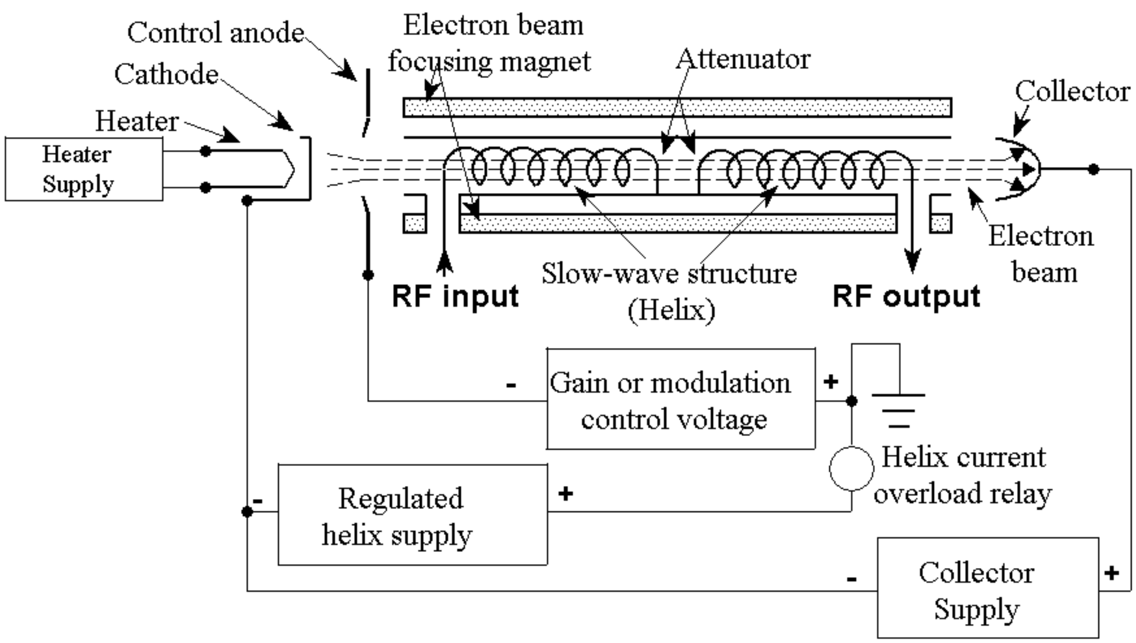

Figure 5.7: Helix type Traveling Wave Tube

The transmission line is not a resonant structure, hence a TWT can have a wide bandwidth of operation. An attenuating material is used to support the helical structure to provide isolation between the input and output (if the attenuation material is omitted, it is a BWO or Backward Wave Oscillator). The entire slow wave structure, electron source (cathode) and collector are housed in a sealed stainless steel vacuum envelope. The beam is confined within the helix with permanent magnet focusing. Some higher power TWTs use powered solenoid magnets, but those used in the Antiproton Source use rare earth magnets. The efficiency of TWTs is typically below 20% and those used for stochastic cooling in the Antiproton Source are about 10% efficient.

The excess beam energy ends up in the collector. To improve efficiency, several stages of collector may be employed. While the stochastic cooling TWTs typically have one or two stages, some may have up to 4 collectors to improve efficiency. An anode may be added to the TWT to provide modulation or gain control. Only the 2-4 GHz TWTs at Fermilab are equipped with a modulation anode, but it is biased to the continuous mode.

The power supplies for a TWT must be very well regulated to produce a stable electron beam. The propagation time through a TWT is approximately 10-15 nanoseconds, while the stochastic cooling systems require timing precision to a few picoseconds. Voltage ripple of just a fraction of a percent is sufficient to cause enough propagation velocity variation in the electron beam to cause system timing problems.

Kicker electrodes or slotted waveguides

Kicker electrodes or slotted waveguides: There are two different systems used to provide the corrective kick to the beam. The stacktail momentum and core momentum systems use kicker electrodes, while all of the Debuncher cooling as well as the Accumulator core transverse systems use slotted waveguides. Both systems provide the same basic functionality, to provide a correction to the error signal measured by the pick-up electrodes or slotted waveguides.

Kicker electrodes are physically identical to their pick-up counterparts. Each loop is terminated with a resistor and is rated to handle up to 10 Watts of microwave power. The stacktail and core kicker tanks in straight section 30 are outfitted with a design of kicker array referred to as a planar loop, which are made on a printed circuit board to simplify fabrication.

The kicker arrays and terminating resistors are cooled with water provided by a closed-loop chilled (55° F) system. Make-up water to the system comes from Pbar 95 LCW, but there are no de-ionizing cartridges used to preserve the low conductivity. The cooling water is usually referred to as “clean” water, and has excess heat removed by a small refrigeration unit that is located on the skid. Chilled water was originally used for cooling the tanks, but proved to be too dirty and caused clogged flow turbines and reduced cooling efficiency.

Although kicker electrodes for transverse and longitudinal cooling systems are physically the same, there is a difference in how the correction signals are applied to them. Simplified diagrams of kickers in both sum (longitudinal) and difference (transverse) modes are illustrated in Figure 5.8. As with pick-up electrodes, excitation of the beam takes place at the gaps between the pick-up and grounded wall. Note that in sum mode the signals applied to the kicker electrodes are in phase with each other. When in sum mode, the electric fields are oriented so that a longitudinal kick is applied to the beam. In difference mode the signals are 180° out of phase with respect to each other and the electric fields result in a transverse kick to off-center particles.

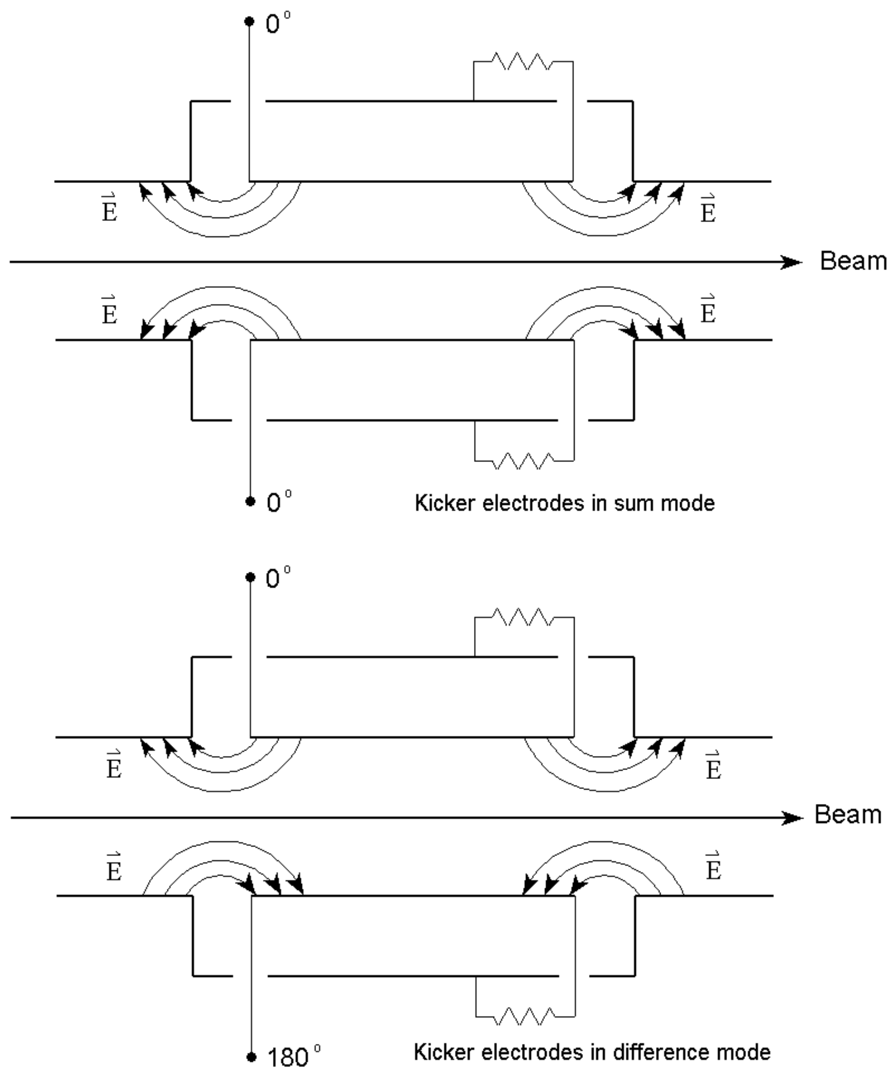

Figure 5.8: Kicker electrodes in sum and difference mode

As with their pick-up counterpart, the kicker waveguides are based on the principle of slowing the phase velocity of the waveguide modes in the beampipe and input/output waveguides to match the velocity of the beam. A transverse correction can be made to the beam by applying a correction with the phase between opposing input/output waveguides at 180 degrees. Likewise, a longitudinal correction can be made by applying the correction with the phase between opposing input/output waveguides at 0 degrees. Slotted waveguide kickers are physically similar to their slotted waveguide pick-up counterparts. In the Debuncher's case, the pick-ups are twice as long as the kickers. There are only four kicker bands per plane, compared to the eight pick-up bands. Each TWT puts out about 150W. One important design consideration is stopping the microwave energy from the waveguides from propagating around the ring. To achieve this, LCW cooled microwave absorbers were added in the tanks at each end in order to absorb stray microwave power. The LCW cooling is provided by the same cooling water system that is used for the kicker electrodes.

System	Debuncher Horizontal	Debuncher Vertical	Debuncher Momentum
Slotted Waveguide Pick-up location	D10	D10	D10
Slotted Waveguide Kicker Location	D30	D30	D30
# of bands	8 pick-up & 4 kicker	8 pick-up & 4 kicker	8 pick-up & 4 kicker
Overall Bandwidth	4-8 GHz	4-8 GHz	4-8 GHz
Bandwidth (Band 1)	4.0-4.95 GHz	4.0-4.95 GHz	4.0-4.95 GHz
Bandwidth (Band 2)	4.85-5.82 GHz	4.85-5.82 GHz	4.85-5.82 GHz
Bandwidth (Band 3)	5.8-6.9 GHz	5.8-6.9 GHz	6.0-7.1 GHz
Bandwidth (Band 4)	6.65-8.1 GHz	6.65-8.1 GHz	7.2-8.3 GHz
# of TWTs per band	4	4	8
# of TWTs (Total)	16	16	32
TWT operating power (each)	150 watts peak	150 watts peak	150 watts peak
TWT trip level	175 watts	175 watts	175 watts

Table 5.1: Debuncher cooling systems

Debuncher Betatron

The Debuncher Betatron systems reduce the transverse emittances of beam in the Debuncher so that the pbars will transfer efficiently into the Accumulator. Each system presently reduces the emittance from about 30 to 3 pi-mm-mrad in 2.2 seconds. The bandwidth of these cooling systems is 4-8 GHz but is comprised of 4 discrete cooling systems of approximately 1 GHz bandwidth each. Because the Pbar intensity in the Debuncher averages only

1.5–2.0 x10^8 particles, the electrodes and preamplifiers are cooled with liquid helium. This serves to reduce the thermal noise, which would contribute to the less efficient cooling. Unwanted signals are also removed by the use of correlator Bulk Acoustic Wave (BAW) two turn delay notch filters. The BAW filters notch out unwanted thermal noise at harmonics and half harmonics (between the betatron sidebands) of the revolution frequency. Then, leaving only the signals from the betatron sidebands, the signals are amplified by the TWTs and applied to the kickers. By increasing the signal to noise ratio, less TWT power is produced as noise that would heat the beam, while leaving more power to cool the beam. Debuncher cooling signals from upstream and downstream pick-up tanks exit different 10 sector stub rooms, but arrive at the same stub room in 30 sector, as shown in Figure 5.9.

There are a total of 8 kicker tanks in straight section 30, each is used for both transverse and momentum cooling. One kicker tank is used for each band in each plane, with the horizontal and vertical tanks of each band also utilized for momentum cooling. Due to the length of the pick-up and kicker arrays and the need to keep the proper phase advance between the pick-ups and kickers, the tanks are separated by 180° of betatron phase advance and combined with a 180° hybrid. There are 16 TWTs in each plane operating at 150W peak output each.

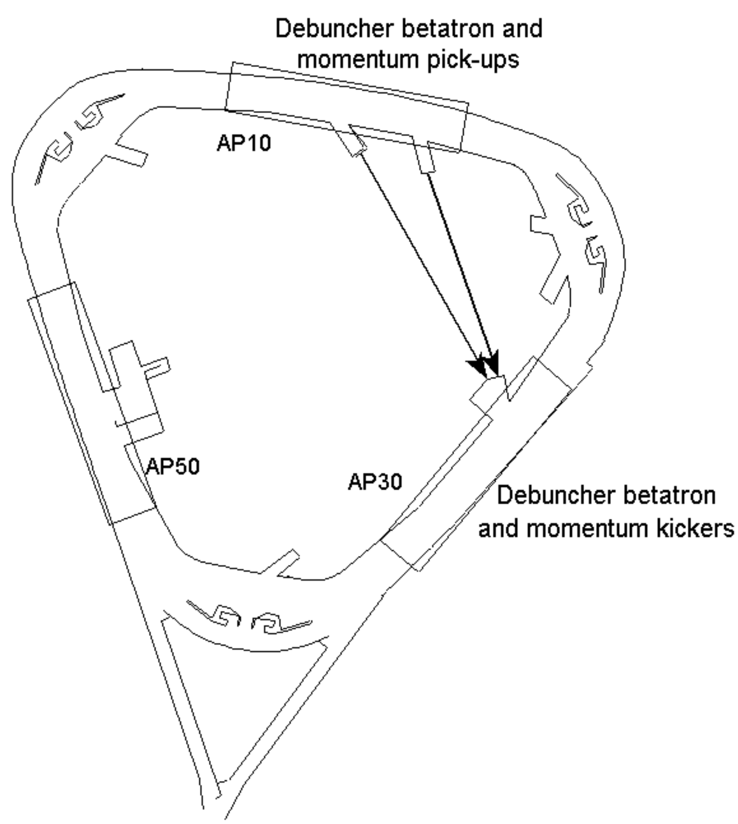

Figure 5.9: Location of Debuncher stochastic cooling components

Debuncher Momentum

Antiprotons that circulate in the Debuncher have their momentum spread further reduced after bunch rotation and adiabatic debunching by means of momentum cooling systems. Momentum cooling was an upgrade that was installed in 1989, and was later updated to a multiple band 4-8GHz slotted waveguide system in 2000. The current system uses the same pick-up and kicker slotted waveguides as those in the Debuncher betatron systems. Instead of using the signals from the pick-ups in the difference mode, however, the signals are summed. Similarly, the signal applied by the kickers to the beam is in the sum mode. The frequency range of this system is 4-8 GHz, and like the betatron cooling is comprised of 4 discrete cooling systems of approximately 1 GHz bandwidth each. This system currently reduces the Debuncher $\Delta p/p$ (momentum spread) from ~ 0.30% to < 0.14% in 2.2 seconds.

System	Stacktail Δp	Core 4-8 Horizontal	Core 4-8 Vertical	Core 2-4 Δp	Core 4-8 Δp
Pick-up Type	Pick-up Electrode	Slotted Waveguide	Slotted Waveguide	Pick-up Electrode	Pick-up Electrode
Pick-up Location	A60	A10	A10	A60	A20
Kicker Type	Kicker Electrode	Slotted Waveguide	Slotted Waveguide	Kicker Electrode	Kicker Electrode
Kicker Location	A30	A30	A30	A30	A50
# of pick-up sets	256 at +13.7 MeV (2 tanks with 128 each) 48 at –6.4 MeV 16 at –22.9 MeV	One slotted waveguide for each band	One slotted waveguide for each band	16 at core orbit 16 at central orbit	32
Number of bands	1	3	3	1	1
Bandwidth	2-4 GHz	**4-8 GHz** Band 1: 4.35-5.65GHz Band 2: 5.35-6.65GHz Band 3: 6.35-7.65GHz	**4-8 GHz** Band 1: 4.35-5.65GHz Band 2: 5.35-6.65GHz Band 3: 6.35-7.65GHz	2-4 GHz	4-8 GHz
# of amplifiers	32 sum 4 delta TWTs	3 five Watt Solid State amps	3 five Watt Solid State amps	1 TWT	2 TWTs
# of kicker pairs	256 with 64 delta kicker pairs (half vertically half horizontally oriented)	One slotted waveguide for each band	One slotted waveguide for each band	32	64
Typical operating power	1,000 watts	150W peak	150 W peak	40 watts	0-10 watts

Table 5.2: Accumulator cooling systems

All of the Debuncher transverse pick-up and kicker slotted waveguides are used for the momentum system – the kickers are driven with both momentum and transverse signals. 32 TWTs are dedicated to momentum cooling, again mounted on the kicker tanks, and run at 150 watts peak per TWT watts. This system also has a notch filter that provides the gain shaping necessary for momentum cooling. The filter utilizes a fiber optic delay that switches between a one turn and two turn delay. At the beginning of the stacking cycle, the momentum spread of the beam is wide and requires a single turn notch filter. At mid-cycle, the two turn delay is switched in optically to create a steeper gain profile, further reducing the momentum spread.

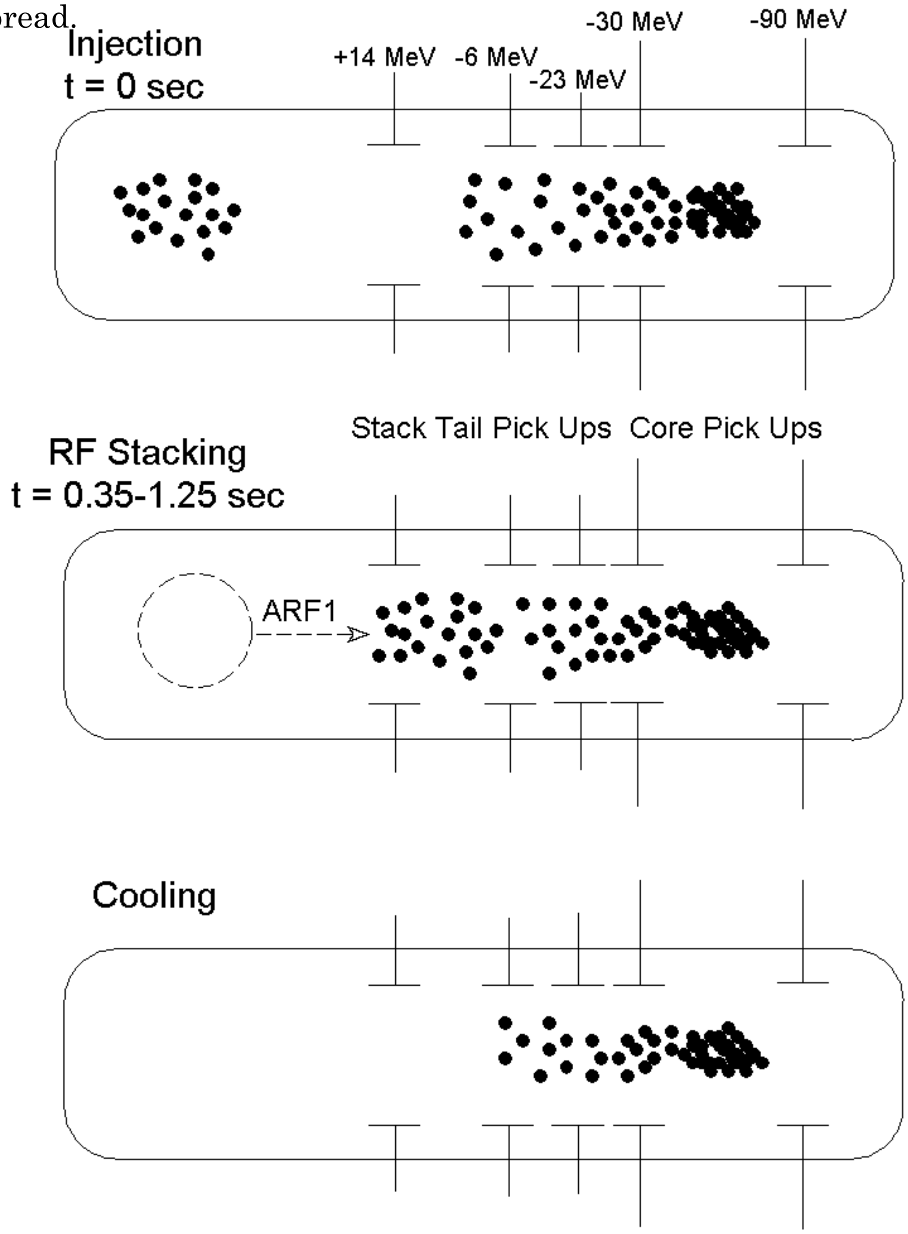

Figure 5.10: Stacktail and core momentum pick-up locations

Accumulator Stacktail Momentum

After antiprotons have been injected into the Accumulator, the particles must be decelerated by roughly 150 MeV to reach the core. The first 60 MeV of deceleration is handled by ARF-1 while the final 90 MeV is accomplished by the 2-4 GHz stacktail momentum system. Because an RF bucket displaces beam that it passes through, it is not possible to use an RF system to decelerate beam the full 150 MeV to the core.

All of the stacktail pick-ups are located in the A60 high dispersion region and are subdivided into three separate arrays called the +13.7 MeV (leg 1), –6.4 MeV (leg 2) and –22.9 MeV (leg 3 or compensation leg) pick-ups. Figure 5.10 shows the relative positions of the stacktail and core momentum pick-ups. The pick-up names identify the part of the stacktail for which the particular pick-up array is most sensitive to, relative to the central orbit of the Accumulator. The stacktail extends from about +30 MeV where ARF1

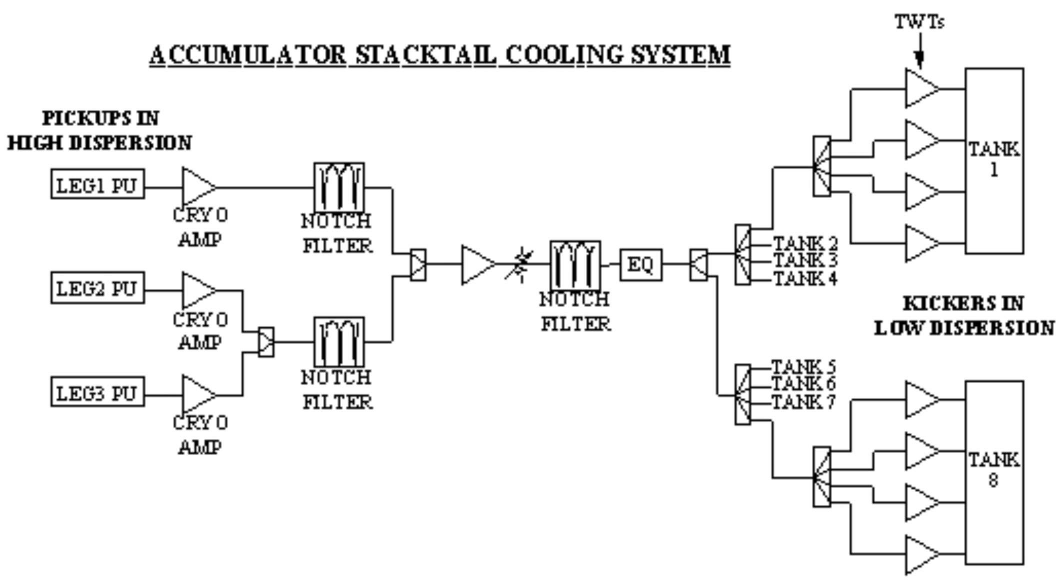

Figure 5.11: Diagram of the stacktail system

deposits beam to the edge of the core at about -30 MeV. In the high dispersion region, where the pick-ups are located, a difference in energy results in a primarily horizontal position shift (there is very little vertical dispersion in the Accumulator). A notable difference in the three arrays is in the number of pick-up elements each one contains. The +13.7 MeV pick-ups are made up of 256 individual pick-up electrode pairs divided evenly between two different tanks. The –6.4 MeV pick-ups, made up of 48 electrodes, and the –22.9 MeV pick-ups having only 16 electrodes, are located inside another tank. Figure 5.11 provides a simplified diagram of the stacktail system and Figure 5.12 shows the signal path from the pick-up tanks in the A60 straight to the kickers in the A30 straight section.

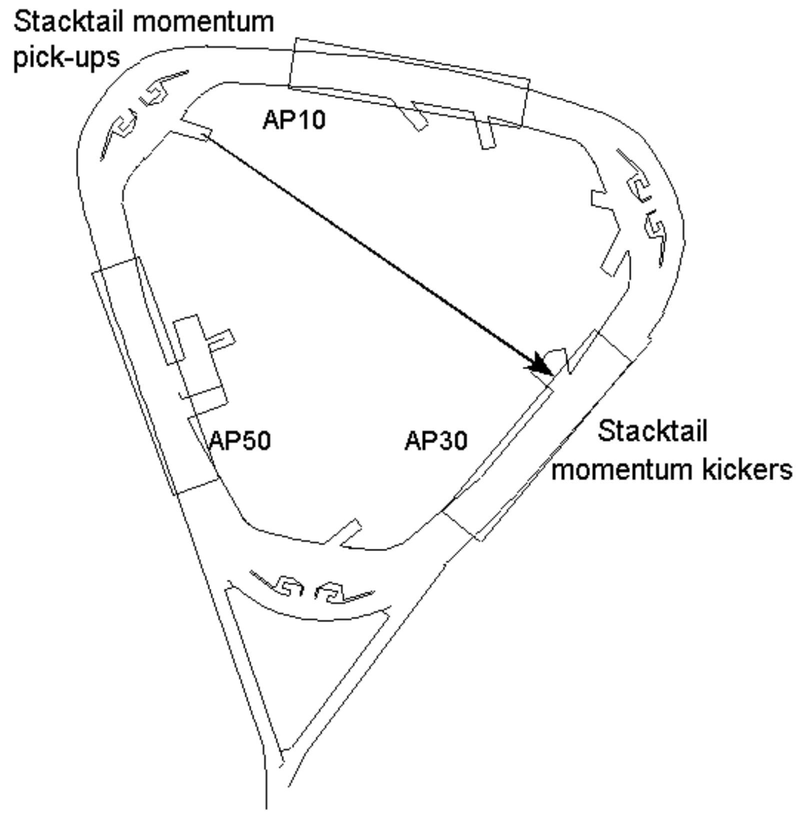

Figure 5.12: Location of stacktail momentum cooling system components

To understand why there are so many pick-up electrodes at +13.7 MeV and so few at –22.9 MeV, consider how beam is distributed in the stacktail. At the deposition orbit, the point where ARF-1 drops off the beam, there is a relatively small amount of beam for the +13.7 MeV electrodes to detect. For the stacktail system to work effectively, a certain amount of the beam signal must be detected above the background noise. Thermal noise from the pick-ups is reduced by cooling parts of the pick-up assemblies to liquid nitrogen temperature. To achieve an adequate amount of beam signal above the noise floor from the +13.7 MeV array, it is necessary to have a large number of pick-ups. The –22.9 MeV pick-ups, on the other hand, are located much closer to the core where there is considerably more beam. Sixteen electrodes are adequate to produce a reasonable signal to noise ratio.

The signals coming from the pick-up arrays are modified by the stacktail electronics to provide the phase and gain characteristics necessary to effectively momentum cool the beam. This must be accomplished while minimizing effects on beam in the core. The system gain changes nearly exponentially across the stacktail, and is highest where ARF-1 drops beam off and lowest at the edge of the core. Because of this, the high energy beam arriving at the edge of the stacktail moves very rapidly away from the deposition orbit. It is important for the stacktail system to have this feature since any beam remaining near the deposition orbit will be RF displaced into the field region of the injection kicker when ARF-1 pulses on the next stacking cycle. Low energy beam on the core side of the stacktail moves very slowly and tends to "pile up" against the core, giving the stacktail its characteristic shape, which is illustrated in figure 5.13.

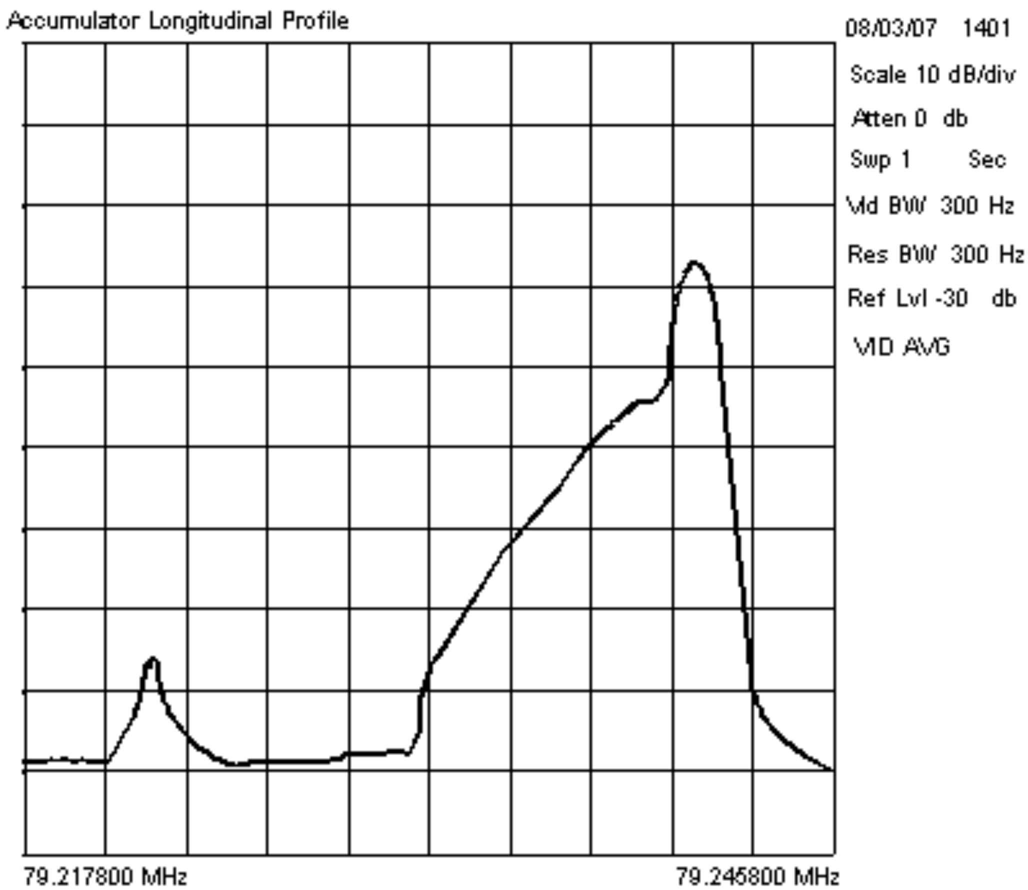

Figure 5.13: Accumulator longitudinal spectrum analyzer display

Transverse kicks induced by the stacktail momentum system, mostly due to imperfect hybrids and kicker misalignment, lead to betatron heating of the beam in the stacktail and core. This can be partially overcome in the stacktail system by applying a small part of the signal from the kicker electrodes in the difference or delta mode (recall that momentum pick-ups and kickers are normally in the sum mode). The first and last kicker tanks in the A30 straight section are stacktail tanks used as "delta kickers". These tanks were selected because they are nearly 90° out of betatron phase with each other. Half of all of the stacktail momentum kicker electrodes are oriented horizontally and the other half are oriented vertically. The delta kickers apply the difference signal to the kicker electrodes, resulting in a transverse kick to the beam. The delay and attenuation values for the delta kickers are calculated using network analyzer beam measurements, then fine-tuned empirically. Delta kickers in the Stacktail have not been used effectively since the upgrade to 2-4 GHz at the beginning of Run II.

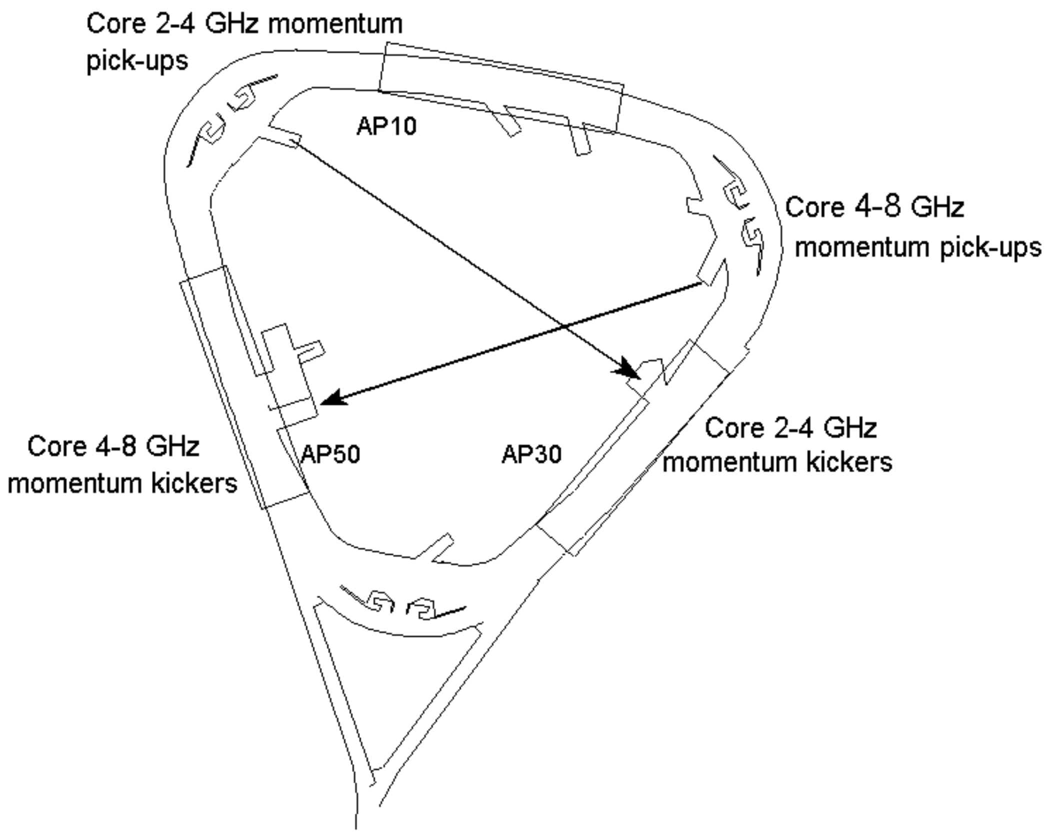

Figure 5.14: Location of core momentum cooling systems

Core Momentum

The Core momentum cooling systems keep the antiproton core contained by decelerating high energy particles and accelerating low energy particles. There are two core momentum systems currently in use. The original 2-4 GHz system has its pick-up tank in the A60 high dispersion straight section and kickers in the A30 area. The 4-8 GHz system, added in 1989, includes a pick-up tank in the A20 section and a kicker tank in A50 (see figure 5.14).

The 2-4 GHz and 4-8 GHz systems are used together to provide momentum cooling for the core. The 4-8 GHz system is able to cool the core to a smaller momentum spread with decreased cooling time (because of its larger bandwidth), while the 2-4 GHz system has a greater frequency "reach". The 4-8 GHz pick-up arrays are moveable, so that system can cool beam away from the core for beam studies. The two core momentum systems are stand-alone systems, so they need to be kept aligned to optimize performance. Normally the pick-ups of the 4-8 GHz system are positioned so that both systems are cooling to the same revolution frequency.

Core Betatron

There are three horizontal and three vertical transverse cooling systems spanning the 4-8 GHz band. Each of the three systems in the transverse planes operates over only part of the octave band, as summarized earlier in Table 2. These systems are used to control the transverse emittances of particles in the core. Pick-up tanks are located in the A10 low dispersion straight section, an area where any sensed position error will be due to transverse oscillations rather than energy. The kickers are in the A30 straight section. Both pick-up and kicker tanks use slotted waveguides, like the Debuncher cooling systems.

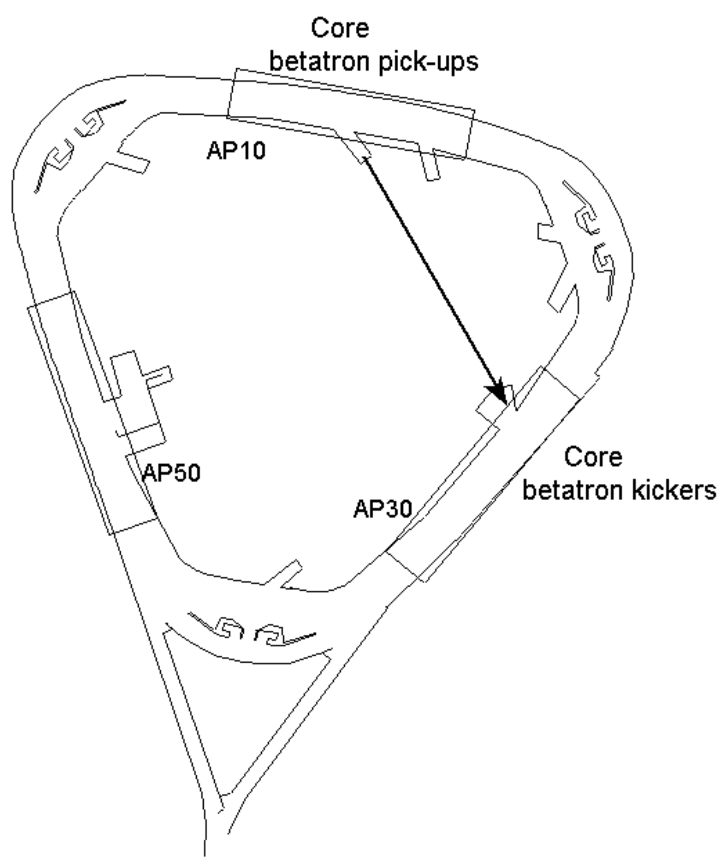

Figure 5.15: Location of core betatron cooling systems

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6 Transport Lines

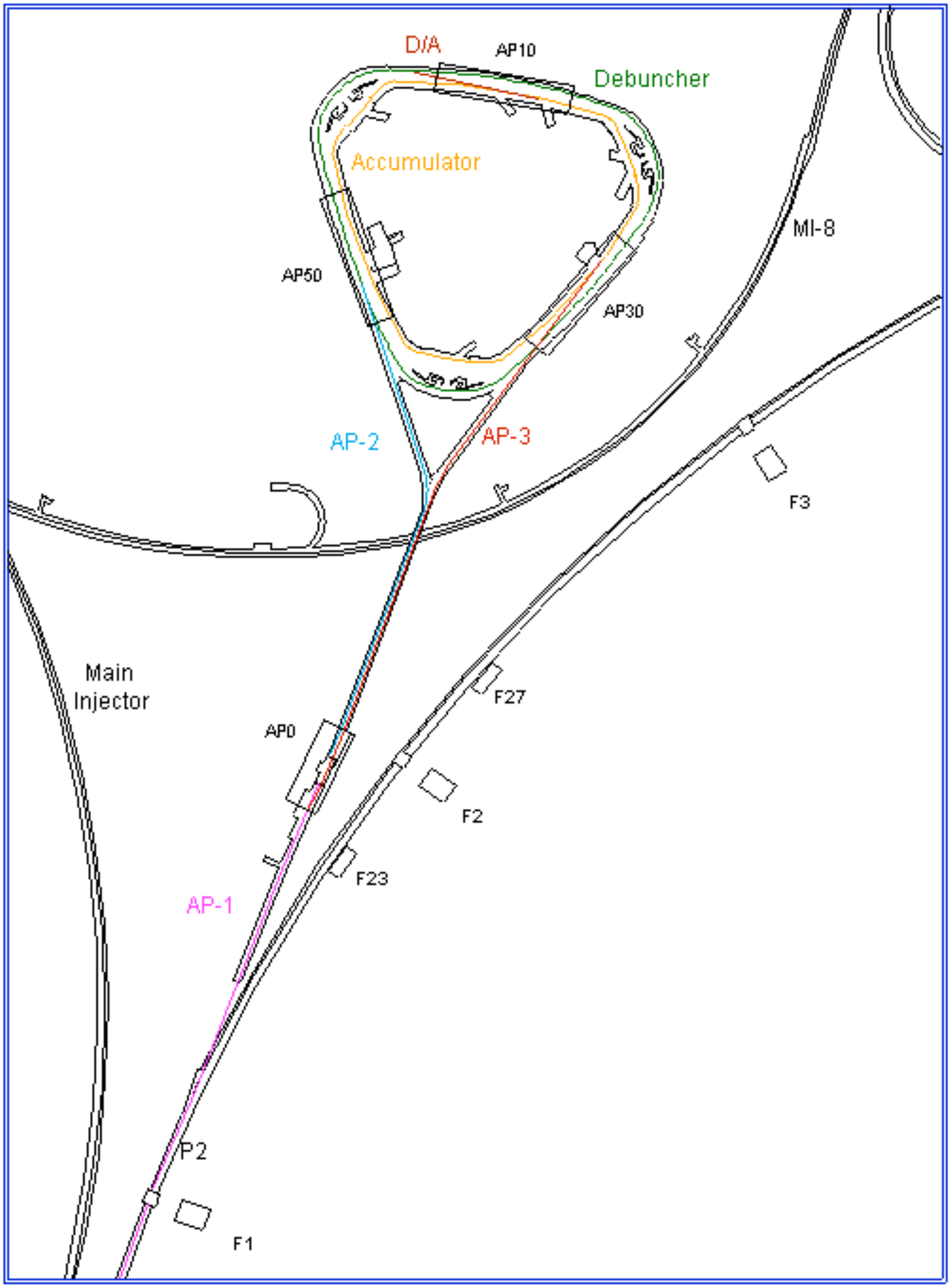


Figure 6.1: Pbar beamlines

Introduction

There are six beam transport lines used to connect the Debuncher and Accumulator to the Main Injector, as well as to each other. Figure 6.1 provides an overview map of the beamlines to help visualize their layout.

- The P1, P2 and AP-1 lines transport 120 GeV protons extracted from the Main Injector to the pbar production target. When operating at 8 GeV, the AP-3, AP-1, P2 and P1 lines deliver antiprotons extracted from the Accumulator to the Main Injector. Protons can also be "reverse injected" from the Main Injector to the Accumulator for transfer tune-up or studies.
- AP-2 transports 8 GeV antiprotons from the Target Station to the Debuncher ring. Protons can be reverse injected from the Debuncher into the AP-2 line for studies. On infrequent occasions, magnet polarities are reversed in the AP-2 line and the Target and Lithium Lens removed to allow 8-GeV protons from the Main Injector to be transported to the Debuncher for studies.
- The D to A line transfers antiprotons between the Debuncher and Accumulator. Protons that have been reverse injected into the Accumulator can also be transferred into the Debuncher for studies.

Detailed maps of the beamline magnet locations haven't been included in this chapter, but are available elsewhere. Specifications of electrical, cooling water and vacuum systems are consistent with those found in the Debuncher, details can be found in the Utilities chapter of this book. The Diagnostics chapter contains information about Beam Position Monitors (BPMs), Beam Loss Monitors (BLMs) Secondary Emission Monitors (SEMs) and other diagnostics found in the transport lines.

Naming Conventions

Beam line	Dipoles Power supplies	Dipoles Magnets	Quads Power Supplies	Quads Magnets	Trims Power Supplies	Trims Magnets
P1	I:HV7**	HV7**	I:Q7**	Q7**	I:HT7**	HT7**
P2	I:HVF1*	HVF**	I:QF1*	QF1*	I:HTF1*	HTF1*
AP-1	M:H10*	PB*	M:Q10*	PQ*	M:HT10*	PQ*-HT
AP-2	D:H7**	IB*	D:Q7**	IQ**	D:HT7**	IQ**-HT
D to A	D:H8**	TB*	D:Q8**	TQ*	D:HT8**	TQ*-HT
AP-3	D:H9**	EB*	D:Q9**	EQ**	D:HT9**	EQ**-HT

Table 6.1: Naming conventions

The naming convention used in the transport lines can be confusing, because there are both magnet names and power supply names. Magnets are generally identified by their installation names since the power supplies are often connected to multiple loads. Table 1 summarizes magnet and power supply names for the beamlines. Note that consecutive magnets at a given location are identified with an additional digit (e.g. HV7071, HV7072) or letter (e.g. PQ9A, PQ9B).

The leading letter in the magnet names for the pbar beamlines represents which beamline it's a part of; for AP-1 magnets the "P" is for "Proton", in AP-2 the "I" is for "Injection", in the D to A line the "T" is for "Transfer" and in AP-3 the "E" is for "Extraction". The second letter is somewhat intuitive, "B" is for "Bend" (dipole), and "Q" is for "Quad." Trims are identified with a hyphenated extension, HT (VT) for a horizontal (vertical) trim. Dipoles are assumed to be horizontal unless otherwise indicated, e.g. IB1 is a horizontal dipole while IBV1 is a vertical dipole. In AP-1, bending magnets that have been rolled to bend in both the horizontal and vertical planes include the letter “R” in the magnet name, e.g. PBR2.

Originally, there were separate AP-1 power supplies for 8 GeV and 120 GeV operation. The dual power supply configuration was used to improve power supply regulation at 8 GeV. Although the 8 GeV power supplies still exist (M:H2**, M:Q2**), they are not used operationally. The change from dual power supply operation to ramping AP-1 was driven by the need to reduce the stacking interruption for transfers to the Recycler.

Kickers and Septa

Beam transfer to and from the Pbar rings is accomplished with kicker and septa pairs. An injection septum bends the beam from a transport line into an accelerator and an injection kicker deflects the beam onto the closed orbit. An extraction kicker deflects beam from the closed orbit of an accelerator into the field region of a septum, which in turn bends the beam into a transport line. There are two styles of kickers in the antiproton source, an Accumulator style and a Debuncher style, that both produce magnetic fields of approximately 500 Gauss. All but one of the septum magnets used in pbar are a single-turn design that are pulsed. The exception is the Accumulator extraction Lambertson (ELAM). Normally ELAM is called the Extraction Lambertson and the name “Septum” refers to a single-turn pulsed septum magnet.

Kickers

The Debuncher injection and extraction kickers are ferrite single-turn transmission line pulsed magnets that are similar in design to those found in the Booster, Main Injector and Tevatron. The 200 nanosecond fall time for the injection kicker and rise time for the extraction kicker required some modifications from kickers previously designed.

Debuncher kickers are made up of three separate modules to limit propagation delay. Figure 6.2 is an end view of the Debuncher injection kicker, to use as a reference in the following description. Each module is about a meter long and is made up of a series of 48 sets of 4 ferrite blocks about 1.8 cm thick stacked around a copper conductor. 12 pairs of capacitors are connected on one end to the central copper conductor that carries the current. The other end is connected to the aluminum case, which is grounded. The module case does not contain the beam tube, which is an external elliptical ceramic chamber 5.7 cm. x 4.1 cm. The module has a "c" shape that surrounds the beam tube on three sides, so replacing Debuncher kicker modules doesn't require breaking vacuum. With the central conductor and ferrites providing the inductance and the capacitors providing the capacitance to the circuit, the magnet electrically looks like a 10Ω transmission line. The ferrites, which are at high voltage like the conductor, are insulated from the outer case with G-10. The capacitors and their power leads are potted with an insulating rubber compound.

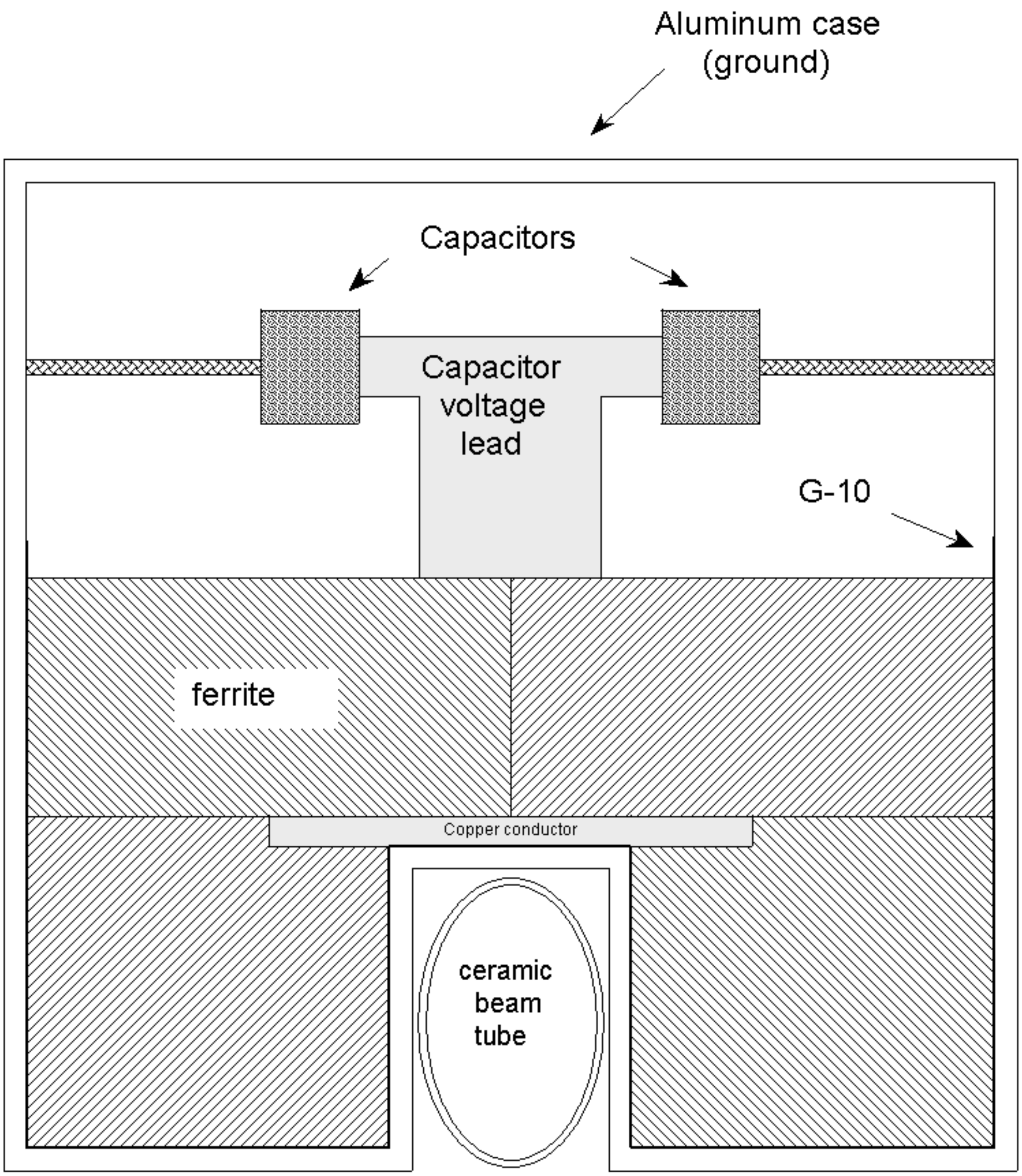


Figure 6.2: Debuncher injection kicker

The Accumulator kickers bear little physical resemblance to those in the

Debuncher, although they are similar electrically. Many of the design considerations were driven by the need for excellent vacuum and a cycling shutter to shield the antiproton core from the kicker pulse. The shutter is a plate of aluminum 5 mm thick and 3 m long. Three titanium arms "rock" the shutter in to and out of place and are driven through linkage by a DC stepping motor. Since the stray fields from the kickers are not as strong as originally anticipated, the shutters are usually only used during reverse-proton operation to keep wayward protons from mingling with pbars.

The Accumulator kickers have a cylindrical conductor surrounded by "c" shaped ferrites. The ferrites are specially prepared and handled to minimize outgassing. Distributing parallel plate capacitors along the length of the magnet provides capacitance in the kicker circuit. High voltage plates are attached to the center conductor and ground plates are located between the high voltage plates. The capacitors make use of an alumina ceramic as a dielectric as well as for various insulating components.

The A20 straight section contains both Accumulator kickers. The kickers are housed in tanks that are similar in appearance to stochastic cooling tanks. Large high voltage cables feeding into the kicker tanks distinguishes

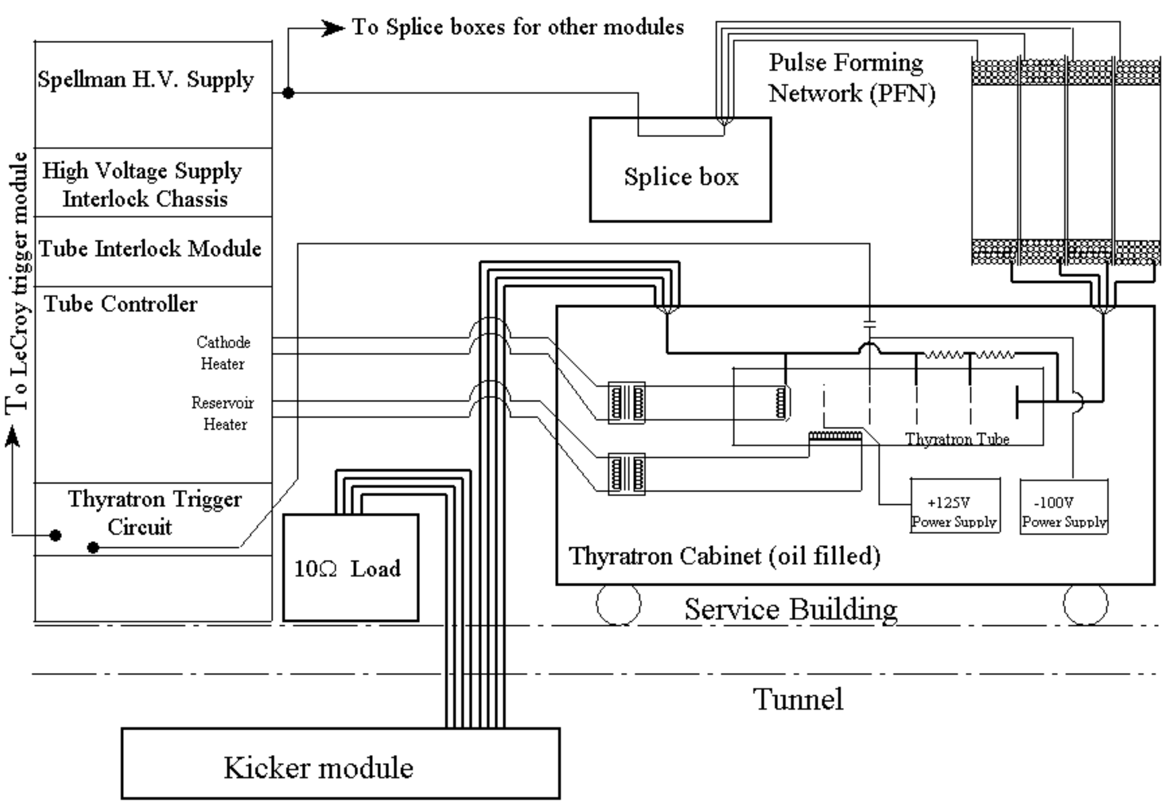


Figure 6.3: Kicker power supply diagram

them from their stochastic cooling counterparts. Due to the ultra high vacuum requirements of the Accumulator, the magnets and tanks are baked out along with other components after vacuum work.

Power supplies are virtually the same for both Accumulator and Debuncher kickers. Figure 6.3 diagrams a typical kicker power supply and associated components. A hydrogen thyratron tube is used as a high voltage switch to allow the electrical current to pulse through the kicker. High voltage cable is coiled on large aluminum frames to provide a Pulse Forming Network (PFN) that helps define the shape and duration of the kicker pulse. During a typical stacking cycle, the PFNs are charged up over about 0.5 sec to approximately 60 kV by a Spellman high voltage power supply. A CAMAC 379 module provides a trigger pulse to a LeCroy 4222 timing module, which in turn provides synchronized pulses to kicker trigger modules at the appropriate time to "fire" the thyratron tubes. This closes the circuit and allows a current pulse to pass through the kicker magnet to a 10Ω load. The thyratron tube is housed in an oil-filled cabinet located in the service building. The 10Ω load and PFNs are located near the thyratron cabinets.

Septa

There are five septa magnets found in the pbar rings, four of them are of a single turn design. Debuncher injection and extraction as well as Accumulator injection (two septa are used here) utilize the single turn pulsed septum. Each septum is 2 meters long and is made by stacking "c" shaped steel laminations in a fixture with a slight (50 m radius) curvature for improved aperture. The vacuum enclosure doubles as a stacking fixture for the magnet. Figure 6.4 provides a cross section of a septum magnet. The septum itself is about 1.3 cm thick (the entire septum magnet assembly has a diameter of about 25 cm) and is made up of four parts. A copper conductor is bonded to a stainless steel plate and both carry the current pulse (the steel plate provides support). A sheet of kapton insulates the conductors from a low carbon steel plate used to magnetically shield the circulating beam adjacent to the septum magnet. The conductor carries up to 25,000 Amps to produce a field of 7,000 Gauss (as compared to 500 Gauss for the kickers). The Debuncher injection septum is built with an integrated beam pipe for circulating Debuncher beam. This special septum was built as a Run II upgrade to the improve aperture by eliminating the space normally taken up by the upper wall of the vacuum chamber.

The Accumulator extraction septum is a Lambertson style magnet made up of a field free region for circulating beam and a field region for extracted beam. A small "C" Magnet is located in the AP-3 line just downstream of ELAM and is powered in series with the Lambertson by the D:ELAM power supply. The Lambertson is normally powered at all times to prevent tune and

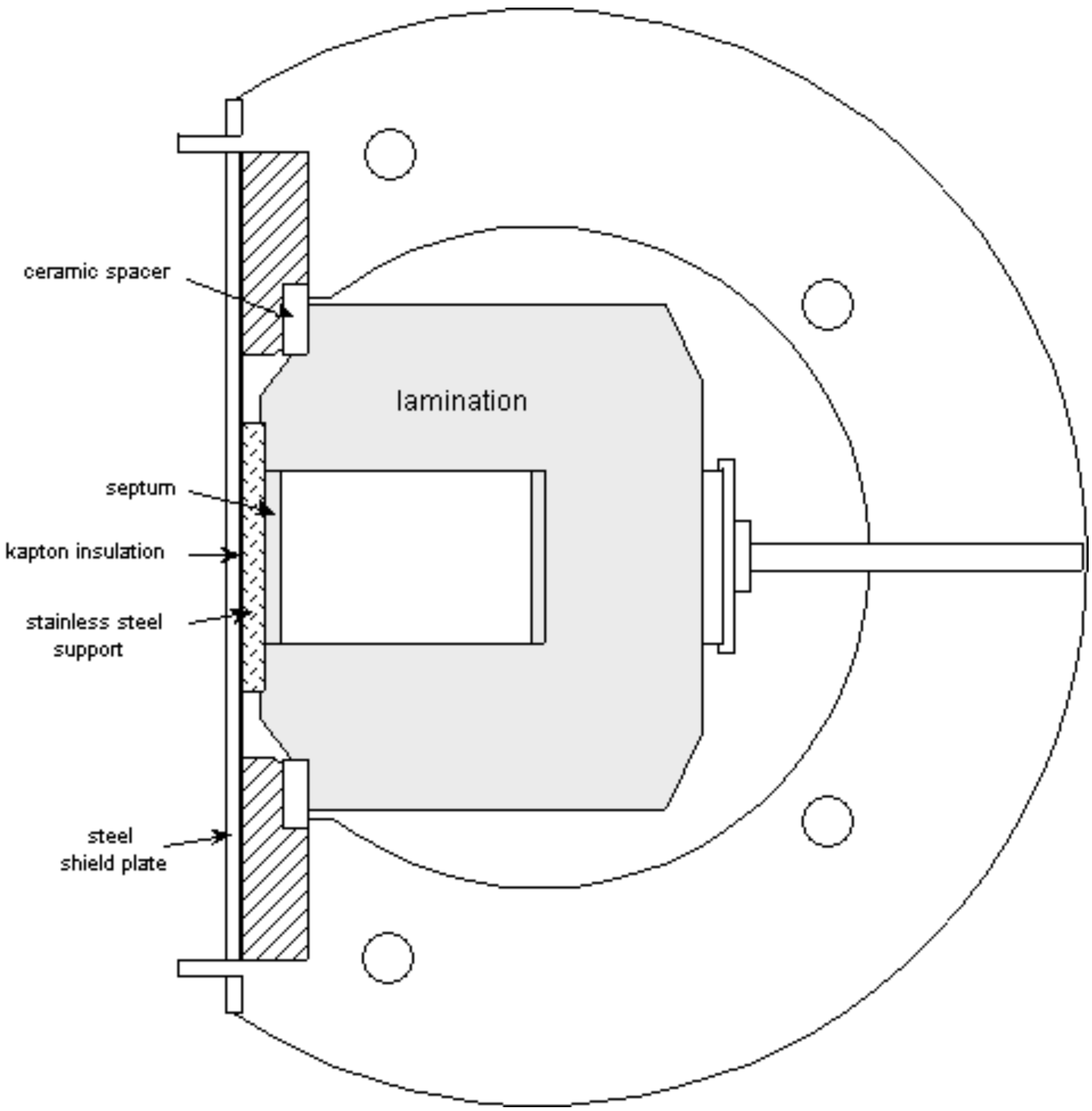


Figure 6.4: Debuncher extraction septum cross section

orbit shifts that would accompany the power supply being turned off and on. Stray fields in the "field free" region of the Lambertson are small enough to compensate for.

P1 and P2

The P1 and P2 lines were built as part of the Main Injector project to connect the Main Injector with the AP-1 line. A detailed description of both lines can be found in the Main Injector Rookie Book. The AP-1 line originally attached to the old Main Ring at the F-17 location before it was replaced by the Main Injector. Although the F-17 Lambertson magnets were replaced by a B3 style dipole to improve aperture, the original C-magnets were retained to accommodate the P3 line to Switchyard. With the addition of the P1 and P2 lines, the transfer lines to and from pbar were extended by 430 meters.

AP-1

AP-1 is approximately 172 meters long from F17 in the Tevatron enclosure to its terminus at the production target in the Vault. Vertically the line increases elevation 2.1 meters between the P2 line and the production target. The AP-1 line's design was predominately driven by the need to efficiently transport 120 GeV protons from the old Main Ring to the Target Vault. An additional requirement was that the proton beam had to be focused to a small spot size on the production target. With these considerations in mind, the optics of the AP-1 line can be broken down into three sections.

The first section runs from the extraction channel at F17 through PB5 (M:HV102) and was designed to cancel horizontal dispersion from the Main Ring. Although beam no longer comes from the Main Ring, the P2 line was designed so that the lattice functions closely matched those in the old Main Ring. A B3 style magnet replaced the original two extraction Lambertsons at F17 to improve aperture. However, two 118.4 inch C-magnets from the original extraction channel remain and are powered in series with the B3 magnet (I:F17B3). The B3 magnet and C-magnets bend beam from the P2 line upwards by 32.6 mrad. To provide clearance for the AP-1 line, the P3 line has a double strength dipole in place of the normal B-2 dipoles at F17-4 and F17-5.

Downstream of the extraction channel, beam continues upward and to the outside (from the perspective of the P2 line and tunnel). Horizontal trim P0-HT (M:HT100) follows, which was originally intended to compensate for the residual angle at F17 of beam extracted from the Main Ring. A four-dipole string, composed of PB1&2 and PBR1&2 (M:HV100), is next. The second pair of dipoles in this string is rolled 41° to provide both vertical and horizontal bending (the "R" in the magnet name stands for "rolled"). Quadrupole PQ1 (M:Q101) and trim PQ1-VTA (M:VT101A) follows and then AP-1 passes through a 'sewer pipe' of about 23.2 meters and on to the Pre-Target enclosure. The first element in this enclosure is trim PQ1-VT (M:VT101) and is closely followed by PQ2 (M:Q102). A series of four dipoles, the first of which is rolled 45°, PBR3 and PB3-5 (M:HV102), follow.

The second section acts to cancel vertical dispersion. It includes PQ3 (M:Q103), PQ4 (M:Q104), and PQ5A&B (M:Q105I&V). PQ5A&B have two power supplies because it was expected that they would run at a higher current than a single supply can deliver. A horizontal trim dipole, PQ5-HT (M:HT105), is next and is followed by two vertical dipoles, PBV1&2 (M:V105), which straightens the upward climb of the beam towards the target. The remainder of the AP-1 line is level between PBV1&2 and the production target.

The final section is composed of eight quadrupoles in four circuits, PQ6A&B (M:Q106), PQ7A&B (M:Q107), PQ8A&B (M:Q108), and PQ9A&B (M:Q109). These elements provide the final focus for the proton beam to minimize the spot size on the target (leading to maximized antiproton yield). A horizontal trim, PQ7-HT (M:HT107), is located just upstream of the final quad doublet and a vertical trim, PQ8-VT (M:VT108), just downstream. These trims are used to finely tune the beam's position on the target to about ± 0.2 mm. This third section is coincidentally housed totally within the Pre-Vault enclosure. Table 2 lists all AP-1 magnetic elements.

Since AP-1 operates at two significantly different energies, 8 and 120 GeV, the magnetic elements are ramped. In the original design, Separate low current power supplies were used for 8 GeV operation to improve regulation. In practice, it was found that ramping the 120 GeV power supplies provided adequate regulation and reduced the time required to switch between stacking and pbar transfers.

AP-1 line power supplies, with the exception the supply powering the F17 B3 magnet and C-magnets (M:F17B3 is located at F2), are found in the F23 service building.

ELEMENT	POWER SUPPLY	TYPE OF DEVICE	COMMENTS
B3 Magnet	I:F17B3	F-17 Vertical dipole	critical device rolled 6°
C-magnet #1	I:F17B3	F17 Vertical dipole	critical device
C-magnet #2	I:F17B3	F17 Vertical dipole	critical device
P0-HT	M:HT100	20" bump	
PB1	M:HV100	EPB dipole	critical device
PB2	M:HV100	EPB dipole	critical device
PBR1	M:HV100	EPB dipole	critical device, rolled 41°
PBR2	M:HV100	EPB dipole	critical device, rolled 41°
PQ1	M:Q101	3Q120 quad	
PQ1-VTA	M:VT101A	20" bump	before sewer pipe
PQ1-VT	M:VT101	35" bump	after sewer pipe
PQ2	M:Q102	3Q120 quad	
PBR3	M:HV102	AIRCO dipole	rolled 45°
PB3	M:HV102	AIRCO dipole	
PB4	M:HV102	AIRCO dipole	
PB5	M:HV102	AIRCO dipole	
PQ3	M:Q103	3Q120 quad	
PQ4	M:Q104	3Q120 quad	
PQ5A	M:Q105I, M:Q105V	3Q120 quad	
PQ5B	M:Q105I, M:Q105V	3Q120 quad	
PQ5-HT	M:HT105	35" bump	
PBV1	M:V105	AIRCO dipole	
PBV2	M:V105	AIRCO dipole	
PQ6A	M:Q106	3Q120 quad	
PQ6B	M:Q106	3Q120 quad	
PQ7A	M:Q107	3Q120 quad	
PQ7B	M:Q107	3Q120 quad	
EB6		SDD dipole	OFF for stacking, critical device
PQ7-HT	M:HT107	35" bump	
PQ8A	M:Q108	3Q120 quad	
PQ8B	M:Q108	3Q120 quad	
PQ8-VT	M:VT108	40" bump	
PQ9A	M:Q109	3Q120 quad	
PQ9B	M:Q109	3Q120 quad	
Sweeper A	M:USWA	Sweep magnet	special magnet
Sweeper B	M:USWB	Sweep magnet	special magnet

Table 6.2: AP-1 Magnetic Elements

120 GeV

120 GeV protons from the Main Injector are extracted in a single turn initiated by a kicker located at MI-52. A series of Lambertson magnets downstream of the kicker bends beam vertically into the P1 line. Beam is directed down the P1 line, then passes into the P2 line at F0 in the Tevatron enclosure. A Lambertson magnet at F0 bends beam downward into the Tevatron when it is powered, so it's left off when beam is desired in the P2 line. The P2 line, sometimes referred to as the "Main Ring remnant", transports the beam between F0 and F17 where the AP-1 and P3 lines begin. Beam to pbar is bent upwards by a B3 type dipole and two C-magnets, powered by the I:F17B3 power supply. I:F17B3 was formally a Main Ring bend power supply and has been specially modified for its current use. If beam is destined for the P3 line (for SY120 operation), I:F17B3 is not powered.

8 GeV

When AP-1 is used for pbar transfers into the Main Injector, the first four quadrupoles, PQ7A&B (M:Q107) and PQ6A&B (M:Q106), encountered by the antiproton beam are used to match the optics of AP-1 and AP-3. As with the AP-1 power supplies, the D:H926 supply is ramped so that the EB6 magnet (which bends beam from AP-3 into AP-1) is not powered during stacking and is at the proper field for 8 GeV operation. After entering AP-1, pbars continue through the P2 and P1 lines en route to the Main Injector. Note that the AP-3 line bypasses PQ8A&B (M:Q108) and PQ9A&B (M:Q109), they only run at 8 GeV current on the infrequent study periods when 8 GeV protons are transferred to the Debuncher via AP-2. Protons can also be "reverse injected" from the Main Injector to the Accumulator via AP-1 and AP-3 for tune-up or studies.

AP-2

Following the Lithium Lens (D:LNV) in the Target Vault, a pulsed 3 degree horizontal dipole known as the Pulsed Magnet (D:PMAGV) is used to momentum select negatively charged 8 GeV secondary particles into the AP-2 line. The AP-2 line then transports the selected particles towards the Debuncher. Most of the secondaries other than antiprotons have a short lifetime and decay during the journey down this beamline. Whatever is left, mostly pions and electrons, does not survive the first several turns in the Debuncher. AP-2 was designed to transport an 8 GeV beam with 20π mm-mrad (190π mm-mrad normalized) transverse emittance and a momentum spread of 4%. The transverse acceptance has been improved to about 30π mm-mrad through various improvements. Table 3 lists the magnetic elements making up the AP-2 line. Note that there are numerous quadrupole shunts to allow flexibility in changing the optics of the beamline.

According to the *Tevatron I Design Report*, the AP-2 line can be broken into five parts. The first section, beginning with the Pulsed Magnet, is described as the "clean-up" section. After exiting the Target Vault, the AP-2 line passes through two pairs of quadrupoles and vertical trim IQ2-VT (D:VT702) that is located between IQ2 and IQ3. Another 3° bend to the left by IB1 completes this portion of the line. There is also a pair of trims, IQ4-HT (D:HT704) and IQ4-VT (D:VT704) located between IQ4 and IB1. Quadrupoles in this section are powered by the D:Q701 and D:Q702 power supplies.

A transport section follows, which consists of a FODO lattice of quadrupole cells. These periodic cells have a length of 27 meters. D:Q707 powers all of the magnets in this section, IQ7 – IQ14. Pairs of horizontal collimators are located immediately downstream of IQ7 and IQ9. Similarly, pairs of vertical collimators are positioned downstream of IQ8 and IQ10. Three vertical and a horizontal trim dipole are contained in this section to fine tune beam position: IQ6-VT (D:VT706), IQ11-HT (D:HT711), IQ11-VT (D:VT711) and IQ14-VT (D:VT714).

Next is a left bend made up of six bending elements, IB2-7 (D:H717), which deflects the beam by a total of 36.53°. Each bending magnet has a shunt for fine orbit control (e.g. D:HS7172). There is also a vertical trim, IQ16-VT (D:VT716) located at the upstream end of the bending string. Four quadrupoles are interspersed amongst these bending magnets, powered by D:Q718 and D:Q719. The large horizontal dispersion in the left bend section results in a wide horizontal beam, particularly in the center of the bends. For this reason, momentum selection can be done in the middle of the section at the IQ19 location with a set of horizontal collimators.

Another long transport section follows, similar to the first transport, made up of repeating FODO cells. However, the magnets are powered by several different power supplies (D:Q716, D:Q719, D:Q724, D:Q725 and D:Q729). Three vertical trims and two horizontal trims dipole are in this section, IQ23-

VT (D:VT723), IQ25-HT (D:HT725), IQ25-VT (D:VT725), IQ26-VT (D:VT726), and IQ27-HT (D:HT727).

The final portion of the AP-2 line is an achromatic vertical translation into the Debuncher called the "injector" section. The section ends at the downstream end of the 2 meter magnetic septum magnet. Beam is deflected downward in this portion of the line with a 3.7° bending magnet, IBV1 (D:V730), and is translated 1.3 meters to be at the same elevation as the Debuncher. Three quadrupoles, IQ31-33 (D:Q731), are located in the injector section as well as a vertical trim IQ30-VT (D:VT730) and a pair of horizontal trims, IQ30-HT (D:HT730) and IQ31-HT (D:HT731). A large quadrupole in the Debuncher, D4Q5, has a large aperture to accommodate both the circulating and injected beam. This large quad is of the same design as those found in the Accumulator high dispersion areas. D4Q5 is powered by both D:IB and D:QT405 for a total current of more than 1,500 A. The large quads have fewer windings and more distance between the pole faces as compared with the small quadrupoles found at the other DxQ5 locations. Therefore, they require considerably more current to produce the same field strength. Because the AP-2 beampipe is offset from the center of this magnet, a strong vertical bend is imparted on the injected beam, bending pbars upward like the injection septum. A pulsed magnetic septum, ISEP (D:ISEPV), and 3-module kicker magnet, IKIK (D:IKIKV), complete the injection process. Two large quadrupoles are located in the Debuncher at the D4Q4 location, just downstream of ISEP, to improve aperture in the injection region. The large quadrupole pair replaced a single small quadrupole that was originally there. The D4Q4A&B magnet pair is powered by a single power supply (D:Q404). Injected beam passes through Debuncher quadrupoles D4Q4A&B and D4Q3 before reaching the injection kickers, located between D4Q3 and D4Q2 in the 50 straight section. Power supplies for AP-2 line magnets in the upstream part of the line are located in AP0, those located in the middle of the line can be found at F27, and downstream supplies reside in AP50. Table 3 lists all of the AP-2 magnets and power supplies.

6.8	POWER SUPPLY	TYPE OF DEVICE	COMMENTS
IQ1	D:Q701, D:QS701	SQC	
IQ2	D:Q702, D:QS702	SQC	
IQ2-VT	D:VT702	NDB	
IQ3	D:Q702, D:QS703	SQC	
IQ4	D:Q701, D:QS704	SQC	
IQ4-HT	D:HT704	NDB	
IQ4-VT	D:VT704	NDB	
IB1	D:H704	modified B1 wide gap	Critical device
IQ5	D:Q701, D:QS705	SQC	
IQ6	D:Q701, D:QS706	SQC	
IQ6-VT	D:VT706	NDB	
IQ7	D:Q707	SQC	
IQ8	D:Q707	SQC	
IQ9	D:Q707	SQC	
IQ10	D:Q707	SQC	
IQ11	D:Q707	SQC	
IQ11-HT	D:HT711	NDB	
IQ11-VT	D:VT711	NDB	
IQ12	D:Q707	SQC	
IQ13	D:Q707	SQC	
IQ14-VT	D:VT714	NDB	
IQ14	D:Q707	SQC	
IQ15	D:Q715	SQA	
IQ16-VT	D:VT716	NDB	
IQ16	D:Q716, D:QS716	SQB	
IQ17	D:Q716, D:QS717	SQD	
IB2	D:H717, D:HS7172	6-4-120 wide gap	Critical device
IQ18	D:Q718	SQB	
IB3	D:H717, D:HS7173	6-4-120 wide gap	Critical device
IB4	D:H717, D:HS7174	SDE wide gap	Critical device
IQ19	D:Q719, D:QS719	SQB	
IQ20	D:Q719, D:QS720	SQB	
IB5	D:H717, D:HS7175	SDE wide gap	Critical device
IB6	D:H717, D:HS7176	6-4-120 wide gap	Critical device
IQ21	D:Q718	SQB	
IB7	D:H717, D:HS7177	6-4-120 wide gap	Critical device
IQ22	D:Q716, D:QS722	SQD	
IQ23	D:Q716, D:QS723	SQD	
IQ23-VT	D:VT723	NDB	
IQ24	D:Q724	SQA	
IQ25	D:Q725	SQD	
IQ25-HT	D:HT725	NDB	
IQ25-VT	D:VT725	NDB	
IQ26	D:Q719, D:QS726	SQA	
IQ26-VT	D:VT726	NDB	
IQ27	D:Q719	SQA	
IQ27-HT	D:HT727	NDB	
IQ28	D:Q719, D:QS728	SQA	
IQ29	D:Q729, D:QS729	SQD	
IQ30	D:Q729, D:QS730	SQD	
IBV1	D:V730	modified B1 wide gap	Critical device
IQ30-HT	D:HT730	vernier trim	
IQ30-VT	D:VT730	NDB	
IQ31	D:Q731, D:QS731	SQE	
IQ31-HT	D:HT731	vernier trim	
IQ32	D:Q731, D:QS732	SQE	
IQ33	D:Q731, D:QS733	SQE	
D4Q5	D:QT405, D:IB	LQE	
ISEP	D:ISEPV	pulsed septum	
IKIK	D:IKIK	3-module kicker	

Table 6.3: AP-2 Magnetic Elements

Debuncher to Accumulator (D to A)

Beam is transferred horizontally from the Debuncher into the Accumulator in the 10 straight section. Extraction from the Debuncher is accomplished with a 3-module kicker, EKIK (D:EKIKV), and septum, ESEP (D:ESEPV) combination. A 3-bump called “Dex Bump” (Debuncher extraction bump) is ramped shortly before beam transfer to position beam closer to ESEP. Dex Bump was implemented to improve aperture at ESEP, allowing circulating pbars to be further from ESEP when they have a larger emittance (before they are cooled). The quadrupole in the Debuncher just downstream of the septum, D6Q6, is a large style quadrupole used in much the same way as D4Q5 is at the end of the AP-2 line. In this case, beam passes horizontally off-center through D6Q6 providing a greater bend towards the Accumulator. The D to A line has a vertical trim (TQ1-VT) between the first two quadrupoles, and a horizontal trim between the second and third quadrupoles (the horizontal trim retains its old name, TQ4-HT, after being moved upstream at the beginning of Run II). Another vertical trim (TQ6-VT) as well as a major bend, TB1&2 (D:H807A&B), are found between the sixth and seventh quadrupoles. The vertical trims can be used together to control the vertical position and angle at injection into the Accumulator. The horizontal trim and dipoles provide some control of the horizontal position and angle at the Accumulator injection septa.

ELEMENT	POWER SUPPLY	TYPE OF DEVICE	COMMENTS
EKIK	D:EKIK	3-module kicker	
ESEP	D:ESEPV	pulsed septum	
D6Q6	D:QT606, D:IB	LQE	
TQ1	D:Q801, D:QS801	SQE	
TQ1-VT	D:VT801	NDB	
TQ2	D:Q801, D:QS802	SQD	
TQ4-HT	D:HT804	NDB	
TQ3	D:Q801	SQD	
TQ4	D:Q804, D:QS804	SQC	
TQ5	D:Q804	SQD	
TQ6	D:Q804, D:QS806	SQD	
TQ6-VT	D:VT806	NDB	
TB1	D:H807A	modified B1	
TB2	D:H807B	modified B1	
TQ7	D:Q807	SQA	
ISEP2	A:ISEP2V	pulsed septum	
ISEP1	A:ISEP1V	pulsed septum	
IKIK	A:IKIKV	shuttered kicker	

Table 6.4: D to A line Magnetic Elements

Beam passes through a septa pair, ISEP2 (A:ISEP2V) and ISEP1 (A:ISEP1V) into Accumulator quadrupole A1Q4, which has a special extended lobe on the vacuum "star" chamber. The beam travels 51 meters and passes through 270° of phase advance in the Accumulator (and another quadrupole with a special star chamber at A1Q8) and then is kicked onto the Accumulator injection orbit with a shuttered kicker, IKIK (A:IKIKV), in the A20 high dispersion straight section. All D to A line power supplies are located in the AP10 service building except A:IKIKV, which is located at AP30.

AP-3

This transport line can be separated into five sections: extraction, a long transport, a left bend, another long transport and a target bypass. When beam is extracted from the Accumulator, a shuttered kicker, EKIK (A:EKIKV) in the A20 high dispersion straight section kicks beam horizontally towards the inside of the Accumulator. The kicked beam goes through 270° of phase advance so that when it reaches straight section 30, it passes through the field region of a Lambertson magnet, ELAM (D:ELAM), on the radial outside of the Accumulator. ELAM bends beam upwards and out of the Accumulator and a 'C' magnet just downstream of the Lambertson supplies an additional upward bend. These devices, both powered by the D:ELAM power supply, raise the extracted beam to a level 1.2 meters above the Accumulator. Two separate downward bends, EBV1&2, of 50 mrad each level the extracted beam at the same height as the AP-1 and AP-2 lines. In the extraction channel there are also five quadrupoles, EQ1, EQ2, EQ3A&B, and EQ4, and a horizontal trim, EQ1-HT. EBV1 and 2 have shunts that serve the purpose of vertical trims, necessitated by the limited available space in this part of the beamline.

After the down/leveling bends, beam passes through the first long transport consisting of ten quadrupoles, EQ5-14. This has a repeating FODO lattice similar to the long transport sections of the AP-2 line, although the cell length is longer. A cluster of three trims, EQ6-HTA, EQ6-VT, EQ6-HTB, is located at the upstream (in the pbar direction) end of this section.

A bend to the left, EB1-3, follows. There are two quadrupoles, EQ15 and 16, located in the bend section. Beam then is directed through a second long transport, which is similar to the previous one. This long transport runs parallel to the first long transport in the AP-2 line. This section includes nine quadrupoles, EQ17-25, and vertical trims, EQ17-VT & EQ25-VT, at each end.

ELEMENT	POWER SUPPLY	TYPE OF DEVICE	COMMENTS
EKIK	A:EKIK	shuttered kicker	
ELAM	D:ELAM	80" Lambertson	
C- magnet	D:ELAM	30" 'C' magnet	
EQ1	D:Q901	SQC	
EBV1	D:V901, D:VS901	modified B1	Critical device
EQ1-HT	D:HT901	NDB	
EQ2	D:Q901	SQD	
EQ3A	D:Q903	SQD	
EQ3B	D:Q903	SQD	
EQ4	D:Q901	SQB	
EBV2	D:V901, D:VS904	modified B1	Critical device
EQ5	D:Q901	SQC	
EQ6	D:Q901	SQD	
EQ6-HTA	D:HT906A	40" bump	
EQ6-VT	D:VT906	NDB	
EQ6-HTB	D:HT906B	NDB	
EQ7	D:Q907	SQE	
EQ8	D:Q907	SQA	
EQ9	D:Q909	SQA	
EQ10	D:Q909	SQA	
EQ10-HT	D:HT910	NDB	
EQ11	D:Q909	SQA	
EQ12	D:Q909	SQA	
EQ13	D:Q913	SQA	
EQ14	D:Q914	SQA	
EB1	D:H914	SDE	Critical device
EQ15	D:Q913, D:QS915	SQC	
EB2	D:H914	SDE	Critical device
EQ16	D:Q916	SQC	
EB3	D:H914	SDE	Critical device
EQ17	D:Q917, D:QS917	SQA	
EQ17-VT	D:VT917	NDB	
EQ18	D:Q917	SQA	
EQ19	D:Q919, D:QS919	SQB	
EQ20	D:Q919	SQA	
EQ21	D:Q919	SQA	
EQ22	D:Q919	SQA	
EQ23	D:Q919	SQA	
EQ24	D:Q924	SQA	
EQ25	D:Q924, D:QS925	SQA	
EQ25-VT	D:VT925	NDB	
EB4	D:H914, D:HS925	SDE	Critical device
Target bypass			
EQ26	D:Q926, D:QS926	SQB	
EB5	D:H926	SDD	
EQ27	D:Q926	SQC	
EQ28	D:Q926, D:QS928	SQD	
EB6	D:H926	SDD	

Table 6.5: AP-3 Magnetic Elements

The AP-3 line then bypasses the target by means of an achromatic transport using three dipoles and three quadrupoles, EQ26-28. The first of the three dipoles, EB4, is electrically connected with EB1-3, which makes up the left bend. Following EB4, AP-3 exits the Transport enclosure and bypasses the Target Vault. After the target bypass, AP-3 enters the Pre-Vault enclosure and encounters two bends, EB5&6, which direct beam into the AP-1 line. The final dipole of the target bypass, EB6, is actually in the AP-1 line between PQ7B and PQ8A. Since it is physically in the AP-1 line, its power supply (D:H926) must be ramped down during 120 GeV stacking cycles.

Three service buildings house AP-3 line power supplies: AP30 for the upstream end, F27 for the majority of the supplies, and AP0 for the downstream portion.

Notes:

7 Diagnostics

Diagnostic devices are employed in the Antiproton Source to provide a means of sensing the beam in each of the accelerator rings and transport lines. Because the pbar beam has relatively low intensity, some special devices and modified devices from other accelerators were required. Be forewarned, this chapter covers diagnostics at a level far beyond what is expected from an Operator. However, it brings together information that was previously scattered amongst several sources for use as a reference.

To organize this chapter, it has been separated into seven broad categories as shown in the following table of contents. In many cases, a single diagnostic will overlap multiple categories. When that happens, we will only cover the diagnostic once and not overlap the other section(s).

Intensity and Losses

The first section of this chapter will cover diagnostics used to measure intensities and losses. This includes the DCCTs (Debuncher and Accumulator), toroids and Beam Loss Monitors. Beam Position Monitors can also measure beam intensity, but they are covered in the transverse beam measurements section instead. Likewise, gap monitors and wall current monitors can be used to measure intensity, but are instead covered in the longitudinal measurements section.

DCCTs

A DCCT or Direct Current Current Transformer is a device used to measure the quantity of circulating beam with high precision. D:BEAM and A:BEAM are beam current or intensity readbacks for the Debuncher and Accumulator respectively that are sourced from DCCTs installed in each ring. Accuracy is one part in 10^5 over the range of 1 mA to 200 mA of beam current. The Debuncher DCCTs accuracy is somewhat less in stacking mode due to the lower beam intensity. As an aside, the revolution period of both the Debuncher and Accumulator for an 8 GeV particle is ~1.6 μs. Based on this coincidence with the units of charge, beam current can easily be converted to intensity:

$$1\ mA = 1\ X\ 10^{10}\ particles$$

because

$$\frac{1.6\ X\ 10^{-19}\ \text{Coulomb/particle}}{1.6\ X\ 10^{-6}\ \text{second}} = 1\ X\ 10^{-13}\ \text{Amperes/particle}$$

For 10^{10} circulating particles, the current is: $1\ X\ 10^{-3}$ Amp or 1 mA.

The pickups are supermalloy tape-wound toroidal cores with laminations, which act to reduce eddy currents. Beam goes through the hole of the donut and acts as a single turn on the toroid transformer. The beam sensing electronics are attached to wire windings on the toroids. Passing beam induces magnetic flux in the toroids and the electronics sense the second harmonic of the 801 Hz pilot signal (caused by the non-linear hysteresis characteristics of the toroid) and produces an equal and opposite current that minimizes the harmonic and thus keeps the net toroid flux at zero. Referring to Figure 7.1, T1 senses the AC portion of the beam while T2, T3, the

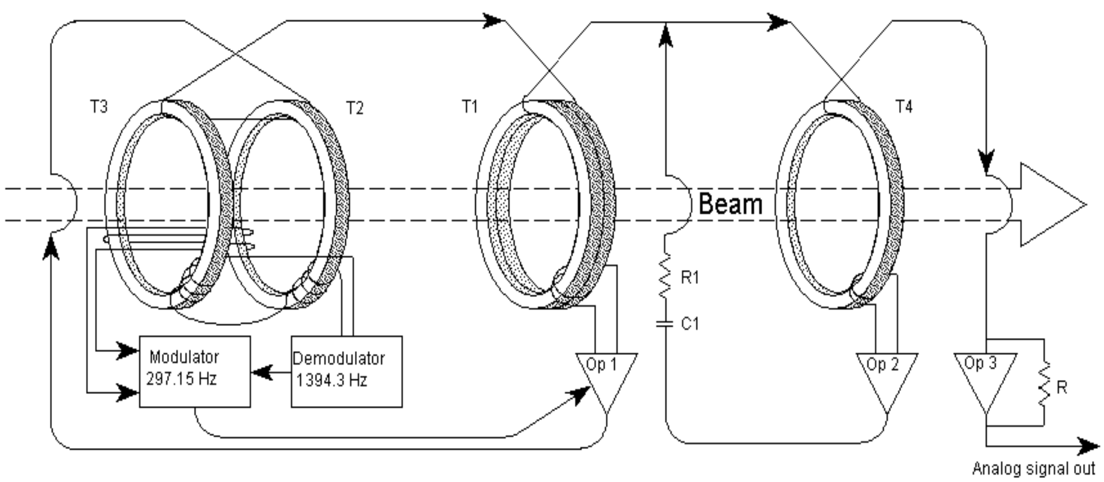


Figure 7.1: DCCT electronics

modulator, and demodulator sense the signal caused by the DC portion. The DC and AC signals are summed in OP1, which drives each toroid just hard enough to cancel the beam-induced flux. The beam cancellation signal is measured across the heat-sinked power resistor R. The accuracy of the measurement is dependent on the resistance staying constant.

The DCCT toroids are contained in 40-inch long by 10-inch diameter structures that reside in straight section 10 of both rings. Both the Accumulator and Debuncher DCCT signals go to a receiver chassis upstairs at AP10. Each receiver chassis has a slow (1 Hz), medium (100 Hz) and fast (220Hz) output. Each output can be configured to be sampled on a small scale (5 mA/V) or full scale (40 mA/V).

Debuncher DCCT:

Figure 7.2 shows the present Accumulator and Debuncher DCCT configurations. Since the hardware is identical, both are shown in the same diagram with the Debuncher specific items in parenthesis. The slow-rate (1

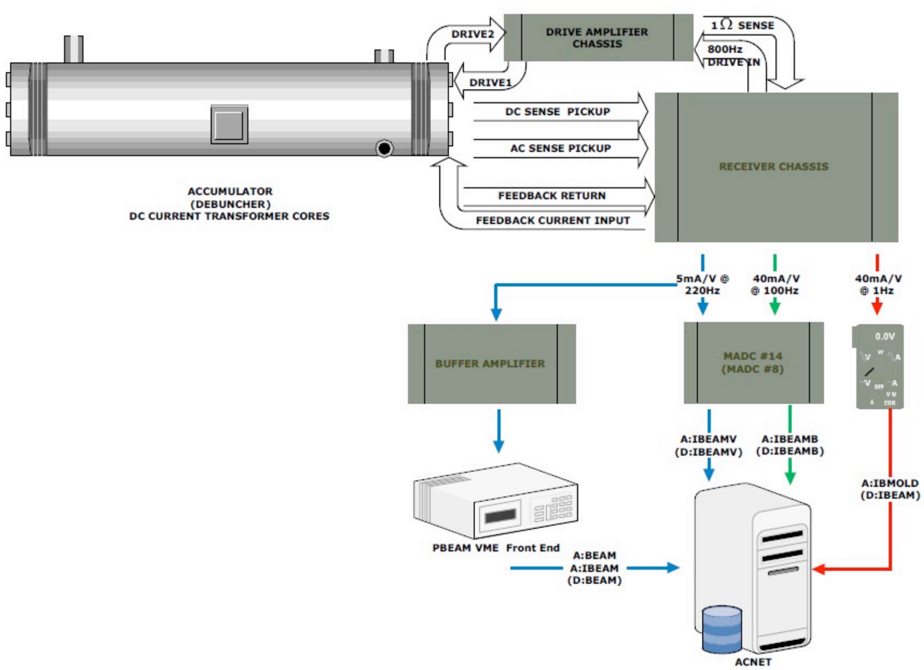


Figure 7.2: Accumulator and Debuncher DCCT layouts

Hz) full-scale (40 mA/V) output of the Debuncher DCCT is routed to a Keithley digital voltmeter (DVM) located in a rack in the AP10 control room. The Keithley DVM is a GPIB device that talks to the control system through the AP1001 front end, resulting in the D:IBEAM readback that updates once per second with a scale in the mA particle range. Due to the slow 1 Hz sample rate and large beam intensity scale, D:IBEAM is not useful to measure stacking beam, but can be used for circulating reverse protons.

The medium rate (100 Hz) full scale (40 mA/V) Debuncher DCCT output is processed through an MADC, using the standard CAMAC 190 card communicating through the Pbar CAMAC front end. This provides the D:IBEAMB readback with a beam scale in the 10^{10} particle range. This range is too large to measure stacking beam, but again can be used to measure reverse protons.

The fast-rate (220 Hz) small-scale (5 mA/V) output is split into two parts, with one signal going to an MADC and the other to the PBEAM VME front end. The MADC signal goes to a CAMAC 190 card communicating through the Pbar CAMAC front end. This provides the D:IBEAMV readback, which measures beam in the μA particle range. This scale is appropriate for measuring stacking beam; however, the baseline of this signal drifts significantly. In the past, attempts were made to implement an automated baseline subtraction using the other available 220 Hz, 5 mA/V signal. The result was the Z:IBMV16 parameter. However, this has been disconnected in favor of processing that DCCT output through the PBEAM front end. PBEAM is a VME front end located in AP10 that over samples the 220 Hz DCCT output at 720 Hz and can provide readbacks with a resolution on the order of a sliding average of twelve 720 Hz samples. PBEAM was designed to provide stable readback that is fast enough to sample Debuncher beam at various times during the stacking cycle. P38 IBEAM <1> - <7> lists the various beam parameters generated by PBEAM. D:BEAMx (x=1-10) are the Debuncher beam intensity sampled at various times in the stacking cycle.

D:BEAM3 is a "no beam intensity" baseline, sampled 30 msec before beam is injected in the Debuncher, D:BEAM4 is measured soon after bunch rotation, and D:BEAM5 is measured prior to extraction. D:BEAM is a sliding average of twelve 720 Hz samples.

Accumulator DCCT:

Figure 7.2 also shows the present Accumulator DCCT configuration. The slow-rate (1 Hz) full-scale (40 mA/V) output of the Accumulator DCCT is routed to a Keithley digital voltmeter (DVM) located in racks in the AP10 control room. The Keithley DVM is a GPIB device that communicates to the control system through the AP1001 front end resulting in the A:IBMOLD readback that updates once per second with a scale in the mA particle range. This readback used to be pointed to A:IBEAM, which was the standard Accumulator intensity readback for stacked pbars. In January 2009, A:IBEAM was changed to point at the PBEAM front-end readback, which is described below.

The medium rate (100 Hz) full scale (40 mA/V) DCCT output is processed through an MADC, using the standard CAMAC 290 card communicating through the Pbar CAMAC front end. This provides the A:IBEAMB readback that measures beam scale in the 10^{10} particle range. This parameter can be useful for measuring both stacked Pbars and reverse protons. It can be read and plotted faster than A:IBMOLD, but also is a noisier signal.

The fast-rate (220 Hz) small-scale (5 mA/V) output is split into two parts, with one signal going to an MADC and the other the PBEAM front end. The MADC signal goes to a CAMAC 290 card communicating through the Pbar CAMAC front end. This provides the A:IBEAMV readback, which measures beam scale in the mA particle range. The other 200 Hz, 5 mA/V output is routed through the new PBEAM front end. Again, the PBEAM VME front end over samples the 220 Hz DCCT output at 720 Hz and can provide readbacks with a resolution on the order of a sliding average of twelve 720 Hz samples. Both A:BEAM and A:IBEAM point to the live readback of this device, which is our standard for both stacking and unstacking beam intensity readbacks. A:IBEAM used to point to the Keithley DVM readback (described above), but was moved over to the PBEAM front end once it was determined that it was a more accurate readback. The PBEAM front end was also designed to sample Accumulator beam at various times during the stacking, unstacking or reverse proton cycles. These parameters can be found on parameter page P38 IBEAM <1> - <7> and are listed below in Table 7.1

Accumulator PBEAM Parameters		
Parameter	**Mode**	**Sample time**
A:BEAM1	Reverse Protons	Before injection
A:BEAM2	Reverse Protons	After injection
A:BEAM3	Stacking	Before Accumulator Injection
A:BEAM4	Stacking	After Accumulator Injection
A:BEAM5	Stacking	Before ARF1 Ramp
A:BEAM6	Stacking	After ARF1 Ramp
A:BEAM7	Unstacking	Prior to bunching
A:BEAM8	Unstacking	Beam on extraction orbit
A:BEAM9	Unstacking	After Extraction

Table 7.1: Accumulator PBEAM parameters

Toroids

Pearson single turn large aperture toroids are located in the transport lines to monitor beam intensity. They are beam transformers that produce a signal that is proportional to the intensity (1 V for every 1 A of current). The toroids make use of integrators that sample over a gated period that is defined by a Main Injector Beam Synch (MIBS) timer. M:TOR109, for example, uses the timing event M:TR109S to start the sample period. The output of the integrator is sampled and held for an A/D conversion.

There are two toroids in the P1 line and one toroid in the P2 line. I:TOR702 and I:TOR714 measure beam intensity in the upstream and downstream P1 line respectively, while I:TORF16 is located in the P2 line near the (proton direction) upstream end of the AP-1 line. I:TR702S, I:TOR714S and I:TRF16S are calibrated for low intensity beams, like pbar transfers.

There are two toroids located in the AP-1 line. M:TOR105 is located in the Pre-Vault enclosure just upstream of P6QA and is used to monitor proton or antiproton intensities in the AP-1 line. The electronics that provide the MADC reading for M:TOR105 saturate at around 4e12, lower than the usual beam intensity during stacking. M:TR105B is a higher intensity scaling of the same toroid and has become the standard device used to determine the proton intensity going to the target. It is also the device used by the Beam Budget Monitor (BBM) in the Main Control Room. M:TOR109 is also in the Pre-Vault enclosure just upstream of the Target Vault. For many years this device was the standard for measuring the number of protons entering the Vault and reaching the target. However, when Beam Sweeping was implemented in 2006, it was found that running the sweeping magnets occasionally adds an offset to this toroid signal, bit not always. M:TR105B does not have this problem, so it has taken over as the default measure of beam on target.

There are three toroids in the AP-2 line and one toroid in the D to A line. D:TOR704 is located just downstream of the Vault. It measures the large flux of negative secondaries entering AP-2, most of which are particles other than pbars. D:724TOR measures negative secondaries just downstream of the AP2 line Left Bends, and D:TOR733 measures negative secondaries at the end of the AP2 line. D:806TOR measures beam in the D to A line.

The four toroids mentioned above were updated earlier in Run II. The original AP2 line toroids had 3-inch apertures, which is smaller than the nominal transport line 5.5-inch aperture. In order to increase AP2 line and D to A line aperture, new 6-inch “large aperture” toroids were installed at 704, 724 and 806. The challenge has been to make these toroids function in a stacking environment. A pulse of 10^{10} particles in 1.6 microseconds is equivalent to 1 mA of current flowing through the toroid. This produces an output signal of only 1 mV, requiring high gain and careful filtering. Tor704 has updated electronics and Tor724 and Tor733 have new electronics that incorporate a shared oscilloscope at AP-50. The scope name is currently AP30-BPM-SCOPE, which reflects the former use of this scope. Tor806 also has new electronics that incorporate a scope named Tor806-Scope at AP10.

There is one toroid in the AP-3 line, D:TOR910, which is located between EQ10 and EQ11. This toroid is used both to measure reverse injected protons directed down the AP-3 line and for measuring pbars extracted during transfers to the Recycler.

Beam Loss Monitors

There are two types of Beam Loss Monitors (BLMs) in the Antiproton Source, ion chamber and plastic scintillator with a photomultiplier tube (PMT). The ion chamber BLMs can be found in the P1, P2, AP-1 and part of the AP-3 beamlines and are used to monitor losses during stacking and pbar transfers. The plastic scintillator BLMs are distributed throughout the Accumulator and Debuncher rings and can be used for studies or for locating loss points.

The ion chamber monitors are the same as those used in the Tevatron. The BLM detector is a sealed glass ion chamber with a volume of 110 cubic centimeters that is filled to 1 atmosphere with Argon. A high voltage power supply is daisy- chained to a string of BLMs and provides about a 1,500 Volt bias to the chamber. The output goes upstairs on an RG58 signal cable to a beam loss integrator and then to a Multiplexed Analog to Digital Converter (MADC). The MADC is read by the control system in the usual way.

The plastic scintillator design BLM is sensitive to a small number of particles, something the ion chamber loss monitors aren't. The loss monitors are made up of a 4"x2"x$^1/_2$" piece of plastic scintillator glued to a 36" long Lucite light guide (see Figure 7.3). At the end of the light guide, a small Lucite coupling attaches it to an RCA 4552 PMT. The PMTs were recycled from old "paint can" loss monitors and are relatively rugged. The intent of the light guide is to keep the scintillator near the magnets but to extend the phototubes up and away from the region of beam loss. This assembly is mounted in a housing made up of PVC pipe and has feed-throughs for the high voltage and signal cables.

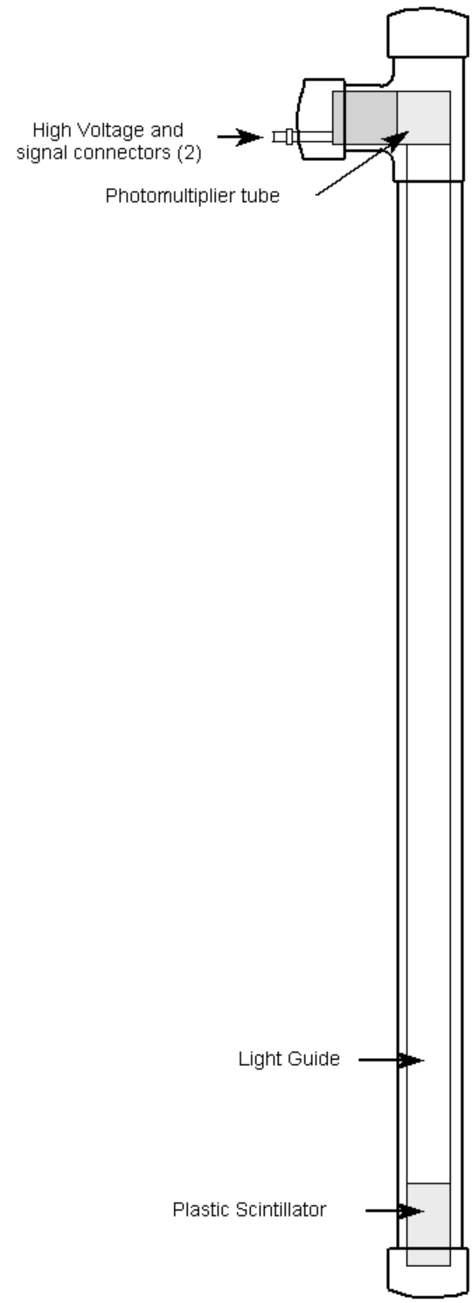


Figure 7.3: Accumulator and Debuncher BLMs

High voltage supplies for the BLMs are located in the AP10, 30 and 50 service buildings. Each supply feeds up to 20 BLMs through a Berkeley voltage divider that allows the gains of all the PMTs to be matched by setting the high voltage to each one individually. In actual practice, all of the high voltages are run near maximum value.

The BLM output is processed through a series of three cards located in one or more NIM crates. Each service building has a single BLM rack processing both Accumulator and Debuncher BLM signals for two sectors. The signals are passed from card to card via LIMO connections in the front panels of the cards. The BLM output first goes to an amplifier card, which handles twelve BLMs and amplifies each BLM signal by approximately 10 times. Each amplified signal is next sent to a quad or octal discriminator, which handles four or eight BLMs. This card levels the signal spike from the PMT caused by the lost particle and sends a NIM level pulse to a Jorway quad scalar, which handles four BLMs. The scalar is really a pulse counter that counts pulses during the gated period defined by the gate module. A CAMAC 377 card provides start, stop and clear times to the gate module for the gate pulse. Output from the Jorway 84-1 card is sent to the control system. Plastic scintillator loss monitor electronics count pulses while Tevatron style argon gas loss monitor electronics accumulates charge on an integrator capacitor.

User interfaces for the rings loss monitors include the RING LOSS MONITORS application (currently P46) and the POWER SUPPLY PARAM pages (currently P60 <ACC##> <9> {##=10, 20, 50} and P60 DEB##> <7> {##=10, 20, 50}>).

Transverse Beam Measurements

The second section of this chapter will cover transverse beam measurements. This includes the Beam Position Monitors (Debuncher, Accumulator, Echotek, and Rapid Transfer), Secondary Emission Monitors, Optical Transition Radiation Detectors, Ion Profile Monitors, Flying Wires, and Quad Pickups.

Beam Position Monitors

The Pbar Beam Position Monitor (BPM) systems provide single turn and multi-turn or closed orbit position information with sub-millimeter resolution. Position information is used to correct the orbit and to measure lattice parameters. In addition, BPMs can also provide beam intensity information. The primary advantage of BPMs is that they do not make direct contact with the beam. The Debuncher has 120 sets of pickups and the

Accumulator has 90. They are split-plate, bi-directional electrostatic pickups that are sensitive to a RF structure on the beam, therefore the beam must be bunched for the BPMs to work. Pickups are generally found at quadrupole locations in the lattice, with horizontal BPMs typically near the horizontally focusing quads and the vertical BPMs near the vertically focusing quads. Circular and rectangular pickups are used depending on location; the beam pipe size is small in low dispersion sections and is very large horizontally in areas of high dispersion. Rectangular pickups are used only in the high dispersion sections of the Accumulator. Accumulator high dispersion BPMs are 10 x 30 cm rectangles, Accumulator low dispersion BPMs are cylindrical and have a 13 cm diameter, Debuncher BPMs are cylindrical with an 18 cm diameter. BPMs can also be found in the AP1, 2 and 3 beamlines. The AP-1 line has 7.6 cm diameter combined horizontal and vertical BPMs at every quadrupole location while the AP-2 and AP-3 lines are single-plane and 13 cm in diameter, generally alternating planes at quadrupole locations.

Debuncher

The 120 Debuncher BPMs are divided into six “houses” of 20 BPMs each (10 horizontal and 10 vertical). The houses are named by tunnel location (10, 20, 30, 40, 50 and 60). Each BPM house has a dedicated electronics rack, resulting in two Debuncher BPM racks in each of the AP10, AP30 and AP50 service buildings. Figure 7.4 is a diagram of the BPM system for a single BPM house.

Debuncher BPM Layout:

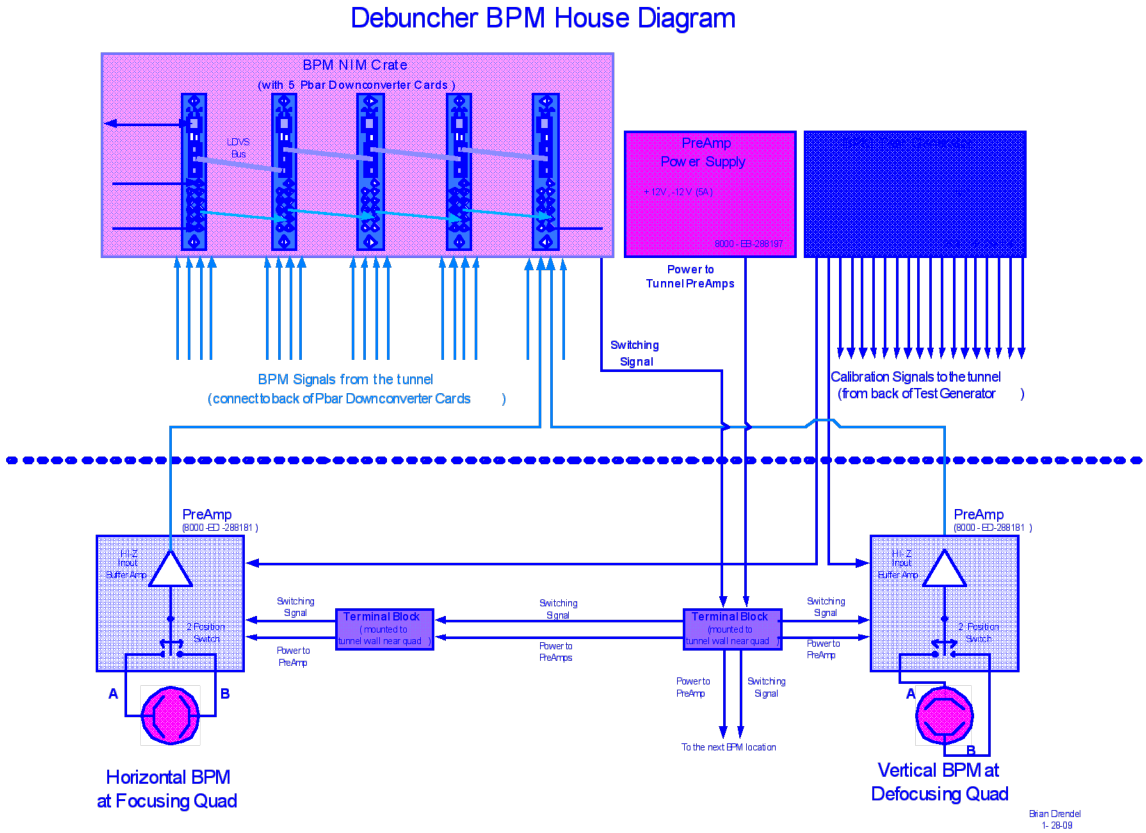


Figure 7.4: Debuncher BPM layout for one house
(only two of twenty BPMs are shown)

Each BPM pickup has a pair of plates (labeled A and B on Figure 7.4) whose signals are fed directly into a switching preamp mounted on the beam pipe. The preamp only connects to a single BPM plate (A or B) at a time, and switches back and forth between plates 500 times a second via a solid state switch. The output of each preamp is sent upstairs to the service building via a ½” heliax coax cable. The signals from twenty BPMs for a single house are fed through the top of the BPM rack and then connect to one of five Pbar Down-converter cards in a 5U NIM crate. The Pbar Down-converter cards for this system have a distinctive blue panel with orange lettering. It should be noted that Debuncher BPM electronics were upgraded from a VME based system to the current Pbar Down-converter Card based system in November

2008. This upgrade allows the use of Debuncher BPMs for both reverse protons and stacked pbars.

Each down-converter card connects to four BPMs on the back of the card, as well as an Ethernet connection, LDVS bus connections, and timer LEMO connections on the front of the card. At each location, one down-converter card serves as the "master" and the other down converter cards act as "targets." The "master" down converter card receives a TCLK via a front-panel LEMO input from a standard CAMAC timer card, which is fanned out by a LEMO daisy-chain to the "targets." The “master” down converter card also receives a 53.1MHz reference signal, which is sourced and fanned out from the A10 BPM house. Each down converter card is continuously observing a narrow band around 53.1 MHz on each of its four rear-panel inputs and synchronously demodulates the modulated signal on each input to derive the A & B plate signals. Each down converter module can decode signals from four BPM units.

The "master" down converter card connects to the "target" down converter cards via a daisy-chained Low Differential Voltage Signaling (LDVS) bus that is terminated at each end. LDVS allows for fast data transfer speeds over economical twisted pair copper cables. The LDVS cables look similar to the standard CAT5 Ethernet cables with RJ45 connectors, but the LDVS cables are flat.

The DRF1 adiabatic cavities play a curve with a 20msec flat top towards the end of the stacking cycle. This provides the 53.1 MHz bunch structure needed for the Debuncher BPMs to be able to detect circulating pbars. The Pbar Down-converter card sums the BPM A and B plate signals while beam is bunched during this time to provide the intensity reading. Since this intensity is a measure of the antiprotons that are bunched, it is not only dependent on beam intensity, but also on RF voltage, Debuncher momentum cooling gain and cycle time.

The "master" down-converter cards have Ethernet connections with network names of PbarDebBPM##.fnal.gov, where ## is the BPM house number (10, 20, 30, 40, 50, or 60). They communicate over Ethernet to the DEBBPM Java Open Access Client (OAC) pseudo front end that generates the BPM intensity and position readbacks.

The BPM Test Generator outputs calibration signals to the 20 BPM preamps in the tunnel for that BPM house. There are six BPM houses for a total of 120 preamps. The calibration signal travels on existing heliax coax cables left over from the previous Debuncher BPM system, and is modulated synchronously with the preamp switching signal to simulate any desired beam displacement.

The primary user interface for the Debuncher BPMs include the BPM parameter page (currently the P57 <DEB> and P57 <DEB2> subpages) and the Java Pbar Debuncher BPM application.

Debuncher TBT:

The vertical BPM at D6Q19 and horizontal BPM at D10Q are part of a turn by turn (TBT) system for use by Pbar experts during reverse proton studies as shown in Figure 7.5. Unlike the other Debuncher BPMs, the A and B plates of these BPMs have separate cables that come upstairs to the service building at the 60 house BPM rack. Recall that the normal Debuncher BPMs have only a single cable and a switching preamp that switches between the two BPM plates. In the top of the service building rack, the BPM signal pairs for the D6Q19 and D10Q BPMs are each run through a hybrid that produces a sum and difference signal. Each sum and difference signal is then run through a preamp, which can be found in the 60 sector BPM house rack under then normal BPM equipment. The output of the of preamps run on thick RG213 coax cable to the AP10 control room where they connect to a scope used to look at the TBT data for reverse protons. This is not related to the “Lava Lamp” TBT application, used for pbar injection, in any way. In addition, there is currently no ACNET interface to this system.

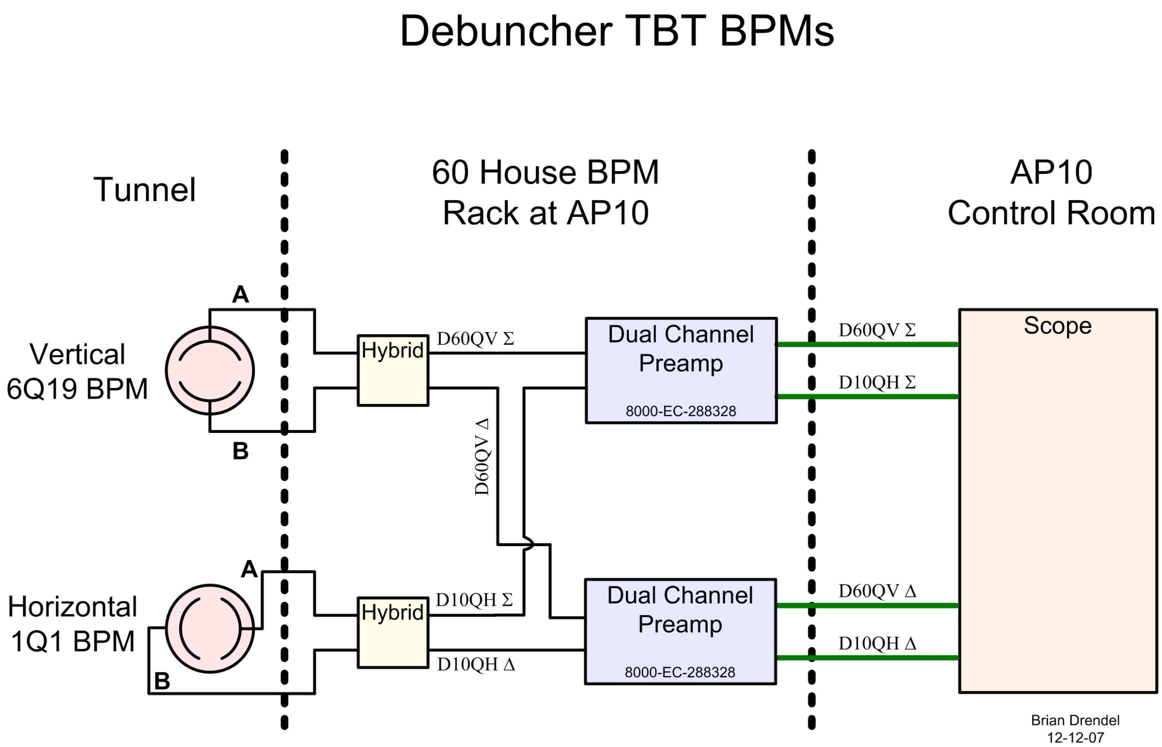


Figure 7.5: Debuncher TBT BPMs

<u>Accumulator</u>

The 90 Accumulator BPMs are divided into six “houses” of 15 BPMs each. The houses are named by tunnel location (10, 20, 30, 40, 50 and 60). Each of the BPM houses have a dedicated electronics rack that includes a VXI front end, resulting in two Accumulator BPM racks in each of the AP10, AP30 and AP50 service buildings. Figure 7.6 is a diagram of the BPM system for a single BPM house.

Signals from the BPM pickups go through an ion clearing box and on to a high impedance preamplifier. The ion clearing box and preamp are mounted directly on the beampipe. There are A and B signals corresponding to the two BPM pickup plates. The matched signal paths have independent gain control, in both cases the output of the preamp is input to the analog card in the VXI front end upstairs in the service building.

The Fermilab designed and built VXI analog card has eight inputs made up of four channel-pairs. Each input is gain adjustable with two modes of operation. Turn-By-Turn (TBT) mode uses down-conversion with a higher 50-55MHz frequency passband. Closed orbit mode has no down-conversion, with a lower 120kHz to 7MHz frequency passband. There is a two position switch in the analog card that allows switching between the TBT and closed orbit modes. The analog card also has a local oscillator (LO) input from a reference signal distribution module in the rack. This provides a 70.9MHz signal that is used in TBT mode. Output from the VXI analog card becomes the input for the VXI digitizer card.

The Fermilab designed and built VXI digitizer card also has eight inputs made up of four channel-pairs. Each input provides a 12-bit digitizer and a 128k buffer. The digitizer card has an on-board Digital Signal Processor (DSP) that processes the digitized data. When in TBT mode, a position for each turn is calculated and when in closed orbit mode an average position is calculated. The digitizer card also has a 25.6MHz ADC clock reference supplied from a reference signal distribution module in the rack.

The BPM VXI crate has a universal clock decoder (UCD) card that provides TLCK input and a Power PC card that contains the crate CPU. The Power PC card runs the VxWorks operating system that allows the VXI crate to communicate with ACNET and an Ethernet interface that provides connectivity to the Pbar Controls Network.

BPM calibration is achieved with three calibration-pulser modules located at the A10, A20 and A50 BPM racks. All three modules communicate using the GPIB protocol to a Power PC card in the A10 BPM rack. The calibration-pulser sends either a pulsed signal that emulates closed orbit BPM data or a burst signal that emulates seven 53MHz bunches. The signal is sent from the pulser modules to the tunnel, then split a number of times so that the signal goes to each BPM preamp in the tunnel. At the preamp, the calibration signal is split one more time, with one signal going to the A plate and the other to the B plate. These calibration signals are then used to calibrate and correct measurements.

The original Accumulator BPM system made use of a reference oscillator signal from an output of the ARF3 low level. With the new system, the expected revolution frequency of the beam is an ACNET device that is set by the user.

In addition to their primary role of detecting beam position, the Accumulator BPM plates also are used as a mechanism to remove trapped positive ions. A –1,000 Volt DC "clearing voltage" is applied to the pickup plates to attract ions. The RF BPM signals are passed to the electronics through blocking capacitors (see figure 7.6).

The user interfaces to the Accumulator BPMs include the Accumulator BPM application (currently P51) and the BPM parameter page (currently P57).

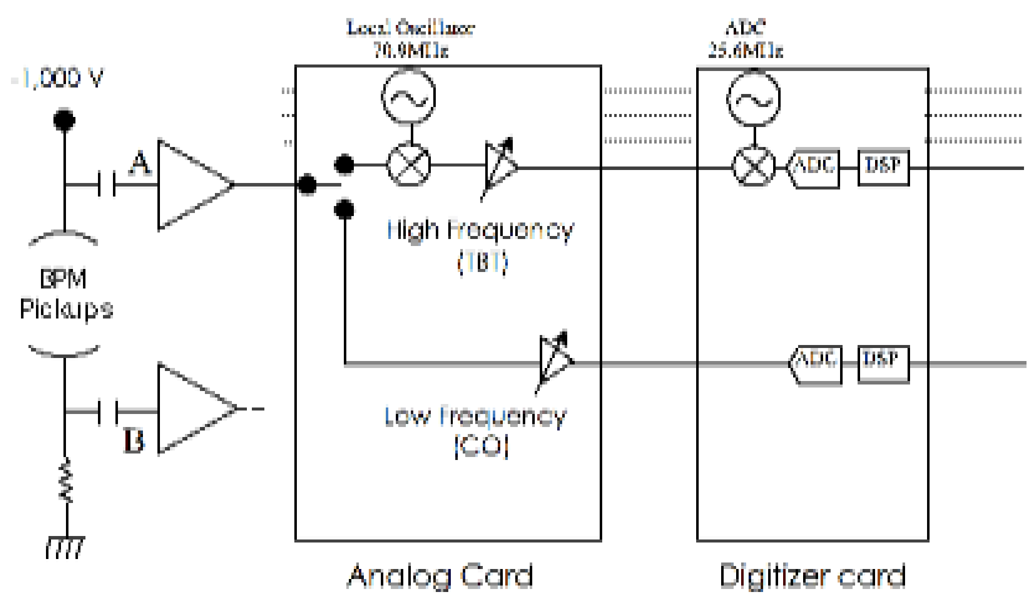


Figure 7.6: Accumulator BPM block diagram

Echotek BPMs

The P1, P2, AP1 and AP3 lines all share the Echotek style BPM electronics that were built as part of the "Rapid Transfers" Run II Upgrade. Electronics racks reside in MI60-S (P1 Line), F1 (P2 Line), F23 (AP1 and AP3 Lines), F27 (AP3 Line) and AP30 (AP3 Line). These BPMs are designed to detect seven to 84 consecutive 53MHz proton bunches in reverse proton or stacking mode, and four 2.5MHz pbar bunches in Accumulator to Recycler antiproton transfer mode. There are two crates used to process the BPM data: the analog crate and the VME crate. Figure 7.7 gives an overview of the Echotek BPM layout.

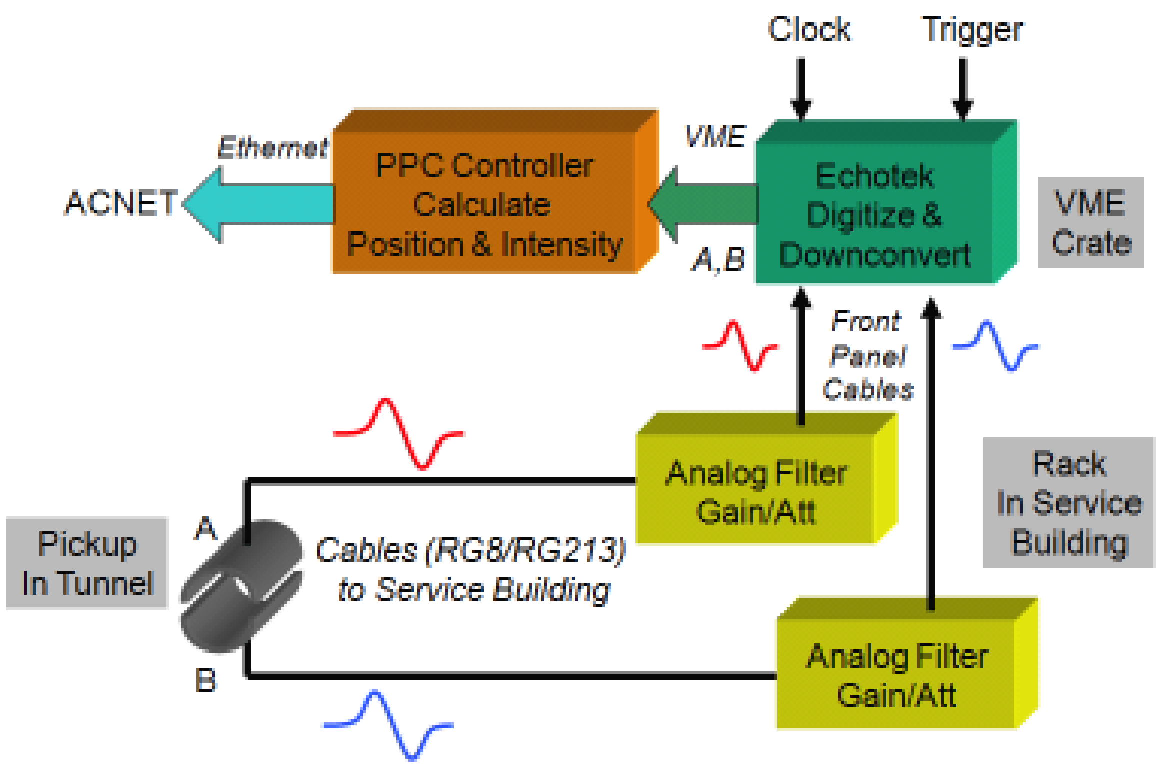


Figure 7.7: Echotek Beamline BPMs
(diagram courtesy of Beams Document Database #1849)

Analog Crate:

Signals from the BPM A and B plates in the tunnel are sent up to the service buildings via RG8/RG213 cables and are connected to the back of the analog filter cards in the analog crate. The analog cards filter, attenuate and amplify the analog BPM signals as needed. Each analog card can handle two BPMs (four BPM plate signals) that are processed and output through the front panel cables to Echotek cards in the BPM VME crate. The analog crate also contains a test/control module that handles setup of the filter modules including test pulses. The entire crate is powered with an external +5V power supply that is found near the bottom of the rack.

VME Crate:

Each Echotek card can handle four BPMs (eight BPM plate signals). These cards digitize and down-convert the signals so that the VME PPC controller card can calculate position and intensity information for each BPM. The VME crate has both TCLK and MIBS inputs. The IP modules decode TCLK, generate trigger and provide calibration I/O for the test/control module in the analog crate. The Trigger Fanout module fans out the MIBS trigger to each of the Echotek cards, and the CD Clock Board fans out TCLK to each of the Echotek cards. The BPM arming events are usually TCLK where synchronization to the beam is not required, while the trigger events are sourced by Main Injector Beam Synch (MIBS), whose reference is the Main Injector LLRF system. The PPC controller handles front end software, readouts and communication. The Ethernet connection on the PPC controller allows communication over the Pbar Controls network. The unique wireless network configuration in the F23 and F27 service buildings are covered in detail in the Controls Chapter of this Rookie Book.

The user interfaces for the beamline BPMs include the Oscillation Overthruster application (currently P156), the Java Beamlines BPM application, the APX Beamline Lattice application (currently P143) and the Pbar Reverse Proton Tune-up application (currently P150).

AP-2 and D-to-A Line BPMs

Secondary particles in the AP-2 line have the same 53MHz bunch structure as the targeted proton beam, so BPMs can be used to detect beam position. There are 34 BPMs in the AP-2 beam line and seven BPMs in the D to A line that share common design features. When stacking, the number of antiprotons and other negative secondaries (mostly pions and electrons) in the AP-2 line is relatively small, on the order of 1×10^{11} at the beginning of the line and 1×10^{10} at the end of the line. The beam intensity in the D to A line is even smaller, with $\sim 10^{8}$ or less reaching the Debuncher. In addition, the AP-2 BPMs on the Debuncher end of the line see significant electrical noise from the Debuncher Injection kicker. For these reasons, the AP-2 and D to A Line BPMs could not be used for measuring pbars in past years. In 2005, new BPM electronics were designed for use in the AP-2 line. After the electronics were installed and deemed a success, they were then propagated to the D to A line BPMs. AP-2 BPMs can be used to look at both bunched stacking secondaries and bunched reverse proton beam while D to A line BPMs are only used under special conditions. During stacking, the D to A BPMs are only used with the Pledge Pin application (currently P155) for tuning on closure into the Accumulator. The D to A line BPMs can also be used to look at bunched reverse protons.

As beam decreases in intensity while traversing the AP2 and the D to A lines, increasing amounts of amplification is needed before the signals can be processed. The upstream AP2 BPM (701-715) plate signals are sent straight up to the F27 service building where they are amplified by 20dB RF amps. The downstream AP2 BPM (716-734) plates have low noise Hittite amps with 25dB gain located in the tunnel. The D/A line BPMs must read even lower intensities, so two cascaded Hittite amps with a total gain of about 50dB are attached to the pickup plates in the tunnel.

BPM signals are routed to racks in the service buildings. There are racks at F27 (upstream AP2 BPMs), AP50 (downstream AP2 BPMs) and AP10 (D to A line BPMs). F27 and AP50 each have two NIM crates, and AP10 has one NIM crate. The NIM crates house four to five Pbar down-converter cards.

Each down-converter card works in a very similar manner to the Debuncher BPM down-converter cards, which were explained in detail above. They have the same “master” and “target” down-converter configuration, with the same LDVS bus. The timing is also daisy-chained in the same manner with AP2 BPMs using MIBS and the D to A BPMs using TCLK. All Pbar BPM down-converter cards have four BPM input connections. Unlike the Debuncher BPMs, each AP2 or D to A BPM plate has a separate signal cable. This means that no switching signal is required, but also means the down-converter cards only connect to two BPMs instead of four. Each down-converter card is continuously observing a narrow band around 53.1 MHz on each of its four rear-panel inputs, which are the BPM plate signal pairs coming from the tunnel. When a trigger arrives, about 5 microseconds of the 53.1 MHz envelope data are recorded in Field-Programmable Gate Array (FPGA) SRAM and integrated to form the "A" and "B" signals for each pair of BPM plates.

The "master" down-converter cards have Ethernet connections with network names of AP2BP4 (F27), AP2BP6 (AP50), and AP2BP2 (AP10). They communicate over Ethernet to the AP2BPM Java Open Access Client (OAC) pseudo front end that generates the BPM intensity and position readbacks.

The user interfaces for the beamline BPMs include the stacking beamline steering (Oscillation Overthruster) application (currently P156), the Java Beamlines BPM application, and the APX Beamline Lattice application (currently P143).

Secondary Emission Monitor (SEM) Grids

SEM grids are used to measure the beam profile in the horizontal and vertical planes. SEMs consist of rows of 30 vertical and 30 horizontal titanium strips that can be placed in the path of the beam. Beam particles have elastic collisions with electrons in the strips and dislodge them (see figure 7.8). This causes a current to flow in the strips, which is amplified by preamplifiers. For every forty protons or antiprotons passing through the SEM, one electron is dislodged yielding a detector efficiency of 2.5%. A clearing voltage of +100 VDC can be applied to foils placed before and after the strips to improve the work function of the titanium and double the efficiency to 5%. Since a small amount of the beam collides with the titanium strips, SEM grids are not completely passive devices. Most SEM grids are located in the transport lines, although a few are located near injection and extraction points in the rings to be used during initial tune-up. If one of the ring SEM grids is left in, beam will be rapidly lost.

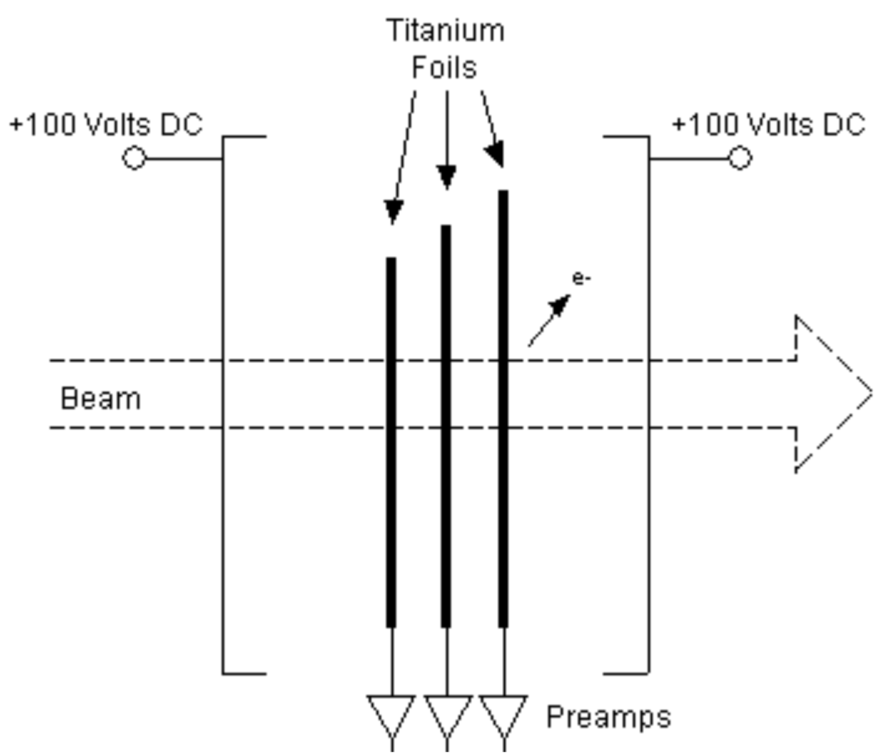


Figure 7.8: SEM grid

Motors move the grids into the beam and are controlled by a CAMAC 181 card. The SEM motor controllers have a safety system input. It retracts the SEM grids from the beam pipe when the beam permit is down. This feature is intended to keep the grids out of the beam pipe should vacuum be broken. Technicians can override this function locally if necessary.

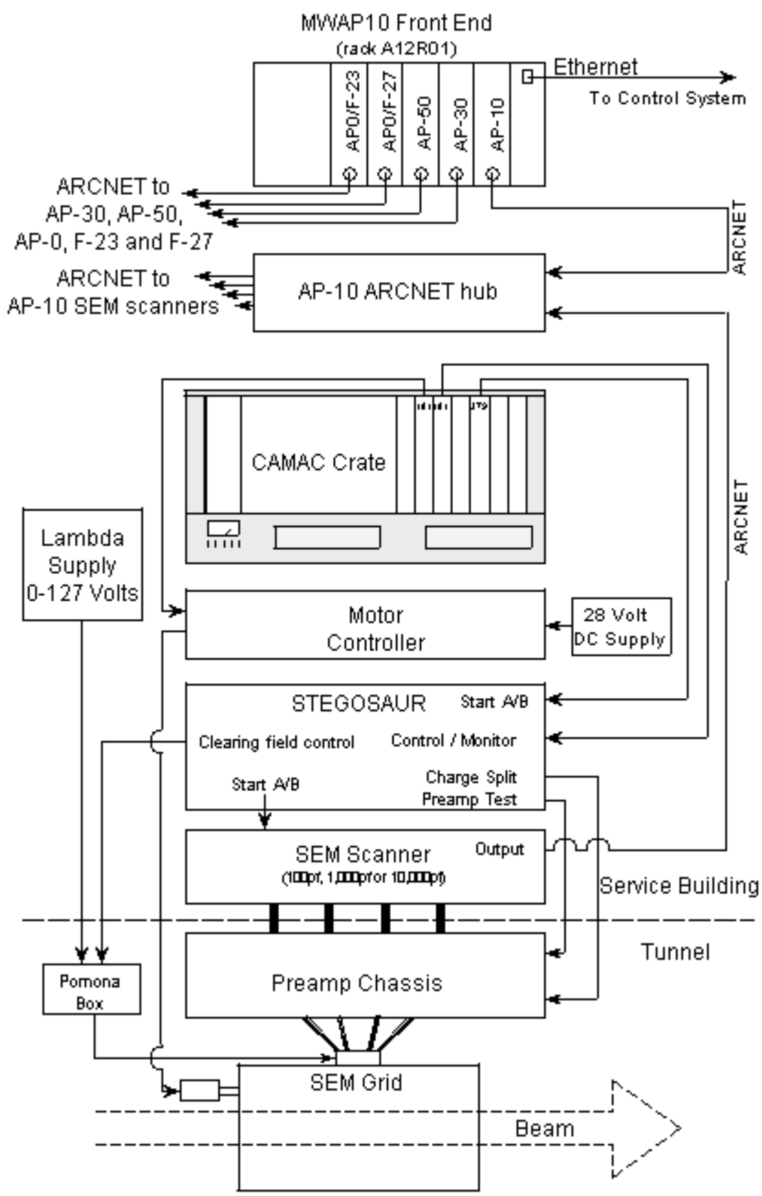
The SEM grids operate at beam pipe vacuum pressure and thus have no gas gain like the Segmented Wire Ionization Chambers (SWICs) found in Switchyard. Preamp boxes are used to amplify the signals generated by the SEM. Preamp boxes contain a pair of motherboards with 30 preamp boards plugged into each (one horizontal and one vertical set). Some versions of the preamp box have charge splitters that, when selected, attenuate the signal to the preamps 15 times when the charge split input is +5V. D to A line SEMs use preamps with two available gain configurations. Switching the gains requires a tunnel access. D to A line SEM gains are up to 260 times more sensitive than those of the other SEMs due to the low beam intensities found during stacking.

SEM Electronics:

The SEM electronics have been updated from the original design, using components already in use for SWICs and multiwires elsewhere in the accelerator complex. The new SEM electronics lacked some basic functionality of the old system, so features such as adequate background subtraction and averaging were added to the Pbar system after the initial installation. The Target SEM and D to A line SEMs were initially not converted to the new system because of the background subtraction problem. The new system still uses the STEGOSAUR, one of the CAMAC timer cards and motor controllers from the old system. The STEGOSAUR is based on the STEG acronym for SEM Test Event Generator. The STEGOSAUR provides timing and test pulsing capabilities for up to six SEMs. Figure 7.9 is a block diagram of SEM electronics and the controls interface.

The scanners come in three varieties: 10,000 pf, 1,000 pf, and 100 pf. In general, the lower the capacitance of the scanner, the more sensitive it is to lower intensity beam. The 10,000 pf scanner can handle intensities down to around the 10^{11} particle range, so all AP1 and the upstream AP2 SEMs use this variety of scanner. The 1,000 pf scanner can handle intensities down to around the 10^{10} particle range, so the downstream AP2 SEMs use this scanner. The 100 pf scanner is sensitive down to the 10^{8} particle range, so these are used for the D to A line SEMs.

Figure 7.9: SEM electronics and control



The output from the new scanner is sent over ARCNET to a hub and then onto the MWAP10 VME front end at AP10. ARCNET is an acronym for Attached Resource Computer NETwork, which is an inexpensive local area network that can be used to connect up to 255 network devices over coaxial cables with data rates up to 2.5Mbps. The MWAP10 front end has one Ethernet connection used to communicate with the control system using the VxWorks operating system and five ARCNET cards that allow the VME to communicate with the SEM scanners. Each ARCNET card connects to one or more ARCNET hub(s) and can interface with up to eight scanners. There is a single dedicated ARCNET card, connecting to a single ARCNET hub, for the scanners at each of the AP10, AP30 and AP50 service buildings. The remaining two ARCNET cards each service two locations. One ARCNET card goes to an ARCNET hub at the downstream (stacking direction) end of AP0, and then to a second ARCNET hub at the F27 service building. Another ARCNET card connects to an ARCNET hub at the upstream end of AP0 and then to a second ARCNET hub at the F23 service building. Table 7.2 shows which SEMs are attached to each ARCNET location (* indicates that, as of this writing, the old SEM electronics are still in use).

MWAP10 SEM Controls			
MWAP10 ARCNET Card	**Scanner Location**	**SEMs Locations**	**SEM numbers**
1	AP10	D/A*, Debuncher, Accumulator	607, 802, 806,807,104
2	AP30	Upstream AP2	900, 906, 909, 913
3	AP50	Downstream AP2, Accumulator	403, 719, 723, 728, 733
4	AP0	Far Upstream AP2	704, 706
	F27	Upstream AP2, Downstream AP3	710, 715, 917, 921
5	AP0	Far Downstream AP3, Target*	926, Target*
	F23	AP1	100, 103, 105, 106

Table 7.2: MWAP10 ARCNET

The STEGOSAUR is still used, but only provides a single trigger to the scanners (unlike the separate clear and start times used by the old SEM electronics). The SEMs receive an MIBS trigger for AP1 and AP3 line SEMs, and a TCLK trigger for AP2 and the D to A line.

The STEGS, MTRS, TIMERS application (currently P95) is used for pre-amp tests, clearing field control and charge splitter control. The PBAR SEM

GRIDS application (currently P58) is used to moves SEMs in and out, display SEM profiles and adjust timing.

Optical Transition Radiation Detectors

Optical Transition Radiation (OTR) is generated when a charged particle beam transits the interface of two media with different dielectric constants. An OTR detector works by placing a metal foil in the path of the beam. The interface between the vacuum and foil creates OTR when beam hits the foil. The foil is thin to minimize beam scattering and is placed at an angle with respect to the beam, so that the reflected OTR can be directed to a camera.

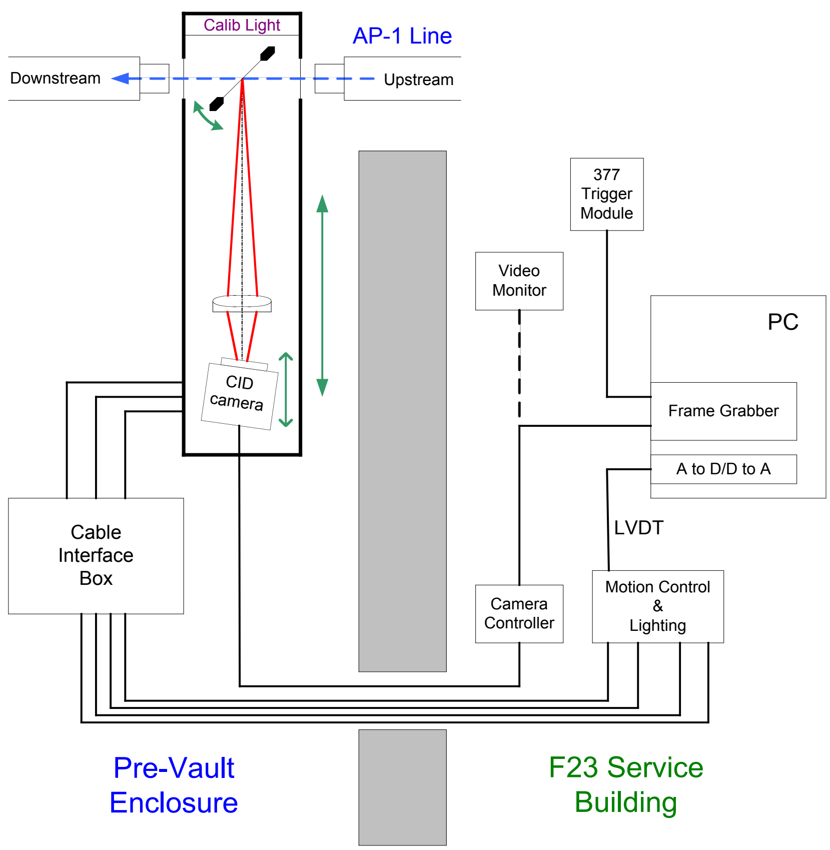


Figure 7.10: OTR Block Diagram
(diagram courtesy of Beams Document Database #2110)

The camera can then record a two dimensional beam profile that includes information about the transverse profile, transverse position, emittance, and intensity of the beam.

OTR detectors are a commonplace diagnostic in electron accelerators. Fermilab experts are attempting to expand the use of this diagnostic to proton and antiproton beams in the various transfer lines. A prototype OTR detector was installed in the AP1 beamline just downstream of EB6 (D:H926) for evaluation. Figure 7.10 is a block diagram of the AP1 OTR system. Foils were composed of 20 μm Aluminum or 12 μm Titanium. It was found that the Aluminum foil provided a brighter signal, but the Titanium foil was more resistant to particle flux. As a result, the choice of OTR foil is dependent on the expected particle flux in the line. A single lens is used to focus the OTR signal onto a radiation-hardened Charge Injection Device (CID) camera. To minimize radiation damage, the camera and lens are placed as far away from the foil as the optics will allow. The foil is located in the beampipe vacuum with a transparent vacuum window between it and the camera and lens that are enclosed inside a light-tight box. Motion control is provided to adjust the angle of the foil and the focus of the camera. For best focus, the camera is placed at the Scheimpflug angle, which defines where the best focus occurs when the subject plane (foil) and image plane (camera) are not parallel. Controlling electronics are connected to a LabVIEW PC located at the F27 service building. Data collection is currently an expert-only task, as there is not yet an ACNET interface to this system.

OTR images were successfully gathered for 120 GeV proton beam during stacking, providing a 2-dimensional beam profile that (unlike a SEM) included the rotation of the beam ellipse. The OTR is downstream (stacking direction) of the AP1 to AP3 line split so that the vacuum windows won't cause pbar emittances to grow during transfers to the Recycler. Also, the OTR was most suitable as a 120 GeV diagnostic because the lower energy 8 GeV beam generates a wider optical distribution, resulting in less light collection. The optical distribution of the OTR peaks at roughly

1/γ, where $\gamma = \frac{1}{\sqrt{1^2 - \frac{v^2}{c^2}}} = \frac{E_{total}}{E_{rest}}$. The gamma (γ) for 8 GeV protons is approximately 13 times smaller than that of 120 GeV protons, so the optical distribution generated by the OTR would be about 13 times larger.

Experts also considered installing an OTR detector in the AP2 line. In this case, one could use secondary particles rather than Pbars to make the OTR signal. All negatively charged secondaries going down the AP2 line have a momentum of 8.9 GeV/c, but all have different gammas since their rest energies are different. As a result, the optical distribution for each type of particle would be different. Beam in the AP2 line is overwhelmingly dominated by pions, which outnumber Pbars by orders of magnitude. In addition, the pions have a gamma that is seven times larger than that of an equal momentum pbar, making the spot size seven times smaller. Consequently, experts believe that it is feasible to put an OTR in the AP2 line if desired.

Ion Profile Monitors

An Ionization Profile Monitor (IPM) provides information about the beam's transverse profile, utilizing the positively charged ions created by the beam interacting with residual gas in the beam pipe. There are several types of IPMs used throughout the accelerator complex, the design presently used in the Debuncher is relatively simple. The density of ions created at a particular location is proportional to the density of the beam particles; therefore, the transverse distribution of ions is the same as that of the beam. Ions then drift in the static electric field created by a set of electrodes, as shown in Figure 7.11.

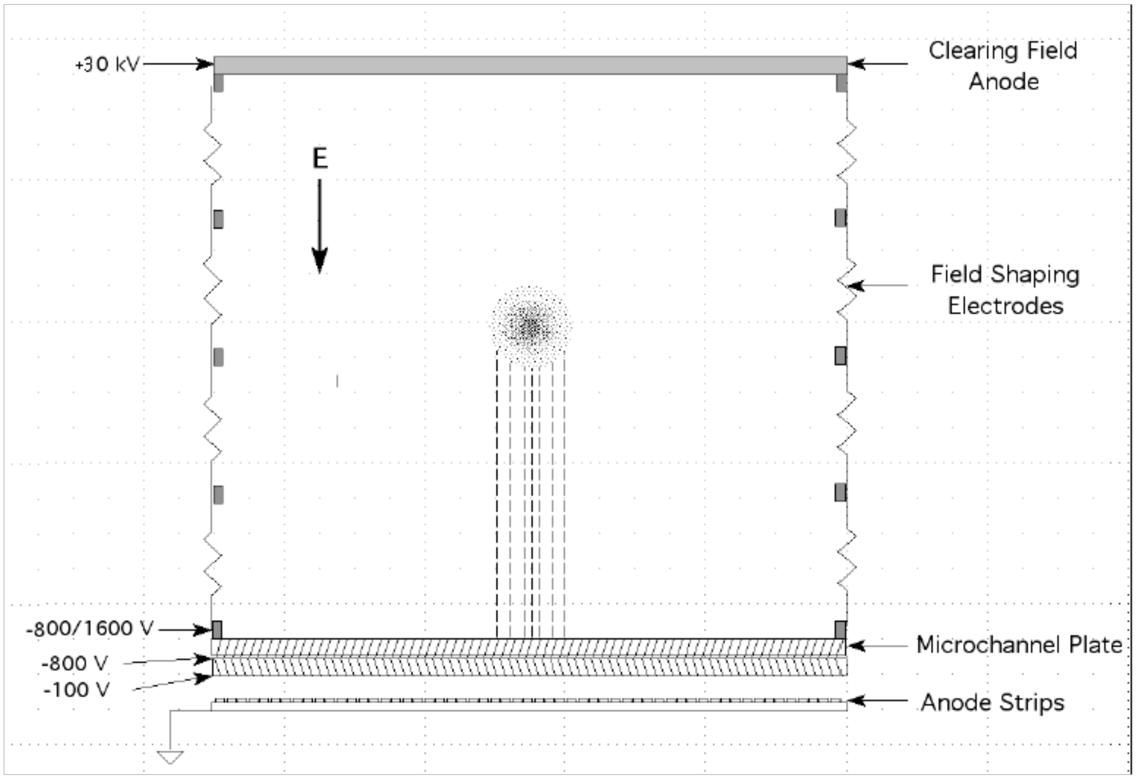


Figure 7.11: IPM components

The initial lateral speed of ions and diffusion during their travel is negligible, so the ion cloud retains its shape until they hit the Microchannel plates (MCP). When the ions collide with the MCP, secondary electrons are created, which continue into the MCP structure. The number of electrons is multiplied by a factor of 104-105 in the MCP, making it possible to easily detect the charge collected on each of the anode strips below the MCP. The transverse distribution of the charge collected on the anode strips has the same shape as the beam.

Beam intensity in the Debuncher is very low, only about 20 μA of DC current. Therefore the integration time of the IPM must be about 50 msec in order to collect appreciable charge. This is too long for observing injection effects, but acceptable for studying the stochastic cooling rates during a stacking cycle. After receiving a trigger from a timer card, an external pulse generator starts sending triggers to a SWIC scanner at the rate of 10Hz. On each trigger the SWIC scanner reads out, integrates and sequentially digitizes the signal on each of the detector anode strips. The Front End process, located in the VME Motorola 2401 CPU card, reads the data buffer from the scanner before the next trigger arrives.

The IPM power supplies, electronics and Front End are located in AP30 in racks A33R04-A33R06. The system connects to the front end using a GPIB interface. High voltage control and other parameters can presently be found on page P38 MISC <12>.

MCPs are susceptible to problems when the high voltage is left on too long. In order to ensure that this does not happen accidentally, the Front End shuts off the IPM high voltage after an adjustable time has elapsed (typically 3 minutes).

An external user application (currently page W112) controls the process of data acquisition. It can also save the processed data on demand to disk storage, available for subsequent viewing. A simplified version of the program, based on SA1158, is running permanently on one of the MCR consoles. This process collects data after receiving a command from the sequencer and saves data into the datalogger buffer. Data saved on the disk and in the datalogger can be viewed using the java program IPM Viewer.

Flying Wires

The hardware for six flying wires exists in the Accumulator, but these devices are not currently used. The flying wires were designed to allow accurate transverse emittance and momentum distribution measurements. Five of the wires are located in a single assembly in the A40 high dispersion straight while the other wire is located in A30 between A3Q7 and A3B7 where the dispersion is relatively low. The three horizontal wires in A40 are positioned to allow separate measurements of beam on the injection orbit, central orbit and core orbit.

There were a few issues with the flying wires that led to their decommissioning. The forks for some of the wires pass through the stacktail when they are run. This beam, though small in quantity, would be lost when the wire was flown. Occasionally, the wire controls would lose track of the wire position, or even run the wires through the beam repeatedly. Recovery required a system reset, which flew the wires in order to determine their position. The wire filaments themselves are fairly fragile and prone to breaking. When a wire would break, repair would require opening up the Accumulator vacuum chamber during a shutdown. The vacuum seals on the wire assemblies were also vulnerable to leaks. The hardware for the flying wires is still in place; however, the wires have been pinned in the tunnel so that they can't be moved. If this system is brought back online in the future, the Accumulator vacuum chamber would have to be opened, since it is believed that some of the wires are currently broken.

Quadrupole Pickup

There is a skew quadrupole pickup located at the upstream end of the A10 straight section. There used to be a normally oriented quadrupole pickup in the same location, but that device was removed from the Accumulator to improve aperture.

A quadrupole pickup can be used to measure transverse quadrupole oscillations of the beam. The pickups are about a meter in length and are made up of four striplines. The quad pickup had the striplines oriented vertically and horizontally on either side of the beam, the skew quad pick up has the striplines rotated 45°. The signals are amplified and sent to electronics in the AP-10 service building, which processes the signals.

Unlike dipole oscillations, which arise from steering errors, quadrupole oscillations are the result of lattice (ß function or dispersion) mismatches between an accelerator and beamline. The primary use of the quad pickup was intended to quantify the lattice mismatch between the P1/P2/AP-1/AP-3 lines and the Accumulator. In principal, the match could be improved by varying AP-3 quadrupole currents and observing and minimizing the amplitude of the quadrupole oscillations from protons reverse-injected from the Main Injector. In practice, however, it was found that the quadrupole oscillations were overwhelmed by the dipole oscillations and were very hard to see. Also, chromaticity is high on the injection orbit, so the quadrupole oscillations break down (decohere) very quickly. Although the skew quad pickup is currently not used, it is available for use as a fast broadband pickup.

Longitudinal Measurements

The third section of this chapter will cover longitudinal beam measurements made with Wall Current Monitors and Gap Monitors. Longitudinal Schottky Detectors are covered separately in the Schottky Device section and longitudinal signal analyzer displays are covered in the separate Signal Analyzers section.

Wall Current Monitor

Beam with a bunch structure causes current to flow on the inside of a metallic beam pipe, such as the stainless steel beam pipes used in the Antiproton Source. By breaking the metal beam pipe with an insulating ceramic gap and placing a resistor across the gap, one can measure the voltage drop across the resistor that is proportional to the beam current.

The frequency response of the pickup rolls off on the low end because of beam pipe conditions external to the pickup, so the pickup is housed in a shielding box loaded with ferrite material to provide a known value of inductance. The geometry of the ceramic gap and the resistors are chosen to form a properly terminated transmission line. The low frequency response of the wall monitor is determined by the time constant set by the ferrite (16 mH) and the gap resistance (0.5Ω), it is about 5 kHz. The characteristics of the ferrite inductors also set the high frequency response of the pickup. Two types of ferrites and a coating of microwave absorbing paint inside the shielding box are used to provide an even frequency response to 6 GHz.

As beam passes irregularities like bellows in the beam pipe, it induces microwave fields at frequencies determined by the dimensions of the beam pipe structures. That energy travels down the inside of the pipe and can be detected by the wall monitor. To avoid those noise problems, ferrite chokes are installed on both ends of the wall detector.

Signals are taken off the gap at four points around the circumference and summed to minimize sensitivity of the output signal to variations in beam position within the pipe. The overall sensitivity of the monitor, accounting for gap resistance, summing of the four signals, 50Ω terminating resistor, etc. is approximately 0.15Ω. That is, the transfer impedance of the pickup is the output voltage over the beam current:

$$Z_{pu} = \frac{V_{out}}{I_{beam}} = \frac{.15V}{1A} = .15\ \Omega$$

There is one resistive wall current monitor (also often called a wall current monitor or resistive wall monitor) in the Accumulator located in the 50 straight section, and another in the AP1 line just upstream of Tor105. Presently, the Accumulator wall current monitor is set up for aligning RF systems. This is an expert-only task, and there is currently no ACNET interface to this system. The wall current monitor in the AP1 line attaches to a scope at AP0 and is broadcast on CATV Pbar channel 7. This diagnostic has two functions. First, it is used to show the bunch structure of 120 GeV protons used for stacking. The ACNET interface is the Proton Torpedo secondary application (currently started from P194), which is shown in Figure 7.12. The second use is to monitor the longitudinal emittance of 8 GeV pbars during transfers. The ACNET interface is the LONG EMIT CALC program (currently P207) and generates profiles for each Pbar transfer from the Accumulator as also shown in Figure 7.12.

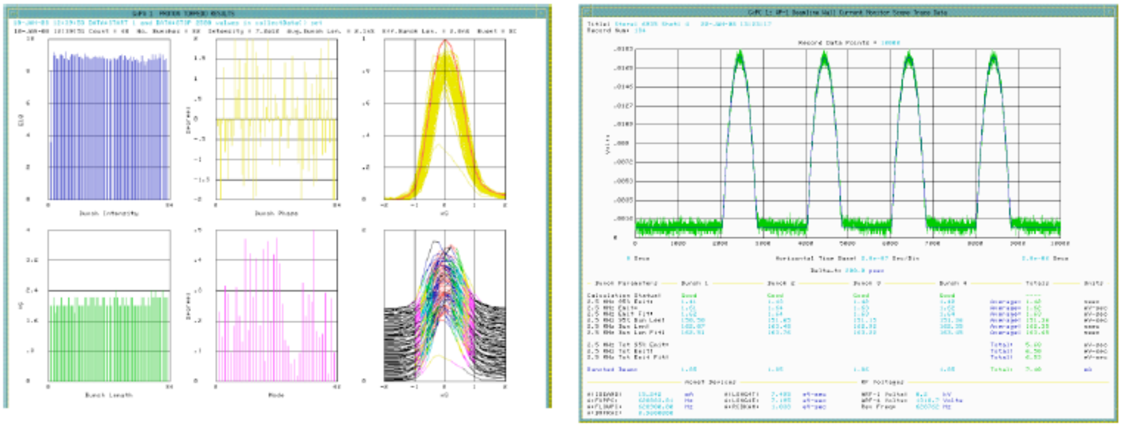


Figure 7.12: AP-1 Wall current monitor displays for
120 GeV protons (left) and 8 GeV unstacked pbars (right)

Gap Monitor

A gap monitor is virtually identical in design to a RF cavity. In fact, the gap monitor used in the Accumulator 10 straight section is the same style resonant cavity used for ARF2 and DRF2. Unlike a RF cavity, which has voltage applied to it to accelerate or decelerate the beam, bunched beam passing through the gap in the cavity produces a voltage.

The gap monitor is not a totally passive device, the beam is decelerated slightly as it passes through the gap (what would be the accelerating gap in a RF cavity). The amount of energy given up by the beam as it passes through the resonant cavity is determined in part by the Q of the cavity (the relative strength of the resonance). The gap monitor cavities are intentionally lower in Q than the RF cavities. The low Q weakens the signals but reduces the effect on the beam. Although the cavities retain the ferrites used in RF applications, the capacitance is kept much lower. The gap monitor is a relatively large bandwidth device but is not sensitive enough to detect Schottky signals.

There are two gap monitors in Pbar, one in each of the Pbar Rings. The Accumulator gap monitor is located in the A10 straight section just downstream of A1Q5. This device is used to produce the "Jello" Display on the AP10-flux-scope located in the AP10 control room and broadcast on Pbar CATV channel 18. This scope can also be used as a backup to the AP0 wall current monitor scope with the LONG EMIT CALC program (currently P207) to calculate the longitudinal emittance of the unstacked bunches.

The Debuncher gap monitor is located in the Debuncher 10 straight section just upstream of D1Q2. Three diagnostic tools use it: the Debuncher turn by turn scope, Flux Capacitor, and Lava Lamp. The Debuncher turn by turn scope (deb-tbt-scope) is located in the AP10 control room and shows the relative intensities of each of the first few turns of beam. The Flux Capacitor uses the AP10-flux-scope in the AP10 control room to display the amplitude and phase of the first turn of Debuncher beam when stacking. The D:INJFLUX parameter is calculated in an OAC (Open Access Client) from this data. This is the same scope that is used for the Jello Display when we are unstacking. The Lava Lamp is started from the Debuncher Injection TBT application (currently P152). It uses both the Debuncher gap monitor and Debuncher damper pickups to make a turn by turn and bull's-eye plot that can be used to reduce Debuncher Injection turn by turn oscillations.

Schottky Devices

The fourth section of this chapter will cover Schottky devices. This includes the Accumulator and Debuncher Schottky detectors and the Accumulator wide band pickups. Common uses of the Schottky Detectors are covered in the Signal Analyzer section.

Schottky Detectors

A charged particle passing through a resonant stripline detector or a resonant cavity creates a small signal pulse known as a Dirac pulse. A particle beam is made up of many charged particles and creates a signal called Schottky noise. Schottky noise is a collection of signal pulses in the time domain, which corresponds to a spectrum of lines in the frequency domain. The lines occur at harmonics of the revolution frequency since the particles circle the accelerator and pass repeatedly through the pickup. The combined response from all the particles in the ring is smeared over a finite frequency range (Schottky bandwidth) at each harmonic. This frequency range is related to the momentum spread of the beam by

$$\frac{df}{f} = \frac{dp}{p}\eta$$

where η (eta, the slip factor) is fixed by the machine.

The revolution period of beam in the Debuncher is 1.6950 μs, therefore the revolution frequency is 590,018 Hz. In the Accumulator, the revolution period of the beam varies between 1.5904 μs at the injection orbit to 1.5901 μs at the core. This corresponds to revolution frequencies of 628,767 Hz and 628,898 Hz respectively. In practice, beams injecting into and extracting out of the Accumulator are at slightly different frequencies. The Debuncher revolution frequency is lower than that of the Accumulator because the Accumulator has a smaller circumference. Table 7.3 shows approximate values of the slip factor, revolution frequency and momentum in the Debuncher and on the injection, central and core Accumulator orbits.

	η	Frev (Hz)	Momentum (MeV/c)
Debuncher	0.006	590,018	8886
Accumulator (Injection Orbit)	0.0159	628,767	8886
Accumulator (Central Orbit)	0.0152	628,840	8804
Accumulator (Core)	0.0138	628,898	8748

Table 7.3: Approximate slip factor, revolution frequency and momenta for various orbits

Signals from the Schottky detectors can be displayed on signal analyzers. A coaxial relay multiplexer or “mux” box at AP10 has eight inputs and eight outputs (not all are used) and is used to remotely connect a signal of interest to one of the analyzers. There are four Schottky detectors, which can connect to one of the four spectrum analyzers (analyzer #2 is normally connected to the Accumulator longitudinal Schottky) via the mux box.

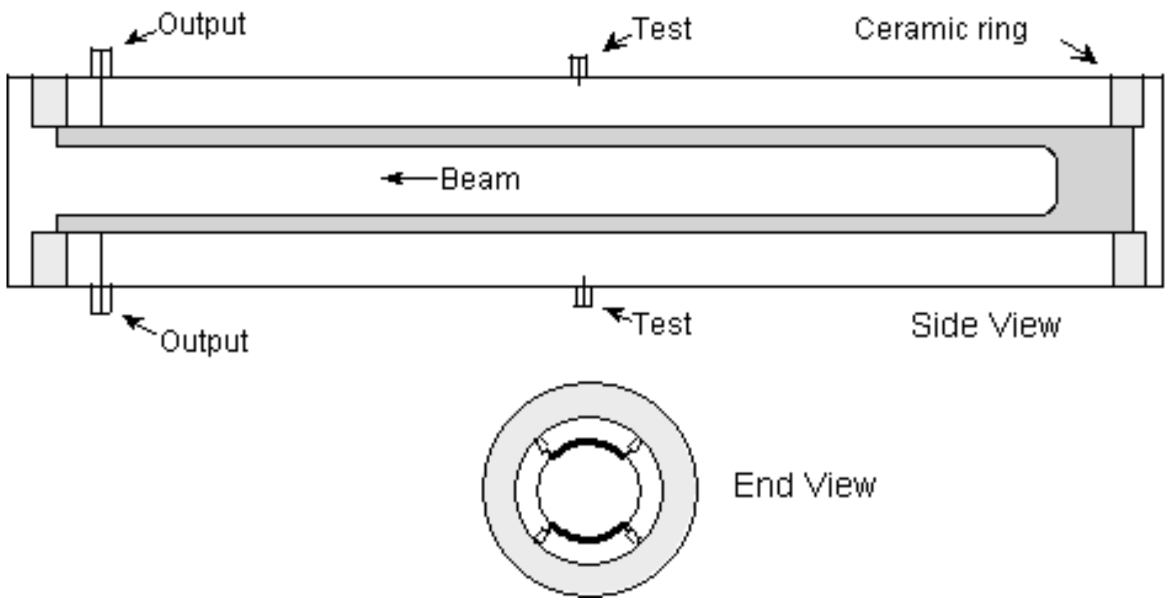


Figure 7.13: Vertical Schottky detectorSchottky pickups (or detectors) are devices that are used to detect Schottky noise.

There are four Schottky pickups used in the Antiproton Source. The Debuncher has a longitudinal pickup and the Accumulator has vertical, horizontal, and longitudinal pickups. Originally there were also horizontal and vertical Schottky detectors located in the Debuncher, but they were removed to improve aperture. All of the Schottky pickups are located in the 10 straight section. The Accumulator vertical and horizontal transverse pickups are approximately 24 inches long and 2 inches in diameter. These pickups detect transverse beam oscillations. The vertical pickup has the striplines above and below the beam with outputs on the top and bottom, the horizontal pickup is rotated 90°. The transverse pickups are a stainless steel tube with a slot cut along much of the long dimension (see Figure 7.13). The pickup is held by ceramic rings, which also electrically insulate it from the outer housing.

Signals from each plate are fed through to a 3/8-inch heliax cable, which is run to the AP-10 service building. Signals are not run directly to the MCR because of the signal loss that would result from the long cable run. The detectors resonate at a frequency determined by the length of the strip inside the cylinder plus the coaxial cable between the output connector and a capacitor. Connectors in the middle are used to inject a signal for tuning the device to the desired frequency. Horizontal and vertical pickups are mounted on motorized stands so that the device can be centered with respect to the beam.

The longitudinal pickups are larger, 37 inches in length and 3.4 inches in diameter. These pickups are tuned quarter-wave cavities that are made by separating a stainless steel tube into two sections with a ceramic across the gap. Charged particles crossing the gap produce Schottky signals. The longitudinal detectors are tuned with plungers or sliding sleeves on the center element. Again, the unused fittings seen on the cavities are used to inject signal for tuning purposes.

The Schottky detectors used in the Antiproton Source are designed to be most sensitive to the 126th harmonic of the beam's revolution frequency. Signals from other harmonics near the 126th can also be detected, but are weaker.

There are several reasons for choosing the 126th harmonic for the design of the Schottky detectors. The spectral power contribution from the 53.1 MHz bunch structure (from ARF-1 in the Accumulator) is minimized by using a frequency located between 53.1 MHz (h=84) and its second harmonic at 106.2 MHz (h=168). The detector must also have an adequately large aperture. Limited space available in the rings limits the pickup length to only 1 or 2m. Schottky detectors designed for the 126th harmonic fit both of these size constraints. For example, recall that the longitudinal Schottky pickups are 1/4 wavelength long. The physical length of the cavity as built is .94 meters ($\frac{1}{4*126}$ of the Accumulator circumference) which would result in a resonant frequency of:

$$f = \frac{\text{velocity}}{\text{length}} \sim \frac{3E8\ \text{m/s}}{4 * .94\ \text{m}} \sim 79.75\ \text{MHz}.$$

That works well for the Accumulator (126 * .628898 MHz = 79.24 MHz), but the Debuncher h=126 falls at 74.34 MHz (126 * .590018 MHz) so a tuning screw is added to its longitudinal pickup to capacitively lower the resonant frequency of the detector.

Schottky pickups have many diagnostic uses. They are used to measure the betatron tune, synchrotron frequency, transverse emittance and momentum spread. Because the spectral power of the signal is proportional to the number of particles in a DC beam, the pickups can also be used to measure small beam currents. The Schottky pickups can be calibrated against the DCCTs at beam currents up to around 100 mA.

Wide Band Pickups

As the name implies, a wide band pickup is able to detect a relatively broadband range of frequencies as compared to other detectors. Actually the resistive wall monitors and gap monitors are also broadband, but have poor response that makes it difficult to observe Schottky signals. The wideband pickups, both horizontal and vertical, are actually made up of three small $^1/_4$ wave stripline Schottky detectors. A 10 inch pickup is sensitive to signals in the 0.2-0.4 GHz range, a 4 inch pickup sensitive to signals in the 0.5-1 GHz range and a 2 inch pickup sensitive to signals in the 1-2 GHz range. Each pickup is attached to hybrids that provide both sum and difference signals for viewing at AP10. All twelve signals (sum and difference signals for three horizontal and three vertical pickups) are connected to amplifiers that must be powered to provide a strong enough signal for the signal analyzers. An analyzer must be connected to the appropriate cable spigot at AP10 to select a particular frequency range. The switch tree can only be used to connect horizontal or vertical sets of pickups to the appropriate analyzer.

The wideband pickups are located in the Accumulator 10 straight section. The 10-inch pickups are used as inputs to the 300MHz Accumulator emittance monitors. This system generates the signal for the standard Accumulator horizontal and vertical emittance parameters A:EMT3HN and A:EMT3VN.

Signal Analyzers

The fifth section of this chapter will cover Signal Analyzers used to measure signals from Schottky detectors and cooling systems. This includes Spectrum Analyzers, Network Analyzers and Vector Signal Analyzers.

Spectrum Analyzer

Spectrum analyzers are used in the Antiproton Source to study the frequency domain of the beam. A spectrum analyzer is a swept-tune superheterodyne receiver that provides a Cathode Ray Tube (CRT) display of amplitude versus frequency. In the swept tune mode, the analyzer can show the individual frequency components of a complex signal. The spectrum analyzer can also be used in a fixed tune or "zero span" mode to provide time domain measurements of a specific frequency much like that of an oscilloscope. Note that a spectrum analyzer does not provide any phase information.

A superheterodyne receiver is a common type of radio receiver that mixes an incoming signal with a locally generated signal. The output consists of a carrier frequency that is equal to the sum or difference between the input signals (but no information is lost). The carrier signal is known as the Intermediate Frequency (IF) signal.

In a spectrum analyzer, the incoming signal is mixed with a programmable Variable Frequency Oscillator (VFO), producing carrier frequencies containing the two original signals and signals at the sum and difference of their frequencies. All but the sum or the difference signals are filtered out. The filter output is the IF signal which can be processed for display. The spectrum analyzer uses the VFO to define the frequencies to be analyzed (center frequency and span) and the sample rate (sweep time, resolution bandwidth).

Network Analyzer

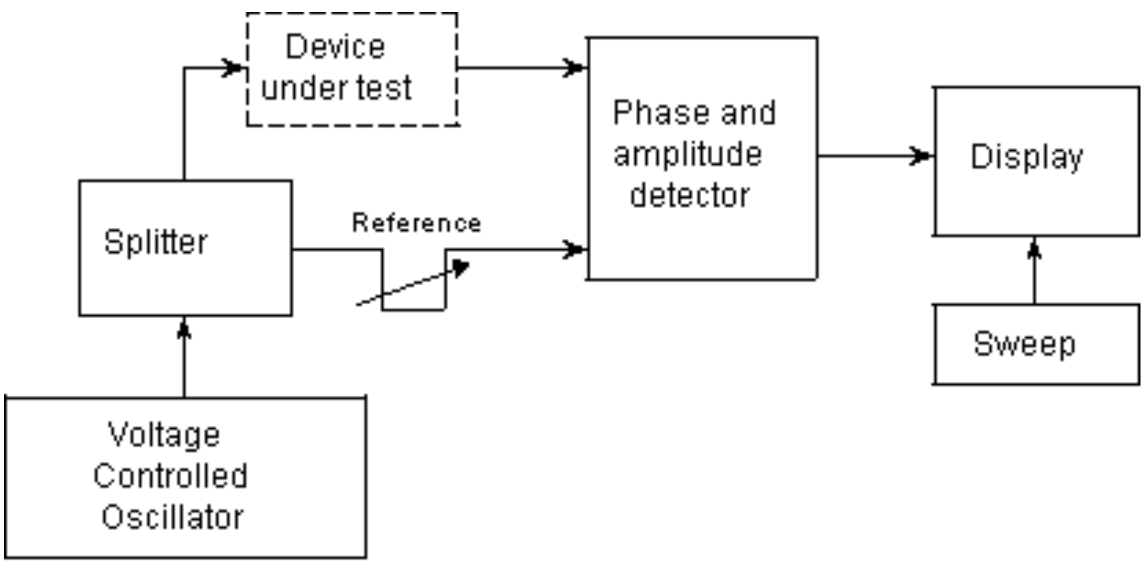


Figure 7.14: Network Analyzer block diagram

Network analyzers are used to study transfer or impedance characteristics of systems. A reference signal is injected into a system under test and the output of the system is displayed on a CRT (see figure 7.14). Although less expensive analyzers only provide frequency and amplitude information, the network analyzer used in the Antiproton Source also provides phase information. Examples of systems that can be analyzed are coaxial cables, stochastic cooling systems, RF amplifiers and other electronic devices.

Operationally, network analyzers are most frequently used for making Beam Transfer Function (BTF) measurements of portions of the stochastic cooling systems. Measurements are said to be either "open loop" or "closed loop". In an open loop measurement, the network analyzer is switched into the stochastic cooling system so that the cooling system is not actually operating (the feedback loop is open). The network analyzer is used to measure how that part of the cooling system (possibly plus the beam) modifies the reference signal. In a closed loop measurement, the reference signal from the network analyzer is injected into the operating cooling system (with the feedback loop closed) and a diagnostic beam pickup is used to measure the signal's effect on the beam. The Pbar network analyzer is interfaced through the Network Analyzer application (currently P31), which also manipulates switches for stochastic cooling measurements.

Vector Signal Analyzer

The Vector Signal Analyzer (VSA) combines the power of digital signal processing with the enormous frequency range and dynamic range found in a swept tune instrument. The VSA attains this with a large parallel digital filter array at its input and on-board signal processing. The VSA was developed to meet the demand for an instrument capable of measuring rapidly time-varying signals and to address problems dealing with complex modulated signals that can't be defined in terms of simple AM, FM, RF, etc.

Spectrum analyzers work very well for signals that don't vary over time, but are difficult to use in situations where the opposite is true. The Accumulator momentum profile typically displayed on CATV Pbar channel 28 provides an approximate "snapshot" of what the beam looks like shortly after ARF-1 has moved beam to the edge of the stacktail. It is not a true snapshot, however, due to the fact that there is a finite sweep time required to measure the signal. The signal being displayed on the low frequency side of the analyzer is sampled at a time earlier than those on the high frequency side. The stacking monitor display on the VSA shows two true snapshots in time, before and after ARF-1 has moved beam from the injection orbit to the stacktail. A VSA can also be used to create a "waterfall" display made up of multiple traces to show variations over time.

There are currently two VSAs used in Pbar. The first VSA is the D to A VSA used in the Accumulator/Debuncher energy alignment procedure. This VSA displays two traces as shown in Figure 7.15.

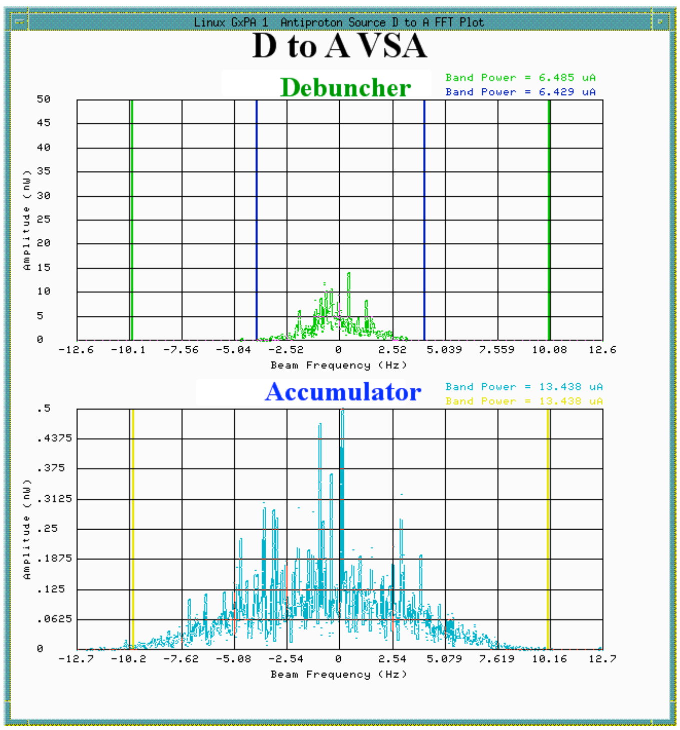


Figure 7.15: D to A VSA display

The top trace shows the Debuncher central frequency and the bottom trace shows the Accumulator injection orbit frequency. The center frequencies on the displays are set so that aligning the traces will match the energies of the two machines. The D/A VSA is displayed on Pbar CATV channel 17. The controls interface, which allows both setup and plotting of the VSA display, is located on the VSA D/A FFT application (currently P148).

The other Pbar VSA runs the Stacking Monitor when Pbar is in stacking or transfer mode, but switches to a display of the Accumulator core when in standby. A:VSARST is the control parameter that sets which mode the VSA is running in. When VSARST is set to 12, the VSA displays the Stacking Monitor that traces the entire longitudinal profile of the Accumulator and calculates a number of stacking parameters as described below. When VSARST is set to 0, the normal running display is shown which does not make the stacking calculations.

The Stacking Monitor is shown in Figure 7.16. The VSA display can be viewed on either Pbar CATV Channel 16, or using the VSA secondary application that is launched from the VSA ACC LONG PROF application (currently P142). In this mode, the VSA display updates every stacking cycle.

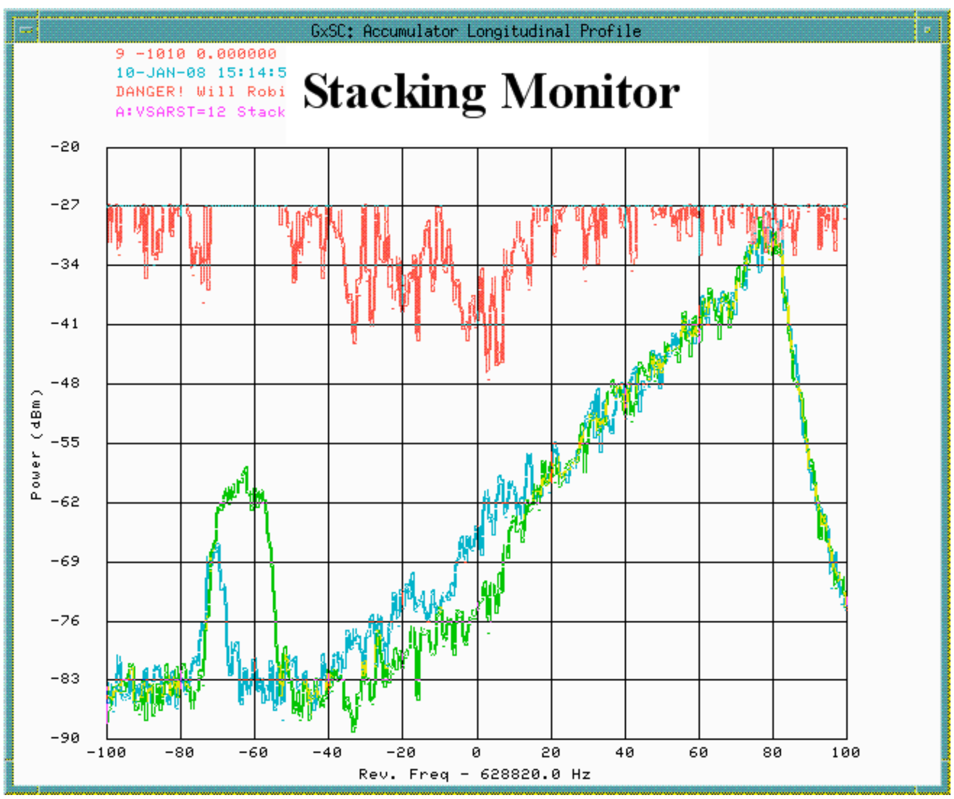


Figure 7.16: Stacking Monitor display

The green trace is the Stacktail profile just prior to ARF1 turning on, the cyan trace is the Stacktail profile just after ARF1 has finished its ramp, and the red trace is the ratio of the green trace to the cyan trace in dB.

The stacking VSA outputs a number of parameters that can be found on the DIAGNOSTICS PARAMS page (currently P38 MCGINNI <15>). Outputs include injection orbit calculations, Stacktail calculations, and core calculations. A:IBMINJ is the amount of beam on the Accumulator injection orbit and is calculated by integrating the green trace over a 40Hz window centered on that orbit. A:LFTOVR is a measure of the beam left on the Accumulator injection orbit after ARF1 has played. It is calculated by taking the ratio of the integral of the cyan trace to the green trace over the same frequency range. ARF1 is normally adjusted to keep this value around 2.0% to 4.0%. The VSA also uses the green trace to calculate A:R1FINJ, which is the frequency of the injected beam. The difference in Hz between this value and the ARF1 injection orbit frequency is output to A:R1FIJD. The ARF1 injection frequency is normally adjusted to make it as close to zero as possible. The Stacking Monitor also calculates “back streaming.” This term is used to describe beam that has moved away from the stacktail towards the injection orbit and will be lost on the next stacking cycle. A:DRIBL1 is calculated using the ratio of the cyan and green traces around the deposition orbit, where ARF-1 has left the beam. A:DRIBL2 is the root mean square of the red trace at the deposition orbit. For both of these parameters, a smaller number corresponds to less back streaming. Lastly, the core calculations are done around 20dB of the maximum density. A:CENFRQ is the mean frequency of the core.

Beam Stability Devices

The sixth section of this chapter will cover diagnostics used to improve beam stability. This includes the Accumulator dampers and Ion Clearing Electronics.

Dampers

Transverse dampers are in the Accumulator for the purpose of damping out transverse coherent instabilities (driven oscillations) at relatively low frequencies. The dampers can also be used as diagnostic tools. The dampers operate in the frequency range of 240 kHz to 150 MHz and act on much larger beam samples than the stochastic cooling does. The lower limit to the frequency response was selected to include the lowest betatron sideband, which is located at 240 kHz. The upper frequency limit of the dampers is dictated by the length of the pickup and the response of the amplifiers.

Transverse information about the beam is contained in the betatron sidebands. Since the pickups are located in a low dispersion region, there should be nearly no difference between beam position at the core vs. the injection orbit. It is important for the beam to be centered in the pickups to properly damp out oscillations. The pickups are mounted on motorized stands for centering them with respect to the beam. Signals at harmonics of the revolution frequency contain no useful information for transverse damping. Notch filters are used to reject revolution harmonic signals that could swamp the electronics during pbar extraction.

The dampers consist of pickups and kickers (both horizontal and vertical), which are located nearly adjacent to each other. Although the pickups and kickers are physically close together, it is actually the *next* beam turn that is corrected. Since the tune is not far from ¾, the beam at the kicker has oscillated nearly the ideal odd multiple of 90° away from the pickup. The damper kickers apply a correcting force on the beam by deflecting or "kicking" the beam.

The pickups are 0.5m long $^1/_4$ wave radial striplines located in the A10 low dispersion straight section to reduce any possible longitudinal coupling. The pickups sense coherent betatron oscillations and the signal passes through an amplification system and an appropriate delay line to match the pickup signal to the transit time of the beam. The amplifiers are able to deliver up to 300W of power (although they normally run with less than 1W of power) to the 50Ω terminated $^1/_4$ wave kicker loops also located in the A10 straight section.

As a diagnostic, the dampers are used to amplify transverse oscillations, or heat the beam, by driving the kickers with a white noise generator. This is useful for performing aperture measurements; beam fills the aperture and a scraper defines the edges of the beam. A reversing switch can be used to connect the damper pickups to a different set of kickers for reverse protons.

There are also dampers in the Debuncher, although they are only used for studies and were never intended to be used operationally. The time that beam resides in the Debuncher is short during stacking and the intensity is low, both tend to discourage the growth of transverse instabilities. The lowest betatron sideband in the Debuncher is located at 110 kHz, which requires a different amplifier than those used in the Accumulator. The Debuncher damper system has a useful frequency band of 10 kHz to 12 MHz and a peak power output of about 100W. The Debuncher dampers do not use a notch filter as the Accumulator does.

Clearing Electrodes/Trapped Ions

There are about 140 clearing electrodes located at various points in the Accumulator. The clearing electrodes are used to reduce the number of positive ions that are trapped in the beam. Before going into detail about the electrodes themselves, a short discussion about the trapped ions and their interaction with the antiproton beam will follow. Most of the effects of trapped ions grow with stack size, so aren't a concern with stacks below approximately 40E10.

Residual gas in the Accumulator vacuum chamber that passes through the antiproton beam can have electrons stripped away, leaving a positively charged ion. The positive ions are being continuously produced as long as the antiproton beam is present. The production rate depends on the quantity and type of residual gas in the vacuum chamber as well as the beam intensity. A typical rate would be on the order of 10 E10 to 20 E10 per second for a 40 E10 stack. In the absence of any outside influence, the number of positive ions will increase until the antiproton beam is totally neutralized.

The production process results in the ions having a small velocity and nearly all of the ions that are produced become trapped in space charge potential wells. The depth of the wells depends on the size of the beam pipe and the size of the beam envelope at a particular location. The ions will move longitudinally towards the deepest potential well that they can reach. The ions oscillate transversely in the antiproton beam, their frequency dictated, in part, by the mass and charge of the particular ion and the depth of the beam space charge potential well. About half of the ions produced are monatomic and molecular hydrogen that have lost an electron (the hydrogen outgases from the beampipe). The oscillation frequency of the hydrogen ions happens to be close to the low order betatron resonant frequency of the beam and will therefore cause the beam to oscillate. It is interesting to note that a proton (or positron) beam also creates positive ions, but they are not attracted to the beam and do not become trapped as they do with an antiproton (or electron) beam.

The net effect of having the trapped ions in the Accumulator is that the beam is very sensitive to instabilities that are driven by these ions. There is a threshold at which the combination of transverse and longitudinal beam size will result in rapid transverse emittance growth of the beam. The rapid emittance growth and recovery can be cyclic, with a period of 30 minutes or so. Trapped ions have another detrimental effect, which is a tune shift for the antiproton beam. This is easier to compensate for as the shift will normally be relatively small and nearly constant.

The most successful strategy for mitigating problems relating to trapped ions has been to eliminate as many of the ions as possible. It is necessary to constantly remove the trapped ions as they are continuously produced and over seconds will return to fill the potential wells. The greatest reduction in trapped ions has come from the use of clearing electrodes. Most clearing electrodes are Beam Position Monitor pick-ups that have a –1,000 Volt DC potential applied to them. Dedicated clearing electrodes are also found at other locations, such as stochastic cooling tanks, which do not have BPMs in close enough proximity.

There are still spots in the Accumulator, such as in the middle of the bending magnets, where a clearing electrode cannot be located. Another method for dislodging the trapped ions is bunching the beam with RF. Only 10-20 volts of RF for small stack sizes and as much as 100 volts or more for large stack sizes is enough to significantly reduce the population of trapped ions in the Accumulator. By bunching the beam, some of the trapped ions can be flushed from the potential wells they reside in. The ions that are dislodged appear to be forced into the vacuum chamber walls instead of being pushed towards the clearing electrodes for removal. If the stabilizing RF is removed, it may take several minutes for the trapped hydrogen ions to return to the equilibrium level maintained in the absence of the RF. ARF-2 has traditionally been used to provide the "stabilizing RF" for the Accumulator. A sequencer-based tool called the “Flusher” automatically increases the ARF-2 voltage and ramps the ARF-2 frequency and is used for stack sizes over 80E10.

Beam Shaping Devices

The last section of this chapter will cover scrapers and collimators that can be used to shape the beam.

Scrapers

Scrapers are devices that can be used to block off part of the accelerator aperture. A physical analogy would be a gate valve in a water line. The scraper could be used to trim the halo off of the beam, to measure the acceptance of the machine, or to define the emittance of the beam. Scrapers are only found in accelerator rings, whereas the beamline equivalent devices are called collimators. There are presently ten scrapers (two individual scrapers and scraper pairs at four locations) in the pbar rings:

> D:RJ306: Debuncher horizontal (Right Jaw) scraper. It enters the beam from the inside of the ring. It is adjacent to D3Q7.
>
> D:TJ308: Debuncher vertical (Top Jaw) scraper. It enters the beam from the top of the ring. It is adjacent to D3Q8.
>
> D:RJ410/D:LJ410: Debuncher momentum scrapers. These are horizontal scrapers that are placed in a high dispersion region to allow one to measure the momentum spread of the beam. They are located between D4Q10 and D4Q11.
>
> A:RJ500/A:LJ500: Accumulator horizontal scrapers. They enter the beam from the inside and outside of the ring. They are located near A5Q1.
>
> A:TJ307/A:BJ307: Accumulator vertical scrapers. They enter the beam from the top and bottom of the ring. They are adjacent to A3Q7.
>
> A:RJ314/A:LJ314: Accumulator momentum scrapers. They are horizontal scrapers in a high dispersion region. They are located in the center of the A40 straight section.

Scrapers are moved with stepping motors and the scraper position is determined with a Linear Variable Differential Transformer (LVDT). Stepping motors allow small and fairly precise position changes. An LVDT puts out a voltage proportional to the position of a slug within a ferrite cylinder with a series of windings. The controlling electronics for the stepping motors are located in the AP-30 and AP-50 service buildings, two CAMAC 057 cards are used to control them. Each scraper has a motor controller card (just like Switchyard septa have). A brown lambda supply provides +24 volts for the motor and +/-15 volts for the LVDT on each scraper.

Normally, scrapers are in the out position on a limit switch, with the digital status showing a "T" indication. An alarm is posted when the scraper is off the limit switch and moved closer to the beam. Scraper motor control parameters can be found on the POWER SUPPLY PARAM page (currently P60 ACC30 <3>, P60 ACC50 <3> and P60 DEB30 <9>).

Incidentally, there are a number of other moveable devices scattered around both Pbar rings that operate on the same principle. These devices are normally moved to either electrically center them (as in stochastic cooling tanks), to improve the aperture (diagnostic devices) or to provide an orbit bump (dipoles that can be rolled and quadrupole magnets that can be moved transversely).

Collimators

Much like their scraper counterparts in the rings, collimators are used in beam lines to skim the halo off the beam, define the emittance of the beam, and measure the acceptance. All of the collimators are located in the AP2 line and use the same type of electronics as the scrapers. The CAMAC 057 control card and the motor controllers are located in the AP0 service building.

There are two sets of horizontal, two sets of vertical and one set of momentum collimators in the AP2 line. All are of similar construction. The momentum collimator is located in the center of the left bend section of the beamline where the horizontal dispersion is high. The magnets and collimator act like a momentum spectrometer. The ACNET collimator names are:

- D:RJ707/D:LJ707: Right and Left Jaw (pbar direction) of a horizontal collimator placed immediately downstream of IQ7.
- D:TJ708/D:BJ708: Top and Bottom Jaw of a vertical collimator placed immediately downstream of IQ8

- D:RJ709/D:LJ709: Another horizontal collimator located immediately downstream of IQ9.
- D:TJ710/D:BJ710: Another vertical collimator located immediately downstream of IQ10.
- D:RJ719/D:LJ719: The jaws for the momentum collimator located in the middle of the dipoles that make the left bend, immediately downstream of IQ19.

The nominal position for a collimator is in the "out" position, with the digital status showing an "O" indication when the scraper is resting against the limit switch. An alarm is posted when the collimator is not on the limit switch. Collimator motor control parameters can be found on the POWER SUPPLY PARM page (currently P60 INJ <5>).

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8 Utilities

Water systems

Cooling water is used to carry excess heat away from power supplies, magnets and other systems in the Antiproton Source. The most extensive water system found in Pbar is the 95° Low Conductivity Water (LCW) system. The Pbar 95° LCW system provides cooling for components in the Rings and Transport enclosures as well as the AP0, 10, 30 and 50 service buildings. LCW is water which has had free ions removed, increasing its resistance to electrical current. This attribute is critical if a device has cooling channels that also act as electrical conductors. Most Rings and beamline magnets, for example, have hollow copper electrical windings that the LCW flows through. The Pbar 95° LCW system is not only used to cool most magnets and their power supplies, but also magnet shunts and TWT amplifiers used in the stochastic cooling systems.

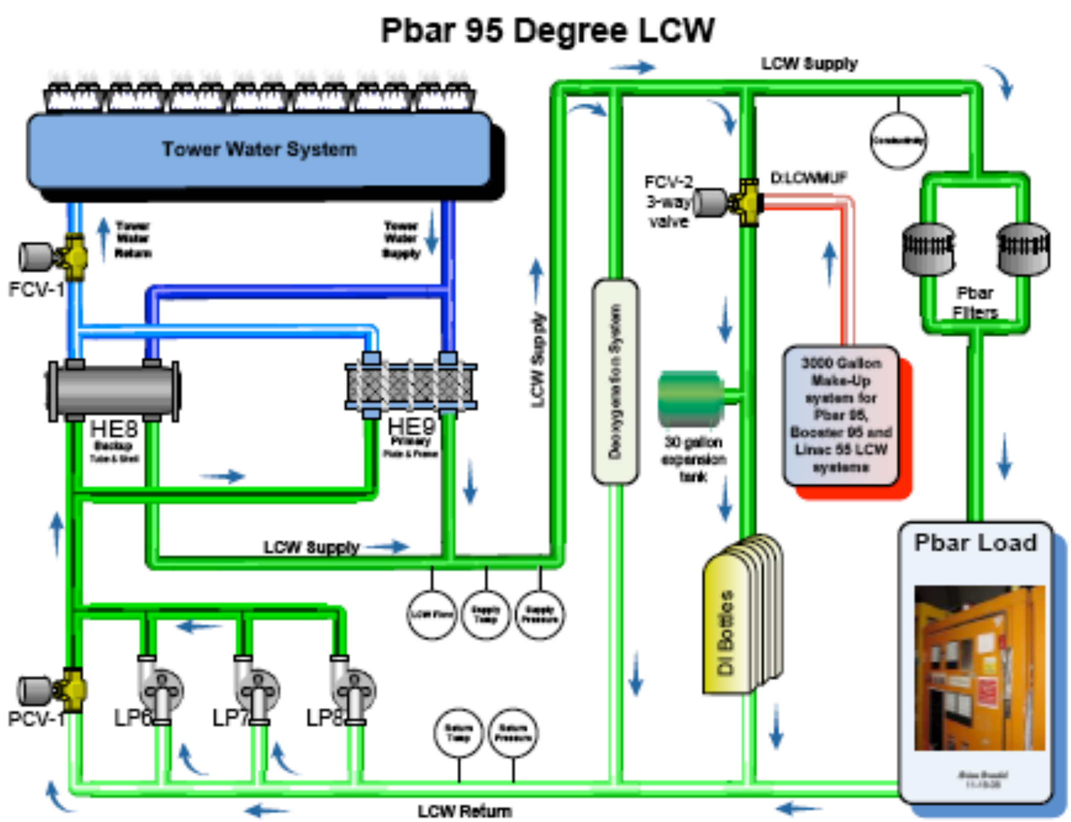

Figure 8.1: Pbar 95° LCW system
(expanded from the MetaSys controls diagram used by FESS)

Figure 8.1 is a block diagram of the Pbar 95° LCW system. The two heat exchangers, three pumps, a thirty gallon expansion tank, and a filter system can all be found on the second floor (frequently referred to as the mezzanine) of the Central Utility Building (CUB). In addition, a 3,000 gallon make-up system, deionizing (DI) equipment and deoxygenation skid are located on the first floor of CUB. The three pumps used to circulate Pbar 95° LCW are called LP6, LP7 and LP8. During normal operation, two of the three pumps are run, which allows flexibility if a pump requires repair. Most of the Pbar 95° LCW flows through one of two large "full-flow" filters before leaving CUB and heading to pbar. Part of the LCW is diverted through two loops that bypass the path to pbar. The first loop has the three-way valve that connects to the 3,000 gallon make-up tank, a 30 gallon expansion tank and the deionizing bottles. The deionizing bottles "polish" the LCW by removing ions. The other loop contains the deoxygenation skid, which removes free oxygen in the LCW. Free oxygen coming in contact with the copper LCW pipes and magnet conductors can cause the formation of a copper oxide (CuO). Deposits of the copper oxide can line the inside of the magnet conductors and can even cause blockages that lead to overheating.

The Pbar 95° LCW heat exchanges with Tower Water (TW), which originates from a 26,000 gallon storage tank located in the northeast corner of CUB. There are two Pbar 95° heat exchangers, but only one of them is used at a time. The primary heat exchanger is a plate and frame heat exchanger called HE9. It is rectangular in shape, much like the heat exchangers used for the Booster 95° LCW system. The backup heat exchanger is an older shell and tube type called HE8. This heat exchanger is cylindrical in shape, much like those in the Tevatron service buildings. HE8 hangs from the ceiling of the mezzanine right next to the plate and frame heat exchanger. Regardless of which heat exchanger is used, a large valve called FCV-1 controls the LCW temperature by regulating how much Tower Water circulates through the heat exchanger.

Figure 8.2 is a block diagram of the Tower Water system. Tower Water is used to provide cooling for the Pbar 95° LCW system as well as LCW systems used by other accelerators. Tower Water can also be used to cool the 55° Chilled Water systems in the winter months. Tower Water is pumped out of the 26,000 gallon storage tank by three Tower Water pumps called TWP-1, TWP-2 and TWP-3. These pumps circulate the Tower Water through the primary Tower Water loop that goes up to the cooling towers on the roof of CUB and back down to the storage tank. These pumps are also variable speed so that they can match the flow through the heat exchanger and chiller loads. As the flow increases through the loads, so does the speed of these pumps.

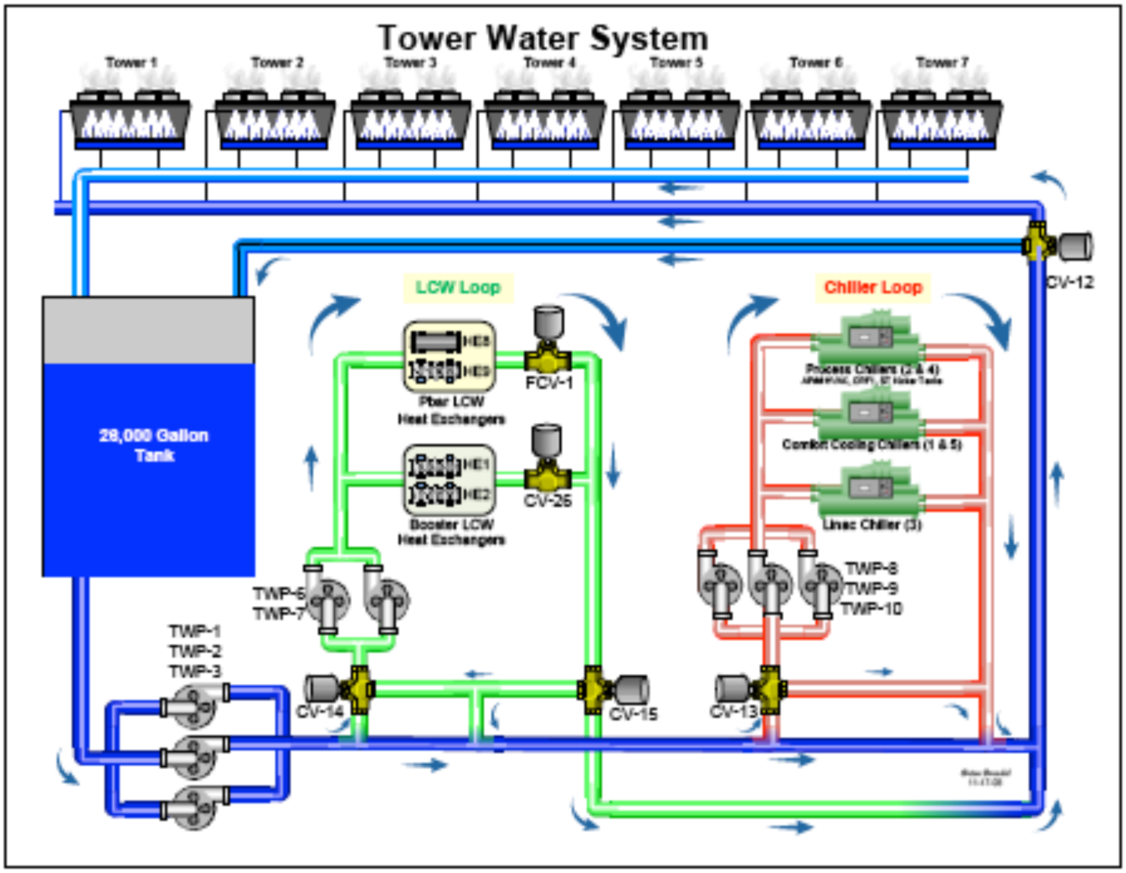

Figure 8.2: Tower Water System
(expanded from the MetaSys controls diagram used by FESS)

Depending on cooling demands, cooling towers can be valved out of the system. During the summer months, when the efficiency of the cooling towers is at its lowest, all seven pairs of towers are needed. The towers are staged based on the discharge water temperature out of the 26,000 gallon tank. The cooling towers use ambient air to cool the Tower Water with a combination of direct contact and evaporation. On warm days, most of the heat removal comes from evaporative cooling.

Figure 8.3[2] shows the air and water flow through a cooling tower. The warm return Tower Water from the Pbar heat exchanger is pumped into the top of the cooling tower, and is sprayed downward onto a wet deck in the tower. Simultaneously, outside air is drawn in through inlet louvers at the base of the tower and travels upward through the wet deck. As long as the outside air is cooler than the Tower Water, the Tower Water will be cooled by direct contact with the air. A small portion of the Tower Water is evaporated into the air passing through the tower, removing heat from the remaining water. The warm moist air is drawn to the top of the cooling tower by a fan and is vented into the atmosphere. The cooled Tower Water drains to a basin in the bottom of the tower. This water is returned to the 26,000 gallon tank and then pumped back to the heat exchangers. During the summer months, the outside air is very warm and humid. On these days, both the direct contact and evaporative cooling mechanisms are much less efficient. On the worst of the hot and humid summer days, the Tower Water temperature can't be maintained, causing the Pbar and Booster LCW to warm. FESS uses the term "Wet Bulb Temperature" to describe the cooling potential of the outside air[3]. A high wet bulb temperature (above about 75° F) will likely cause both the Booster and Pbar 95° LCW systems to lose temperature regulation during the hottest part of the day.

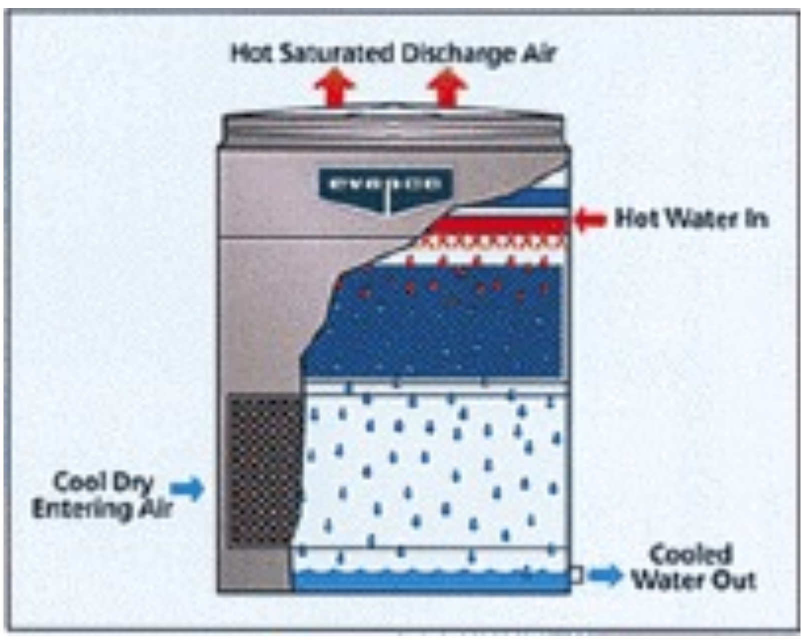

Figure 8.3: Cooling Tower diagram from Evapco website2.

There are two secondary Tower Water loops labeled “LCW Loop” and “Chiller Loop” in figure 8.2. For the “LCW loop,” two water pumps called TWP-6 and TWP-7 pull Tower Water from the primary loop to the secondary loop that includes both the Booster 95° and Pbar 95° LCW heat exchangers. The temperature of the Tower Water in this loop can be controlled by regulating how much of the water in this secondary Tower Water loop is re-circulated and how much is put back in the primary Tower Water loop. This is done using a bypass line and two valves called CV-15 and CV-14. On the Tower Water output side of the heat exchangers, valve CV-15 is either fully open or closed. When open, all of the water in the secondary loop is routed back to the primary Tower Water loop. This configuration provides maximum cooling and is used during the summer. When CV-15 is closed, the water is sent down a bypass line, where another valve, CV-14, regulates how much Tower Water is recirculated in the secondary loop. This mode of operation is used during cooler weather.

Tower water also provides cooling to the Chilled Water (CHW) system via the “Chiller Loop” shown in figure 8.2. Three secondary pumps called TWP-8, TWP-9 and TWP-10 pull Tower Water from the primary tower water loop to a secondary loop that provides cooling to five process chillers used in three different cooling systems. Chiller CH-3 provides cooling for the Linac 55° LCW, Chillers CH-1 and CH-5 provide cooling to the “Comfort Cooling” (Wilson Hall, HVAC), and chillers CH-2 and CH-4 provide cooling to the “Process CHW” which is used by Pbar. The Tower Water of this secondary loop is temperature controlled by regulating a valve called CV-13 that regulates how much water is recirculated in the secondary loop.

Figure 8.4 is a block diagram of the “Process” Chilled Water (CHW) system, which provides cooling water for the Pbar service building air conditioning units, the DRF1 cavities, and the stochastic cooling kicker tanks. It also removes heat from the closed loop LCW systems at AP0 and F27, which are described below. Process CHW is strained and chilled to approximately 45° Fahrenheit. In periods of warmer weather, the Process CHW is circulated by two chillers running in parallel (CH-2 and CH-4). Two valves called CV-2 and CV-3 control how much flow is sent through CH-2 and CH-4 respectively. During the winter months, there is an option to run through a heat exchanger called HX-1 instead of the chillers. HX-1 is a free flowing heat exchanger that gets its cooling from the Tower Water system mentioned above.

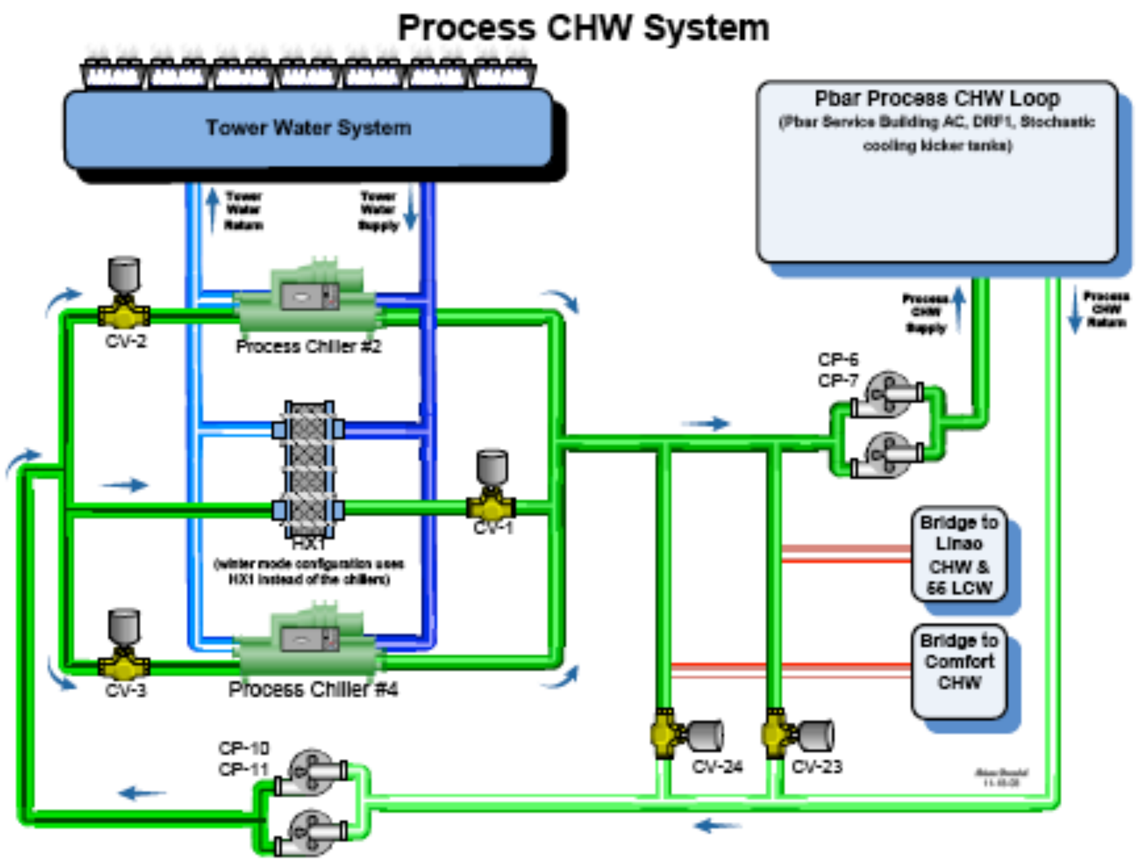

Figure 8.4: Process Chilled Water
(expanded from the MetaSys controls diagram used by FESS)

The CHW system is sometimes confused with the ICW system. ICW (Industrial Cooling Water) makes up the fire hydrant network and is unrelated to the Chilled Water system. To add further confusion, CW (condenser water), ICW and TW (Cooling Tower water) all eventually go through the 26,000 gallon tank.

Tevatron 95° LCW flows through the AP1 and AP3 line magnets in the Pretarget and Prevault enclosures. Tevatron LCW is also used to cool power supplies at the F23 service building. LCW from the Tevatron system was used for reasons of convenience and economy.

There are four closed loop, stand-alone LCW systems in the Pbar complex. Each of these systems consists of a pump, heat exchanger, deionizer bottle, expansion tank, and associated plumbing and instrumentation, similar to the low energy Linac water systems. Chilled Water is used to heat exchange with each closed loop LCW system. Three of the systems are located in AP0: one provides cooling for the Lithium Lens and transformer, one for the beam dump and one for the Pulsed Magnet and collimator. When needed, make-up water to fill these systems is taken manually from the Pbar 95° LCW header located on the wall nearby. The other closed loop system is located in the F27 service building and provides cooling water for the power supplies in that building. When required, Water Group personnel make up LCW at F27 from a 55-gallon drum of de-ionized water. When the F27 service building was built, there weren't any LCW lines in the vicinity. It was more convenient (and economical) to tee off of an existing chilled water header that ran between CUB and the RF building.

Important water system parameters are monitored via ACNET and/or FIRUS. Temperature, pressure, oxygen level, turbidity and conductivity monitoring for the Pbar 95° LCW system can be found on page P75. Temperature and pressure readbacks for the Chilled Water and Tower Water loops can also be viewed from P75. In addition, the amount of water leaking out of the Pbar LCW system can be determined through the ACNET parameter D:LCWTOT. This device reads back the total amount of make-up water that has been transferred from the 3,000 gallon tank over an arbitrary amount of time (normally 24 hours, beginning at midnight). The Pbar 95° LCW system has a 30 gallon reservoir, shown in figure 8.1, which is filled up every time that amount of LCW has leaked out of the system. Under normal no-leak running conditions, 50 to 100 gallons per week is added to the system. A plot of D:LCWTOT would indicate 30 gallon increments at regular intervals if there were a leak (this parameter is reset to 0 gallons every day at midnight). D:LCWMUF monitors the flow into the makeup tank and normally reads zero. Only when the LCW system is automatically filling the 30-gallon reservoir should this parameter have a non-zero reading.

FIRUS also alarms if certain parameters are out of limits. In general, poor conductivity, incorrect pressures or tripped chillers or cooling towers should be brought to the attention of on-shift plant maintenance personnel (i.e. the Duty Mechanic). Pressure or temperature alarms should be checked against their ACNET counterparts. Generally, the ACNET devices have more accurate alarm set points.

Vacuum systems

All of the Pbar beam lines and both Rings have unique vacuum systems, sometimes isolated from each other via vacuum windows. In all cases, distributed ion pumps provide most of the pumping. The beamline and Rings vacuum systems can broken into smaller segments with beam valves. A number of pump-out ports are built into each system to provide easy connection of mobile turbo molecular pump stations. Tevatron-style CIA crates are used to control the vacuum components. Beam valves are interlocked to close if three or more ion pumps in a section are tripped or indicate poor vacuum. Each of the systems is outlined below. For the sake of clarification, Torr is normally the unit of measure used for vacuum although millibar (mbar) is the proper metric unit. The units are very similar in magnitude, average atmospheric pressure is 760 torr or 1,013 mb. Since the units are so close in magnitude, Torr and mbars can be used interchangeably.

Vacuum in the AP-1 line is common to that of the P2 line on the upstream end and AP-3 on the downstream end. Beam valve M:BV100, located immediately downstream of the second (of two) 'C' magnets in the AP-1 line, is interlocked to close if too many pumps trip in the P2, AP-1, or AP-3. A vacuum window located just inside the Target Vault isolates AP-1 from the Target Station. Beam Valve D:BV926 can isolate AP-1 from AP-3. Distributed sputter ion pumps rated at 270 liters/second maintain the nominal AP-1 line pressure of 10-8 Torr. Pump supplies and controls hardware for this system can be found in the AP0 service building.

The Target Vault is not under vacuum and serves as the break between AP-1 and AP-2 vacuum. Another window within the Target Vault isolates the AP-2 line at its upstream end. AP-2 vacuum is common with the Debuncher, although there used to be a vacuum window immediately upstream of the Debuncher injection septum magnet. After an upgraded septum magnet with better aperture was installed, the vacuum window was removed and beam valve D:BV728 installed. Like AP-1, the injection line vacuum is maintained through the use of distributed sputter ion pumps rated at 270 l/s. The nominal pressure of the beamline is 10^{-8} Torr.

The Debuncher, similarly, has its vacuum maintained with sputter ion pumps. The average Debuncher pressure is a decade better than the beamlines, 10^{-9} Torr. Beam valves at each '10' location can effectively subdivide the Debuncher into 6 separate vacuum sectors. Beam valve D:BV610 doubles as the safety system coasting beam stop for the Debuncher.

The D to A line is a stand-alone vacuum system with vacuum windows at the upstream end of the Debuncher injection septum magnet and the downstream end of the downstream Accumulator injection septum. Ion pumps keep this line's vacuum in the 10^{-8} Torr range.

Because the Accumulator was designed for use as a storage ring, its vacuum requirements are the most stringent. One of the significant considerations in determining the beam lifetime in a storage ring is the beam-gas interaction rate. Improving the vacuum lowers this interaction rate, thereby reducing beam loss. The design pressure of the Accumulator is 3 X 10^{-10} Torr. This level of vacuum is accomplished through the use of sputter ion pumps and titanium sublimation pumps supplemented by a bake-out system. As with the Debuncher, the Accumulator has six vacuum sectors. Beam valves in sectors 10 through 30 and 60 are found at the '7' locations. The valves for the 40 and 50 regions were moved from their original location to immediately upstream and downstream respectively of straight section 50. This provided isolation for the experiment that was located in the A50 Pit, so that work could be done there with minimal impact on the Accumulator. As a consequence, the Accumulator 40 and 60 vacuum sectors are larger than the others. Like D:BV610 in the Debuncher, beam valve A:BV607 acts as the safety system coasting beam stop for the Accumulator.

Titanium sublimation pumps are used in the Accumulator to provide the additional pumping required for a vacuum of 3 X 10^{-10} Torr or better. A sublimation pump is a form of getter pump that operates on the principle that chemically stable compounds are formed between gas molecules (H_2, N_2, O_2, CO, CO_2) and the getter (titanium). The SNEG in the Tevatron is another form of a vacuum getter pump. The getter is the material that gas molecules combine with. Noble gases (such as helium) cannot be pumped by getters, but can be pumped by ion pumps. In a sublimation pump, a filament containing a high titanium content is heated resistively and the boiled off titanium forms a thin layer on the surrounding walls of the vacuum chamber. For the Accumulator, the walls are adjacent to the beam pipe rather than being the beam pipe itself. As gas molecules impinge on the getter film, stable compounds are formed and the vacuum pressure improves since there are fewer gas molecules in the beam pipe volume. However, this decreases the amount of getter material available to capture other gas molecules.

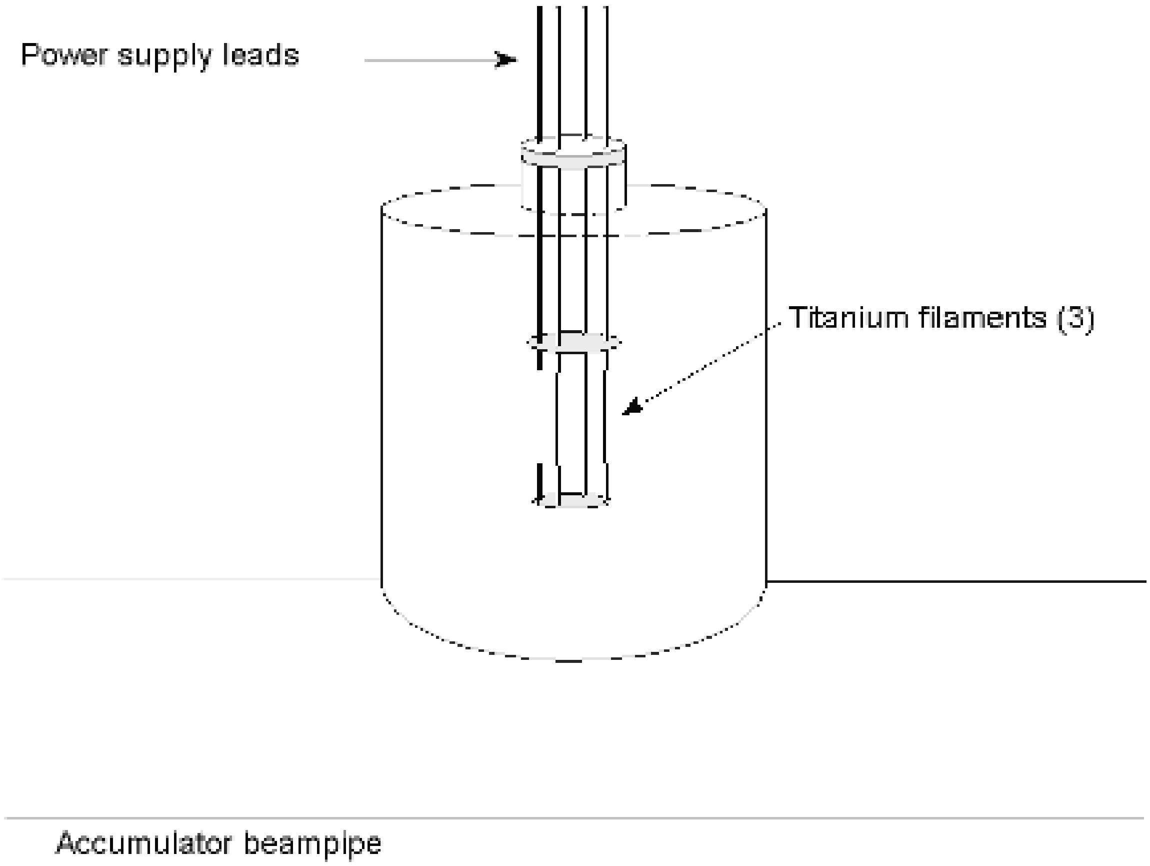

Figure 8.5: Titanium sublimation pump

Unlike ion pumps, which are powered all of the time, the sublimation pumps in the Accumulator are powered infrequently. The sublimation pumps are "fired" over 90 seconds to sublimate approximately 10 monolayers of titanium onto the pump's interior surface. During normal operation, sublimations are spaced weeks or months apart. Each Accumulator sublimation pump contains 3 filaments to extend the lifetime of the pump, although only one filament at a time is sublimated (see figure 8.5). Because sublimation pumps have no effect on inert gases, sputter ion pumps are still an important component of the system. To date, the best average vacuum in the Accumulator has been 6.8 x 10^{-11} Torr (as read by ion gauges), although a typical value is 1 - 3 x 10^{-10} Torr.

A permanently installed bake-out system in the Accumulator makes it possible to bake each of the six sectors independently when conditions warrant. Usually when a portion of the Accumulator is let up to air, a bake-out follows the work. Baking the beam pipe makes it possible to liberate water vapor on the inner surface of the beam pipe and remove deep-seated impurities. Bake-out temperatures range from 130° C for stochastic cooling

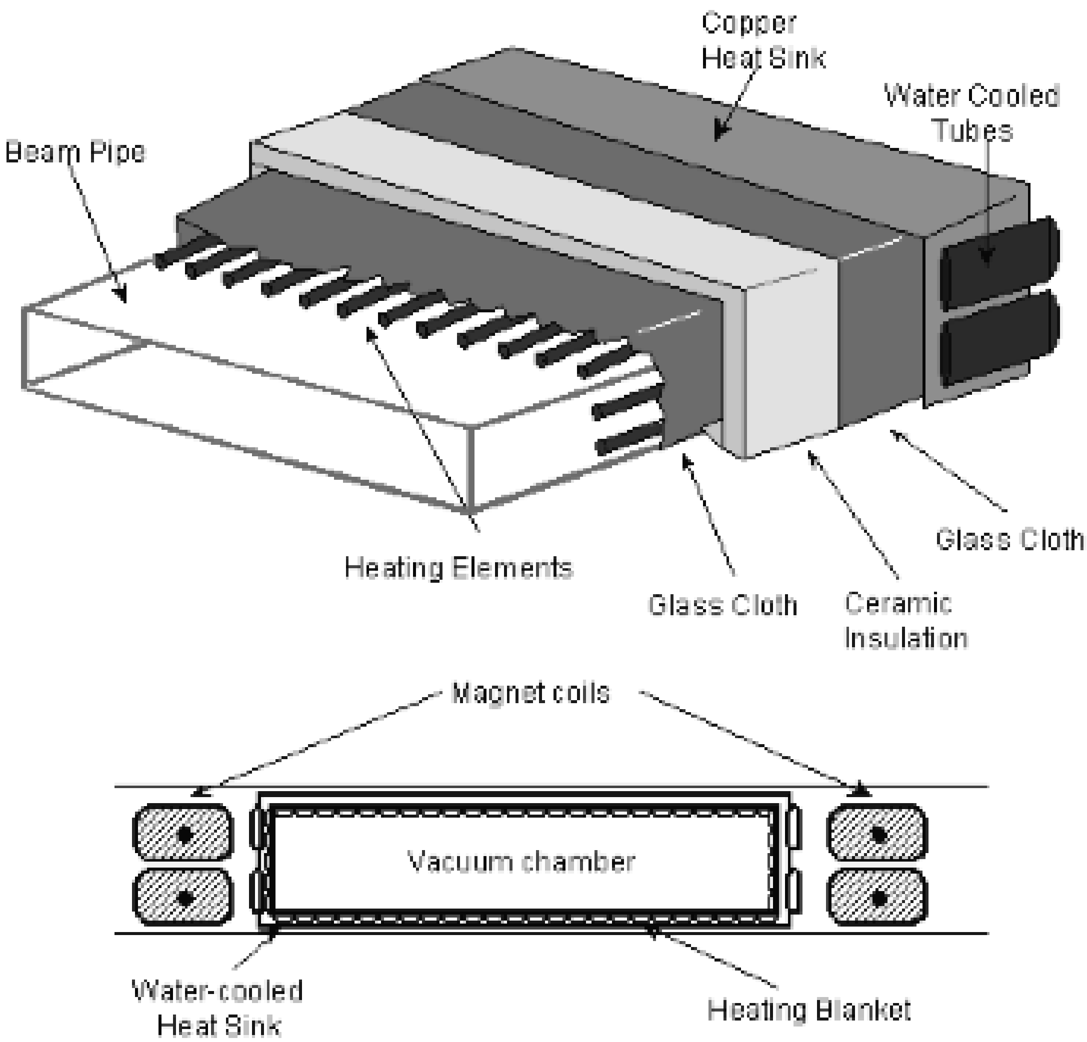

Figure 8.6: Accumulator dipole bake-out components

tanks to 250° C for quadrupoles. Pumping during a bake is achieved by using mobile turbo-pump carts. The bake is controlled by a single microprocessor in AP10 while an ACNET applications program is used for human interface. The processor receives inputs from thermocouples located in the tunnel and controls heaters to regulate the temperature. It typically requires several days to heat the components to the desired temperature, hold that temperature during the bake and slowly cool back down to room temperature.

Heaters and insulation coexist in the blankets, which are wrapped around the beam pipe and non-magnetic components. The magnets are not encased in blankets, rather, special channels for LCW lines and heating elements are sandwiched between the beam pipe and magnet laminations (see figure 8.6). Such an arrangement permits the beam pipe to be baked while protecting the magnet.

The AP-3 line vacuum is common to the Accumulator because of concerns that a vacuum window at the junction of the Accumulator and the beam line would cause excessive transverse emittance blowup during transfers. Despite the absence of a vacuum window, Accumulator vacuum does not degrade significantly near the junction because of additional capacity built into the ion pumps at the upstream end of the line. A beam valve, BV900, provides protection in case there is a loss of vacuum in either the Accumulator or AP-3 line. Vacuum is maintained in AP-3 with 270 l/s sputter ion pumps. The pressure is typically 10^{-8} mbar. Beam valve D:BV926 located in the Prevault enclosure provides isolation between the AP-1 and AP-3 lines.

Electrical systems

Feeder 24, a 13.8 kV feeder, provides most of the power requirements for the Antiproton source complex, which is the output of transformer 83A in the Master Substation. 13.8 kV is stepped down to 480 V in transformers outside of AP0, 10, 30, 50, and F27. Breaker panels and additional transformers distribute power to all tunnel and house loads as well as nearly every power supply. The Debuncher and Accumulator bend bus supplies have separate outdoor transformers connected to feeder 24 at AP50 (see figure 8.7). A 13.8KV distribution switch called DSTR-AP50-1 allows the bend bus transformers to be isolated from the house power transformer.

There are two sources of power for F23: one source for the large power supplies and one for the lighting, trim power supplies and rack power. Power for the large AP1 line supplies come from feeders 94/95, the beamline feeders, which are downstream of the manual operated switch called MOS 89. Feeders connected to MOS 89 cover the beamline (P1, P2 and P3) supplies in F-Sector (some elements spill over into Transfer Hall), as well as MI-52 (Main Injector Sextupoles). As a result, anytime an access is made into Main Injector, F-Sector or Transfer Hall, MOS 89 is switched off and power is lost to the large supplies at F23. F23 lighting, trim and rack power comes from an underground feed from the F2 service building. This power originates from Master Substation Feeder 45 (Tevatron conventional power), and is not

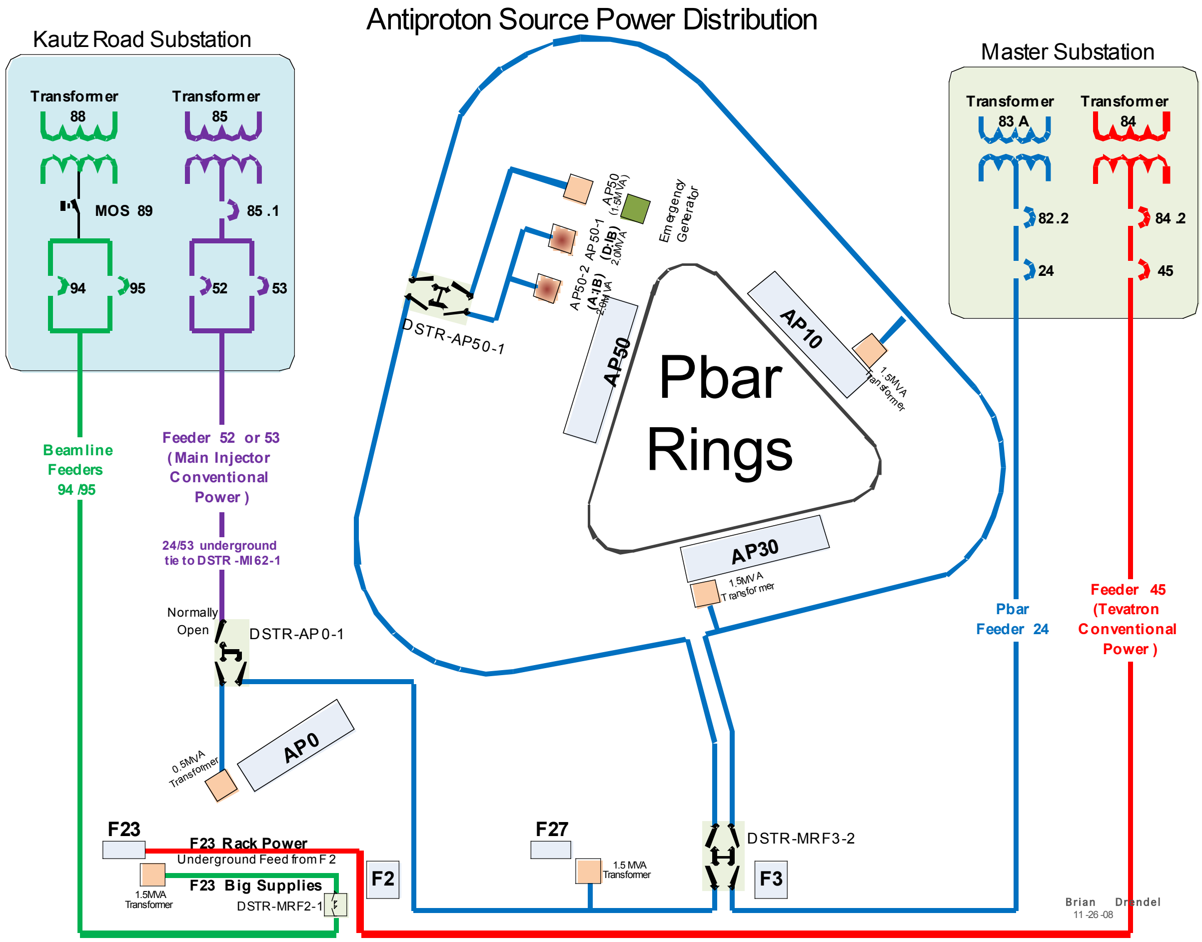

Figure 8.7: Antiproton Source Power Distribution

interrupted when accesses are made.

The Kautz Road Substation feeder 52 or 53, which powers Main Injector service buildings by means of a transfer switch called DSTR-AP0-1, powers the Antiproton Source. This is not used during normal operation and is reserved for long shutdown maintenance activities. Normally, feeder 24's sole load (and transformer 83A) is the Antiproton Source.

In case of a power outage, an emergency diesel generator located at AP50 keeps Antiproton Source sump pumps, ventilation equipment, and the overhead crane in AP0 operational. When power is lost at AP0, 10, 30, or 50 the generator is automatically turned on and the emergency feeder energized. Meanwhile, transfer switches in or below the building(s) without power switch in the emergency feeder. The generator is automatically tested on Wednesdays around noon. Controls for the generator are located at AP0.

Cryogenic systems

Liquid helium is used to cool the pickup electrodes and low level amplifiers for all of the Debuncher stochastic cooling systems, as well as the Leg 1 stacktail notch filter located at AP30. Similarly, liquid nitrogen is used on pickups for the stacktail and core 2-4 GHz momentum cooling systems. Liquid nitrogen is also used as a shield for the liquid helium flowing through the transfer lines. By reducing the temperature of the stochastic cooling pickup electronics, the electronic noise they generate is greatly reduced. Electronic noise scales linearly with absolute temperature so there is a considerable reduction in the noise level. The signal to noise level is especially critical in the stacktail and Debuncher cooling systems, which operate on low intensity beams. Pickups for the core systems detect a much larger signal due to the beam intensity. The core 2-4 GHz momentum cooling system pickups use liquid nitrogen only because the pickup tank is located in A20 next to the stacktail pickups. Performance of the system is only improved by a minimal amount, but little additional hardware was required to provide liquid nitrogen to the tank.

Cryogens are provided to the A60 (stacktail and core 2-4 GHz momentum) and D10 (Debuncher) locations by means of transfer lines traveling above ground from AP30. They then pass downwards through penetrations into the tunnel. AP30 houses a satellite refrigerator, which is connected to the Tevatron cryogenic system via helium and nitrogen lines between it and the F3 refrigerator building. There is a refrigerator room within the AP30 service building that contains the wet and dry engines and other cryogenic components normally found in a Tevatron refrigerator building. The heat exchanger is suspended from the ceiling of AP30, outside of the refrigerator room.

Control for the majority of the pbar cryogenic systems is identical to that of the Tevatron and Switchyard refrigerators. Feedback loops manipulate valves to control each stochastic cooling tank's temperature. The house names for the two microprocessors servicing Pbar are: 'PR' for the Pbar Refrigerator equipment at AP30, and 'P1' for the area 10 and 60 loops.

References

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2) Evapco REP Model 217-914 Cooling Tower Documentation, Evapco Website, http://evapco.com/rep_principle_of_operations.asp, 2008.

3) J. Morgan, Pbar and Booster LCW temperature problems during the Summer, Accelerator Division Document Database #3259, https://beamdocs.fnal.gov/AD-private/DocDB/ShowDocument?docid=3259, October 2008.

3) MetaSys Cooling System Control Pages for Pbar LCW, Tower Water and Chilled Water systems, http://fess.fnal.gov/metasys.html, 2008.

4) KRSS and MSS Feeder Diagram, Facilities Engineering Services Section Drawing, December 1997.

5) Feeder 24 for Antiproton Area Diagram, Facilities Engineering Services Section Standard Policies and Procedures, No. 5303.1, February 1999.

6) Feeders 94 and 95 Main Ring/Injector F Sector Pulsed Power Supplies, Facilities Engineering Services Section Standard Policies and Procedures, No. 5303.2, February 1999.

Notes:

9 Controls

Pbar CAMAC Link

As with the other accelerators, the Antiproton Source is largely controlled and monitored from the Main Control Room via ACNET. Consoles send and receive information by means of the Accelerator Division's control system and the Pbar VME type front end computer. A dedicated serial link connects all of the service buildings, including F23 and F27, with the Pbar front end. In actuality there are six serial loops: PIOX, TCLK, PIOR BTR, MRBS, Pbar Beam Permit Loop, and a link for remote ACNET consoles.

The Pbar CAMAC link is connected within and between service buildings with repeaters (figure 9.1 shows the layout of the crates and repeaters in the service buildings). An applications program currently residing on D20 graphically displays the status of the link and the contents of each crate. Crates are numbered according to the service building they are located in. AP10 houses the $1n crates, the 30 and 50 houses contain the $3n and $5n crates respectively. Crates $70 through $74 are located in AP0, $80, $81 and $82 in F23, and $90 and $91 in F27 (see figure 9.1).

Not all Antiproton Source devices are controlled through the Pbar CAMAC front end. It is sometimes more convenient to control devices from nearby CAMAC crates attached to a different front end. For example, Pbar LCW parameters from CUB are read back through the Booster front-end. Sometimes a particular subsystem, such as the Accumulator or Debuncher BPMs, will have a VME crate system of their own. In these cases, the VME crate communicates directly to the control system instead of through the Pbar CAMAC front end. Similarly, there are also three utility VME crates (AP1001, AP1002, and AP5001) that connect all of the Pbar GPIB diagnostics to ACNET. In addition, some Pbar devices are calculated through pseudo front ends that run on Java controls computers.

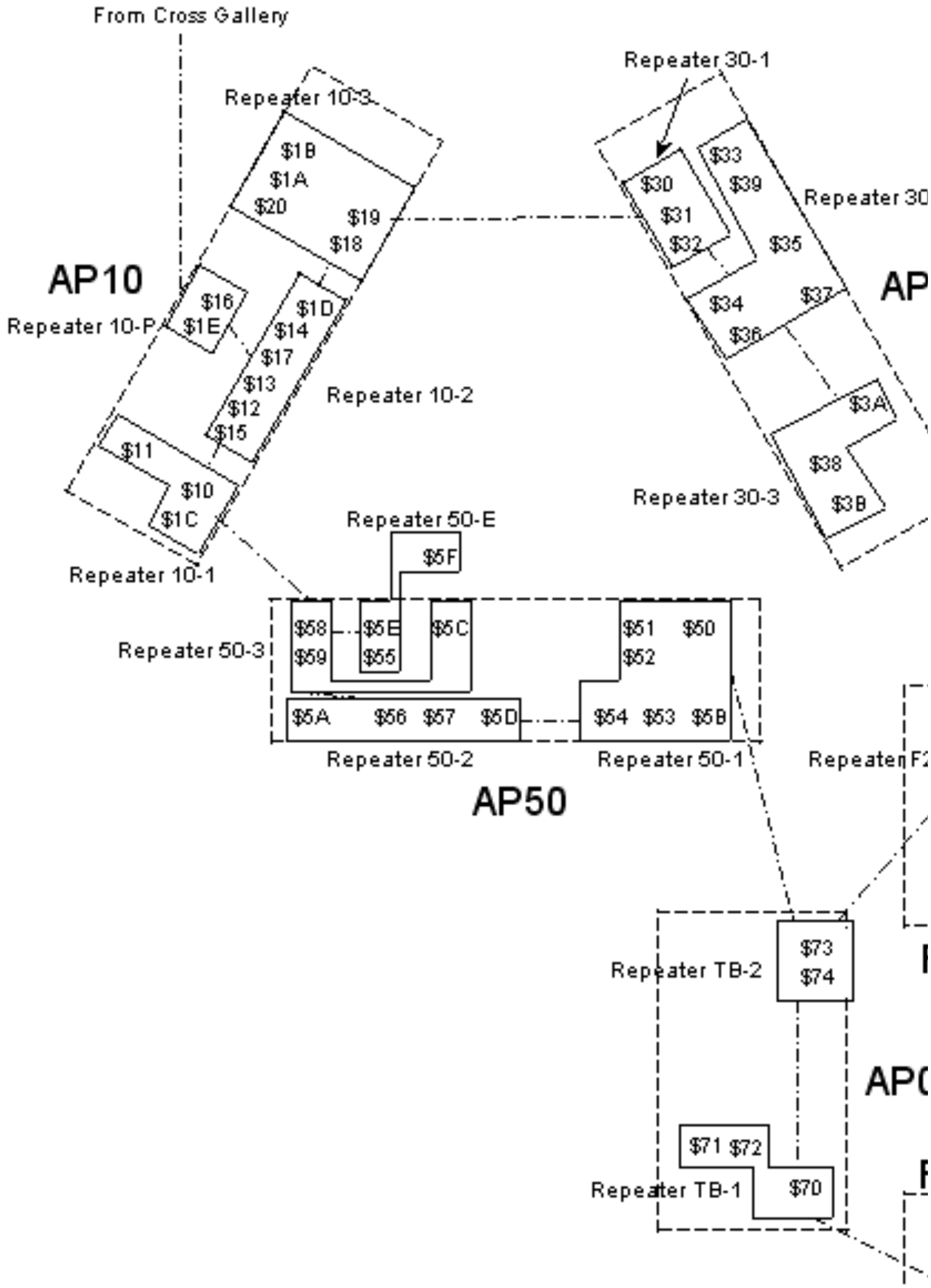

Figure 9.1: Pbar Source CAMAC serial link

MACALC is an example of such a front end. It calculates a number of important parameters including the Accumulator emittances, stacking rate and production efficiency.

The Pbar source has a dedicated beam permit/abort loop. The Pbar Beam Permit Loop is a serial loop of CAMAC 200 modules that is sourced in the MCR back racks in a unique 201 card. The 201 sends out a 5 MHz signal, which, if each 200 module has no faults, is passed along and returned to the 201. If one of the eight inputs to a 200 module is low, the 5 MHz signal is not passed along and the loop collapses. There is no beam dump in the Rings into which beam can be aborted. The Beam Switch Sum Box (BSSB) in the Main Control Room inhibits beam using both Pbar and NuMI permits on Mixed-Mode stacking cycles ($23). This extra precaution is needed since the $23 event has beam destined for both Pbar and NuMI in the Main Injector at the same time. Tying the Pbar and NuMI permits together on the $23s prevents unwanted beam from going to Pbar or NuMI when either one of their permits drop. On Stacking only cycles ($29), the BSSB just monitors the Pbar permit (NuMI permit status is ignored). The Main Injector Beam Synch (MIBS) events associated with extraction from the Main Injector to Pbar ($79, $7D, and $7E) will also be disabled if the P1 line, P2 line or Pbar permit is down. Only a limited number of devices will pull down the permit loop. These inputs included the Rings and Transport Radiation Safety Systems, a summation of radiation monitors (chipmunks) located in the Antiproton Source service buildings, the I:F17B3 supply, AP1 power supplies, a number of Target Station devices, and the software inhibit. Analog inhibits for the AP1 power supplies are included with the help of a CAMAC 204 module at F23. The output of the CAMAC 204 module connects into the CAMAC 200 beam permit input. Each AP1 supply has a dedicated 204 module channel with its own settable alarm limits. Live data sampled on a particular event is compared to the alarm limit. If a device is outside of the alarm limit, the 204 module will trip, which in turn takes away the beam permit.

General Purpose Interface Bus

The Pbar control system is unique in the number of diagnostic devices such as spectrum analyzers, which can be controlled and displayed remotely. This is made possible through the use of the GPIB protocol. GPIB is an acronym for General Purpose Interface Bus and has been in use for over 30 years.

GPIB Primer:

Each GPIB device is assigned a unique GPIB address, ranging from 0-31, by setting address switches on the device. Up to 15 devices connect to one eight bit parallel bus. Connections to GPIB devices are made either via the 24-conductor GPIB cable with D-shaped male and female connectors at both ends (see Figure 9.2), or a standard Cat5 Ethernet cable with RJ-45 jack connectors. When the GPIB cabling is used, the connectors can be stacked up to four deep, so that devices can be linked using a linear configuration, star configuration, or combination of both. The GPIB bus can either connect directly to a GPIB connector on the front end, to a GPIB to Ethernet converter box (often called an ENET box), or directly to Ethernet. The Pbar GPIB implementation has examples of each of these three configurations.

Figure 9.2: Typical GPIB connector

Each GPIB device connects to a VME front end. The front end runs an operating system called VxWorks, which is a commercial multitasking operating system used by the AD/Controls Group to connect microcomputers to ACNET.

A controller is where the GPIB bus connects to the front end. Each front end can have up to eight controllers. There are six different types of controllers, where the controller type is called the interface. The GPIB_VME (also called GPIB1014) interface is the traditional GPIB implementation where the GPIB bus connects directly to the front end. This implementation is becoming obsolete, so there are no plans of adding any future GPIB devices using this interface. GPIB_ENET and GPIB_ENET 10/100 are interfaces where the GPIB bus connects to an ENET box. In this case there is no direct connection between the VME front end and the GPIB devices. Instead, communication occurs over the network through the ENET box. VXI11 is a newer interface where the front end talks directly to the GPIB device over the network. This interface requires that the GPIB device have an Ethernet port. There are a number of newer scopes that are configured in this manner. There are two additional interfaces (PMC-GPIB and LECROY) that will not be covered in this document since they are not used in Pbar.

Pbar GPIB Device List:

Table 9.1 is a listing of the Pbar GPIB devices. The device column is a listing of Pbar GPIB devices. The location column shows the service building and rack number for the GPIB device. The GPIB address shows the manually set GPIB number for that device. The GPIB device column shows the front end controller number. The Front End column lists the front end with the rack number in parenthesis below. The interface column indicates which GPIB interface is used and, where appropriate, that interface's network name and location. The table is organized by GPIB device location, then front end, then interface type and then GPIB address.

Pbar GPIB Devices

Pbar GPIB Device	Device Location (Rack #)	GPIB Address	GPIB Device	Front End (Rack #)	Interface Type (network name) (Rack #)
Proton Torpedo Scope (TDS 680B or TDS684A)	AP0 (THSBS R3)	1	4	AP5001 (B55R06)	GPIB-ENET (pbar-gpib-09.fnal.gov) (THSBS R3)
A:QTPSI Keithley 2000 DVM	AP10 (A:QT)	2	6	AP1001 (A14R05)	GPIB-ENET (pbar-gpib-05.fnal.gov) (A16R53)
D/A VSA HP 89410A VSA (vsa10b.fnal.gov)	AP10 (B14R07)	4	5	AP1001 (A14R05)	GPIB-ENET (pbar-gpib-01.fnal.gov) (B14R02)
Acc Horizontal Emittances 300 MHz frequency generator (D:FFTLOF)	AP10 (B14R06)	7	5	AP1001 (A14R05)	GPIB-ENET (pbar-gpib-01.fnal.gov) (B14R02)
Acc Vertical Emittances 300 MHz frequency generator (A:FFTLOF)	AP10 (B14R06)	8	5	AP1001 (A14R05)	GPIB-ENET (pbar-gpib-01.fnal.gov) (B14R02)
A:IBEAM Keithley 2000 DVM	AP10 (B14R03)	9	5	AP1001 (A14R05)	GPIB-ENET (pbar-gpib-01.fnal.gov) (B14R02)
D:IBEAM Keithley 2000 DVM	AP10 (B14R03)	10	5	AP1001 (A14R05)	GPIB-ENET (pbar-gpib-01.fnal.gov)
Pbar Spectrum Analyzer #1 Agilent E4445A pbarsa1.fnal.gov	AP10 (B14R03)	14	5	AP1001 (A14R05)	GPIB-ENET (pbar-gpib-01.fnal.gov) (B14R02)
Network Analyzer HP8720B	AP10 (B140R2)	16	5	AP1001 (A14R05)	GPIB-ENET (pbar-gpib-01.fnal.gov) (B14R02)
Former FFT Box SR 785 FFT	AP10 (B14R04)	20	5	AP1001 (A14R05)	GPIB-ENET (pbar-gpib-01.fnal.gov) (B14R02)
AP BPM Calibration hp 8110A pulse generator	AP10 (B16R04)	10	0	APABPM10 (B16R04)	GPIB-ENET (adabpm10gpib.fnal.gov) (B16R04)
AP BPM Cal Clock Rohde & Schwarz 9kHz to 1.040 MHz Signal Generator	AP10 (B16R04)	22	0	APABPM10 (B16R04)	GPIB-ENET (adabpm10gpib.fnal.gov) (B16R04)
AP BPM Cal Clock Rohde & Schwarz 9kHz to 1.040 MHz Signal Generator	AP10 (B16R04)	21	0	APABPM10 (B16R04)	GPIB-ENET (adabpm10gpib.fnal.gov) (B16R04)
AP BPM Cal Clock Rohde & Schwarz 9kHz to 1.040 MHz Signal Generator	AP10 (B16R04)	20	0	APABPM10 (B16R04)	GPIB-ENET (adabpm10gpib.fnal.gov) (B16R04)
HP 54600B scope (lower)	AP10 (A14R05)	1	0	AP1001 (A14R05)	GPIB-VME
Debuncher TBT Scope (Tektronix TDS 3014B) (deb-tbt-scope)	AP10 (A14R04)	2	0	AP1001 (A14R05)	GPIB-VME

Pbar GPIB Devices (continued)					
Pbar GPIB Device	Device Location (Rack #)	GPIB Address	GPIB Device	Front End (Rack #)	Interface Type (network name) (Rack #)
Accumulator TBT TDS7104	AP10 (A14R02)	3	0	AP1001 (A14R05)	GPIB-VME
Flux Capacitor Scope (Tektronix TDS 3034B) (ap10-flux-scope)	AP10 (A14R05)	7	0	AP1001 (A14R05)	GPIB-VME
HP 54600B scope (upper)	AP10 (A14R05)	8	0	AP1001 (A14R05)	GPIB-VME
Pbar Spectrum Analyzer #4 Agilent E4445A (pbarsa4.fnal.gov)	AP10 (A14R01)	9	0	AP1001 (A14R05)	GPIB-VME
Pbar Spectrum Analyzer #5 HP8568B	AP10 (A14R02)	10	0	AP1001 (A14R05)	GPIB-VME
Stacking VSA HP VSA89440A (vsa10.fnal.gov)	AP10 (A14R04)	18	0	AP1001 (A14R05)	GPIB-VME
Accumulator bakeout system HP 37204 GPIB extender	AP10 (B11R06)	1	0	BAKER (B11R06)	GPIB-VME
Accumulator bakeout system HP 37204 GPIB extender to 10 Stub	AP10 (B11R06)	3	0	BAKER (B11R06)	GPIB-VME
Accumulator bakeout system HP 37204 GPIB extender to 50 Stub	AP10 (B11R06)	5	0	BAKER (B11R06)	GPIB-VME
Debuncher TBT Scope Tektronix TDS 3014B	AP10 (A14R04)	0	0	AP1002 (A14R05)	VXI11 (deb-tbt-scope.fnal.gov)
Flux Capacitor Scope Tektronix TDS 3034B (pledgepin.fnal.gov)	AP10 (A14R05)	1	0	AP1002 (A14R05)	VXI11 (ap10-flux-scope.fnal.gov)
Debuncher EKIK Scope Tektronix TDS 3014B	AP10 (A13R01)	3	0	AP1002 (A14R05)	VXI11 (deb-ekik-scope.fnal.gov)
Accumulator EKIK Scope Tektronix TDS 3014B	AP10 (A:KIK)	4	0	AP1002 (A14R05)	VXI11 (acc-ekik-scope.fnal.gov)
Pbar Spectrum Analyzer #2 Agilent E4445A Spectrum Analyzer	AP30 (B33R01)	14	7	AP1001 (A14R05)	GPIB-ENET (pbar-gpib-06.fnal.gov)
AP BPM Calibration HP 8110A pulse generator	AP30 (B32R02)	10	0	APABPM20 (B32R02)	GPIB-ENET (adabpm20gpib.fnal.gov) (B32R02)
Debuncher Horizontal IPM MCP Power Supply	AP30 (A33R05)	6	0	MWDIPM (A33R04)	GPIB-ENET (dipm-gpib.fnal.gov) (A33R05)
Debuncher Horizontal IPM Clearing Field Power Supply	AP30 (A33R05)	7	0	MWDIPM (A33R04)	GPIB-ENET (dipm-gpib.fnal.gov) (A33R05)

Pbar GPIB Devices (continued)					
Pbar GPIB Device	**Device Location (Rack #)**	**GPIB Address**	**GPIB Device**	**Front End (Rack #)**	**Interface Type (network name) (Rack #)**
Debuncher Vertical IPM MCP Power Supply	AP30 (A33R06)	4	0	MWDIPM (A33R04)	GPIB-ENET (dipm-gpib.fnal.gov) (A33R05)
Debuncher Vertical IPM Clearing Field Power Supply	AP30 (A33R06)	5	0	MWDIPM (A33R04)	GPIB-ENET (dipm-gpib.fnal.gov) (A33R05)
Accumulator IKIK Scope Tektronix TDS 3014B	AP30 (A32R01)	6	0	AP1002 (A14R05)	VXI11 (acc-ikik-scope.fnal.gov)
Accumulator NMR Scope Tektronix TDS 3012B	AP30 (B37R03)	8	0	AP1002 (A14R05)	VXI11 (acc-nmr-scope.fnal.gov)
A:IBPSI Keithly 2000 DVM	AP50 (A:IB)	1	1	AP5001 (B55R06)	GPIB-ENET (pbar-gpib-07.fnal.gov) (B56R02)
D:IBPSI Keithley 2000 DVM	AP50 (D:IB)	2	1	AP5001 (B55R06)	GPIB-ENET (pbar-gpib-07.fnal.gov) (B56R02)
A:LQPSI Keithly 2000 DVM	AP50 (D:LQ)	3	1	AP5001 (B55R06)	GPIB-ENET (pbar-gpib-07.fnal.gov) (B56R02)
A:QDFPSI Keithly 2000 DVM	AP50 (D:QDF)	2	2	AP5001 (B55R06)	GPIB-ENET (pbar-gpib-08.fnal.gov) (B53R03)
A:NMR50/D:NMR50 Metrolab NMR Tesla Meter	AP50 (B51R07)	0	0	AP5001 (B55R06)	GPIB-ENET (pbar-gpib-10.fnal.gov) (B51R07)
AP BPM Calibration hp 8110A pulse generator	AP50 (B56R03)	10	0	APABPM50 (B56R03)	GPIB-ENET (adabpm50gpib.fnal.gov) (B56R03)
Debuncher IKIK Scope Tektronix TDS 3014B	AP50 (A52R03)	5	0	AP1002 (A14R05)	VXI11 (deb-ikik-scope.fnal.gov)
Roaming Tektronix scope for general testing.	Mobile	2	0	AP1002 (A14R05)	VXI11 (pbar-scope233.fnal.gov)

Table 9.1: Pbar GPIB devices

Pbar VME Front Ends for GPIB Busses:

AP1001, AP1002 and AP5001 are VME/GPIB utility front ends that interface most of the GPIB Pbar diagnostics. There are a few other front ends that interface GPIB devices for specific systems. Examples of this include BAKER (Accumulator bake out system), MWDIPM (Debuncher IPM), and ABPM## (Accumulator BPM calibration system).

The AP1001 VME crate houses both the AP1001 and AP1002 front ends. There are separate software reboot capabilities for both front ends, but a hardware reboot spans both front ends. AP1001 has an Ethernet connection to the Pbar Controls network as well as a GPIB connection with a stack of four GPIB connectors. The Ethernet connection allows for communications with the control system, GPIB ENET boxes and individual GPIB scopes. The GPIB stack is a combination star and linear configuration with each of the connectors in the stack having a series of attached devices. Devices that are on a GPIB bus that attach directly to AP1001 include Spectrum Analyzer #4, Spectrum Analyzer #5, the Stacking VSA, the Flux Capacitor Scope, the Debuncher TBT scope and the Accumulator TBT scope. AP1001 also interfaces ENET boxes named PBAR-GPIB-01, PBAR-GPIB-05 and PBAR-GPIB-06. PBAR-GPIB-01 connects to the Network Analyzer, Spectrum Analyzer #1, 300 MHz frequency generators for horizontal and vertical Accumulator emittances, DVMs for the Accumulator and Debuncher beam intensity read backs, and the D/A FFT VSA. PBAR-GPIB-05 connects to the DVM that provides the A:QTPSI readback at AP10. PBAR-GPIB-06 connects to Pbar Spectrum Analyzer #2 at AP30, which is the Accumulator longitudinal profile that is viewed on Pbar CATV channel 28.

The AP1002 front end accesses Ethernet enabled scopes in AP10, AP30 and AP50 over the network. Scopes connected to this interface include the Debuncher TBT, Flux Capacitor, Debuncher extraction kicker, Accumulator extraction kicker, Accumulator injection kicker, Debuncher injection kicker and Accumulator NMR.

The AP5001 front end is located in the AP50 service building and interfaces ENET boxes named PBAR-GPIB-07, PBAR-GPIB-08, and PBAR-GPIB-09. PBAR-GPIB-07 connects to DVMs that provide the A:IBPSI, D:IBPSI, and A:LQPSI readbacks, PBAR-GPIB-08 connects to the DVM that provides the A:QDFPSI readback, and PBAR-GPIB-09 connects to the AP0 Wall Current Monitor scope that is used for the Proton Torpedo display.

The BAKER VME front end is used for the Accumulator bake-out system. It connects to three HP 37204 GPIB extenders that carry the GPIB bus to the 10, 30 and 50 stubs in the Pbar Rings tunnel. In the tunnel, the GPIB bus in each stub connects to an HP 3497A controller that interfaces thermocouple readbacks and relays for switching power to the electrical blankets used for the bake-out.

The Accumulator BPM Calibration and Debuncher IPM GPIB busses will be covered in the diagnostics chapter and need not be repeated here.

Pbar GPIB Map:

When troubleshooting GPIB problems it is helpful to know how the GPIB busses are connected to their respective front ends. This can be confusing since GPIB busses can connect directly to the front end or over the Ethernet. In addition, GPIB busses can be combinations of linear and star configurations. Figure 9.3 is a map of how the GPIB busses connect to the AP1001, AP1002 and AP5001 front ends in Pbar. The upper portion of the diagram shows the Ethernet connections to the Pbar Controls Network. This includes the front ends, the GPIB ENET boxes and the GPIB scopes that can talk directly over Ethernet (VXI11 interface). The bottom portion of the diagram shows the GPIB bus configurations for devices connecting directly to a front end (GPIB_VME interface) and devices connecting to an ENET box (GPIB_ENET interface). Using Figure 9.3 to determine the GPIB bus configuration and Table 9.1 to get specific details for that bus could prove to be of use when troubleshooting a GPIB problem.

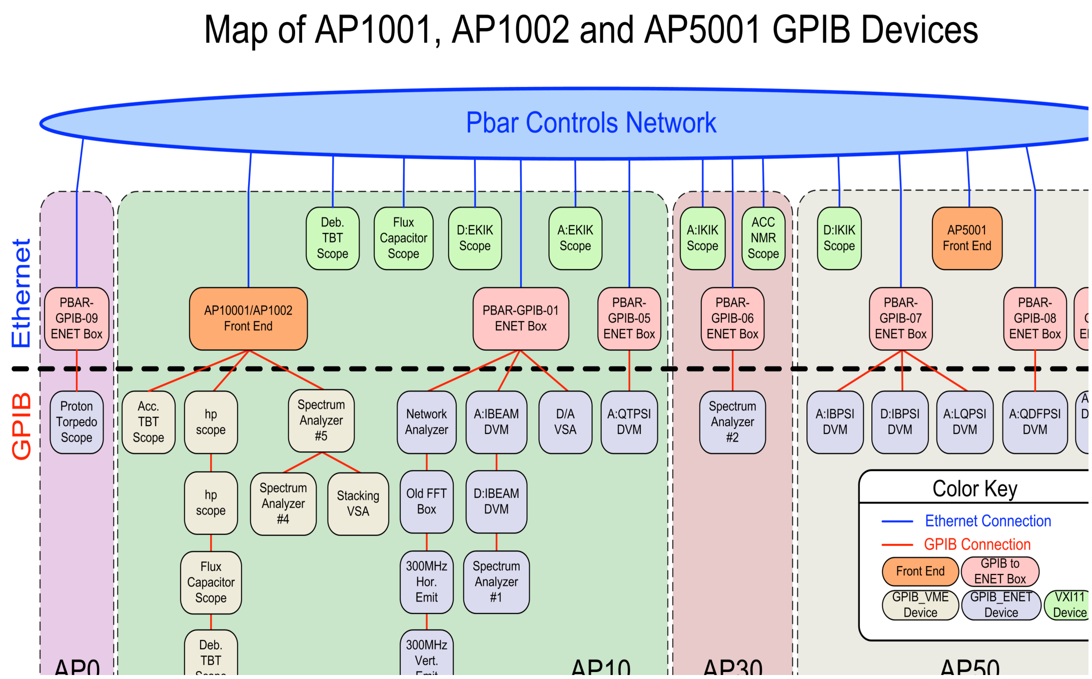

Figure 9.3: A map of the AP1001, AP1002 and AP5001 GPIB devices

Other Front Ends:

There are many other VME front ends that are not covered in this section since they are part of other systems and do not use GPIB. All can be polled on ACNET page D31. DBPM## (where the sector is specified by ## = 10, 20, 30, 40, 50, or 60) interfaces the Debuncher BPMs, ABPM## (where the sector is specified by ## = 10, 20, 30, 40, 50, or 60) interfaces Accumulator BPMs, ARF4 interfaces the Accumulator LLRF, DRF1 is used for DRF1 cavity temperature regulation, PBEAM is used to calculate the A:BEAM and D:BEAM intensity readbacks, FRIGPR is the AP30 Frig I/O and Thermometry interface, PBCOOL is used for stochastic cooling, TWTACC is used for Accumulator TWT protection, TWTCOM is used for Accumulator core momentum TWT protection, TWTDEB and TWTDB2 are used for Debuncher TWT protection, and PBVAC is used for Pbar vacuum.

Programmable Logic Controller

A number of Pbar devices are controlled and monitored using Programmable Logic Controllers (PLCs). This includes stochastic cooling devices, Debuncher motorized quadrupole stands, the Pbar Rings tunnel exhaust fans, Pbar Rings tunnel wireless Ethernet on/off switches, Accumulator BPM crate resets, DRF3 ENI control, ARF3 cavity short movement and AP3 line LCW leak detectors.

PLC Primer

PLCs are popular because they provide a cost-effective interface to hardware components. They are designed to withstand ambient temperature fluctuations, electrical noise and vibrations encountered in the service buildings. A variety of commercially available analog and digital I/O modules allow the PLCs to connect to various external devices. Each PLC is capable of housing multiple I/O modules. When the number of available I/O module slots is not sufficient, additional modules can be added through the use of extender boards. PLCs have a CPU that allows programs to be written to control the external devices that the PLC interfaces. The PLCs have a battery backup to retain their memory contents during occasional power outages. Pbar PLCs communicate on the Pbar controls network through Ethernet to a single VME front end running VxWorks, which provides access to the AD control system.

History

The Antiproton Source utilizes a large number of military grade microwave components. Many of these operate from 24 to 28 volts DC. The large number of channels of control and status required new types of hardware from the Controls Department. Originally, Fermi built cards and crates provided the power distribution, control, and status referred to as "Beechy Boxes" in honor of Dave Beechy, the Controls Department engineer. Eventually Dave Beechy went to the SSC and Dave DuPuis, the technician who maintained the boxes, retired. By the late 1990's a large Stochastic Cooling upgrade was planned and it became evident that commercial controllers were cost effective and readily available. Inexpensive Koyo built PLCs from what was then called PLC Direct had performed well in the small He3 Linac for P.E.T isotope production. Ethernet modules were becoming available so the interface to ACNET was fairly easy to implement. Currently, Pbar uses PLC CPU models DL-440, DL-450 and DL-260 purchased from Automation Direct

Pbar PLCs

All of the PLCs that interface the stochastic cooling systems have a status parameter that continually updates if the PLC is talking to the VME front end. The status parameters for the tunnel PLCs also have a digital status field that can be used to remotely reset the PLC. The PLCs in the service buildings do not have remote reset capability. A number of the PLC units for the stochastic cooling systems are located in the stub rooms in the Pbar Rings tunnel. A tunnel PLC failure could result in reduced stacking and/or inability to cool the core. Experience has shown a common, possibly radiation induced, failure mode is the loss of the PLC's internal 5 volt switching power supply. A set of four conductor 10 Ga. cables were added from each of the stub room PLCs to one of three backup + 5V Acopian power supplies located in service buildings. This arrangement allows for diagnosing and potentially correcting tunnel PLC power supply problems without accessing the tunnel.

Pbar PLCs

Network Name (*.fnal.gov)	PLC Status & Reset Device	PLC Location (Rack #)	Backup +5V Location (Rack #)	Front End(s) (Rack)	Devices interfaced through the PLC
PbarPLC01	**A:PLC01S** (status only)	**AP10** (B14R04) *back of rack	None	**PBCOOL** (B11R06)	PLC Resets (PLC2, PLC3, PLC9, PLC11), Accumulator BPM 10 and 60 house power reset (A:B1POWR & A:B6POWR), Switch Tree, and Accumulator horizontal and vertical damper reversing switches.
PbarPLC02	**A:PLC02**	**10-1 Stub** (A10-1SR1)	**AP10** (B13R04)	**PBCOOL** (B11R06)	Core Betatron Cooling Systems, wide band amps, 10 sector tunnel exhaust fan, and A10 Accumulator bakeout controls.
PbarPLC03	**A:PLC03**	**10-2 Stub** (A10-2SR)	**AP10** (B16R04)	**PBCOOL** (B11R06)	Debuncher stochastic cooling band 3 and 4 systems (A10-2 stub room medium level RF).
PbarPLC04	**A:PLC04S** (status only)	**AP10** (A14R07)	None	**PBCOOL** (B11R06)	Debuncher stochastic cooling (low level RF), and AP10 tunnel wireless on/off switch (D:WIFI10).
PbarPLC05	**A:PLC05**	**20-2 Stub** (A20-2SR)	**AP30** (B31R07)	**PBCOOL** (B11R06)	Core 4-8GHz momentum cooling (low level and medium level RF), and 20 sector tunnel exhaust fan.
PbarPLC06	**A:PLC06S** (status only)	**AP30** (A35R02)	None	**PBCOOL** (B11R06)	Debuncher stochastic cooling (high level RF), and AP3 line LCW leak detector (D:LKESUM),
PbarPLC07	**A:PLC07S** (status only)	**AP30** (B33R03)	None	**PBCOOL** (B11R06)	Accumulator Stacktail cooling (medium and high level RF), 2-4 GHz core momentum (high level RF), Debuncher Momentum medium level optical delay line (D:POTMF setting), Accumulator BPM 20 and 30 house crate resets (A:B2POWR & A:B3POWR), DRF3 ENI (D:R3HLSC), PLC resets (PLC 5 and 10), 40 location tunnel exhaust fan, and AP30 tunnel wireless on/off switch (D:WIFI30).
PbarPLC08	**A:PLC08S** (status only)	**AP50** (B51R06)	None	**PBCOOL** (B11R06)	Core 4-8GHz momentum (high level RF), Accumulator 50 bake, and Accumulator BPM 40 and 50 house crate resets (A:B4POWR & A:B5POWR).
PbarPLC09	**A:PLC09**	**60 Stub** (A60SR)	**AP10** (B13R04)	**PBCOOL** (B11R06)	Core 2-4GHz momentum (low level and medium level RF), Stacktail (low level RF), and 60 location tunnel exhaust fan.
PbarPLC10	**A:PLC10**	**30 Stub** (A30SR)	**AP30** (B31R07)	**PBCOOL** (B11R06)	Debuncher momentum (A30 stub room medium level RF: oven temp, pin attenuators, diodes, various amps)
PbarPLC11	**A:PLC11**	**10-1 Stub** (A10-1SR2)	**AP10** (B13R04)	**PBCOOL** (B11R06)	Debuncher cooling band 1 and 2 systems (A10-2 stub room medium level RF).
PbarPLC12	**A:PLC12S** (status only)	**AP50** (B55R07)	None	**PBCOOL** (B11R06)	ARF3.
PbarPLC13	**A:PLC13** (status only)	**AP30** (B34R05)	None	**PBCOOL** (B11R06)	Core 4-8GHz betatron (HLRF).

Pbar PLCs (continued)					
Network Name (*.fnal.gov)	**PLC Status & Reset Device**	**PLC Location (Rack #)**	**Backup +5V Location (Rack #)**	**Front End(s) (Rack)**	**Devices interfaced through the PLC**
PbarPLC14	None	**AP10** (A12R02)	None	**AP1002** (A14R05)	Motor controls for Debuncher quad (6Q2, 6Q7, 6Q14, 6Q17) and Debuncher extraction kicker stands.
PbarPLC15	None	**AP10** (A16R05)	None	**AP1002** (A14R05)	Motor controls for Debuncher quad (1Q3, 1Q5, 1Q8, 1Q11, and 1Q17) stands.
PbarPLC16	None	**AP50** (A53R05)	None	**AP1002** (A14R05)	Motor controls for Debuncher quad (4Q9, 4Q10, 4Q14, 4Q17, D4Q20, 5Q17, 5Q12, 5Q9, 5Q6, 5Q4 and 5Q3), Debuncher Injection Kicker, and Debuncher Injection Septum stands. AP50 tunnel wireless on/off switch (D:WIFI50).
PbarPLC17	None	**AP30** (A34R06)	None	**AP1002** (A14R05)	Motor controls for Debuncher quad (2Q2, 2Q10, 2Q14, 2Q17, 2Q20, 3Q6, 3Q9, 3Q12, and 3Q17) stands.

Table 9.2: Pbar PLCs

PLC Device List:

Table 9.2 provides details for each of the 17 PLCs used in Pbar. The network name column lists the network name, minus the ".fnal.gov" to save space. The PLC status and reset device column lists and, where applicable, the ACNET device used to monitor and/or reset the PLC. Remember that only the tunnel PLCs have remote reset capability. The PLC location column lists the service building and rack number where the PLC resides. The backup +5V rack column lists which PLCs have backup +5V supplies and the rack number of the supply. This only applies to PLCs located in the tunnel. The front end column lists which VME front end is used to provide the interface between that PLC and the control system. The last column lists the devices interfaced through the PLC.

Ethernet

The Pbar network is divided into two separate Ethernet networks. There is a controls network that is protected by the Accelerator Division controls firewall, and a general network that is not protected by the firewall. Both networks are separated from the general Fermilab network and Internet via an Accelerator Division border router that provides some additional security restrictions. The two Pbar networks are composed of a diverse set of components containing many different varieties of Ethernet including Gigabit, FastEthernet, Ethernet, Thinwire, Thickwire and 802.11 wireless, with network speeds ranging from switched 1,000 Mbit/sec all the way down to shared 10Mbit/s. Communication with Pbar network devices requires an understanding of which network both the accessing and destination computer are located on as well as the network path between the devices. Below is an outline of both the Pbar controls and Pbar general networks.

Pbar Controls Network:

The Pbar Controls network is a secure network for devices associated with accelerator components or the control system. The Accelerator Division controls firewall stops computers outside the firewall from direct access to computers inside and restricts computers inside the firewall from direct access to networks outside the firewall. Computers inside the firewall not only are restricted from accessing the Internet, but also are restricted from access to other Fermilab network devices including the Fermilab email servers. Access to the outside networks can be made indirectly through the use of a terminal server called Beams-TS.

Figure 9.4 shows an overview of the Pbar controls network. 1000Base-LH/LX gigabit Ethernet is run over multi-mode fiber optic cable from the controls Cisco 6509 router/switch in the Cross Gallery computer to a Cisco Catalyst 3508 switch at AP10. The “LH” in this Ethernet spec stands for “long haul” which is a special spec needed to extend Ethernet on long paths like that from the computer room to AP10. Ideally for these distances, it would be better to run the 1000Base-LH/LX over single-mode fiber optic cable, which allows even longer path lengths, but Pbar only has multi-mode fiber available. It turns out the distance between the computer room and AP10 is about as long as possible for stable Ethernet over multi-mode fiber.

From the Cisco Catalyst 3508 switch at AP10, we branch out with 1000Base-SX gigabit over multi-mode fiber optic cable to two Cisco Catalyst 2960 switches at AP10, one Cisco Catalyst 2960 switch at AP30, and one Cisco Catalyst 2960 switch at AP50. In this case the standard 1000Base-SX gigabit is used instead of the long haul variety since the distances between services buildings are short enough. The service building Cisco Catalyst 2960 switches provide all of the 100Mbit/s FastEthernet and 10Mbit/s Ethernet connections over Category 5 (usually called Cat 5) cable. This is the standard network cable, which contains four twisted pairs in a single cable jacket with end connectors that look like extra wide phone jacks, used for most Ethernet connections.

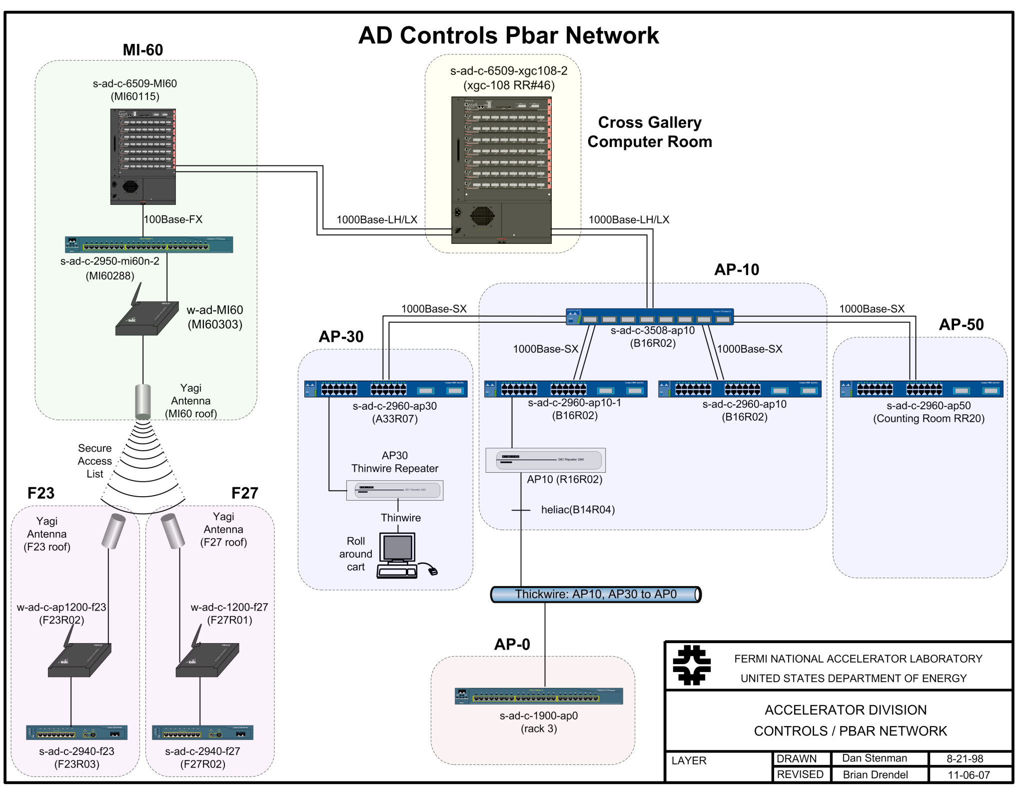

Figure 9.4: Pbar controls network

Controls Thinwire:

At AP30, one of the Catalyst 2960 Ethernet connections goes to a 10Base2 repeater. 10Base2 is a legacy 10Mbit/s network that is most often referred to as Thinwire because it runs on thin flexible coaxial cable, often RG-58 or similar. On a Thinwire network, segments of coax cable with BNC end connectors are connected in series, BNC T-connectors allow the insertion of devices to the network, and the physical end of the network contains a 50-ohm BNC terminator. Thinwire is a shared network, meaning that all of the computer network cards on the network will see all of the traffic to and from all other computers on that network. As a result, if there are a lot of computers on a Thinwire network, network performance will suffer. In this case, there isn't a problem since the portable ACNET console (often found at AP30) is the only device that is connected to this network. The Thinwire remains in place due to the legacy network card in the console as well as the existing Thinwire infrastructure that allows connecting the console to various locations in the building.

Controls Thickwire:

At AP10, one of the Catalyst 2960 Ethernet connections goes to a 10Base5 repeater. 10Base5 is another legacy 10Mbit/s shared network that is most often referred to as Thickwire because it runs on a rigid 50-ohm coax cable that is 0.375 inches in diameter, noticeably larger than the Thinwire mentioned earlier. Thickwire is used to get network to AP0 since no fiber optic cable path is available. It should also be noted that there is no Pbar general network at AP0, so the controls Thickwire is the only network available. A Thickwire network consists of a cable, called a Heliac, with network connectivity provided via transceivers attached to the cable. The transceiver is connected to the cable using what is called a vampire tap, which is a spike that pierces through the outer shielding of the cable to the center conductor, with other spikes contacting the outer conductor. The Thickwire at AP10 connects via a DEMPR (acronym for Digital Ethernet

Multi-Port Repeater) to a heliac line that goes to AP30. At AP30 there is a heliac patch panel that includes the heliacs for AP10 and AP0. The heliac line that has the 10base5 from AP10 is a jumpered through the heliac panel to AP0. The distance is short enough that no repeater is needed at AP30. A transceiver is attached to the Thickwire at AP0 that connects to a Cisco Catalyst 1900 via an Attachment Unit Interface (AUI) connection. The AUI is a 15 pin, two-row D-style connector, with sliding clips that allow the connector to lock into place. The Cisco Catalyst 1900 switch provides 10Mbit/s Ethernet connectivity via the standard Cat 5 network cable.

F23 & F27 Controls Wireless:

The F23 and F27 networks are unique due to infrastructure limitations. There is no easy network path to these buildings. The closest buildings are F2 and AP0, neither of which currently have unused fiber optic network cables. Both buildings run shared 10Mbit/s Thickwire networks, so tapping off of either of these networks would not be desirable. The closest fiber optic network is at F0, which would be a long and expensive network run that involves finding a cable path along the Tevatron berm. To get network to these buildings, a unique wireless network solution was employed that involves connecting to the MI60 controls network via 802.11b wireless as is described below.

1000Base-LH/LX gigabit Ethernet is run over single-mode fiber optic cable from the controls Cisco 6509 router/switch in the Cross Gallery computer to another Cisco Catalyst 6509 router/switch in the south end of MI-60. Unlike, the network to AP10, the more current Main Injector fiber optic cable infrastructure allows the more ideal single-mode cable, which is better suited for long path lengths. The MI60 Cisco 6509 router/switch then connects to a Cisco Catalyst 2950 switch at the far north end of MI60 using 100Base-FX over multi-mode fiber optic cable. The 100Base in the spec is also called FastEthernet, which runs at 100Mbit/s. From the Cisco 2950, Cat 5 cable is run to a Cisco Aironet 1200 802.11 wireless access point in the middle of the building. The access point is not used for wireless connectivity inside the MI60 service building, but instead is used to get the MI60 controls network out to F23 and F27. There is a long antenna cable that runs from the MI60 wireless access point to a Yagi antenna on the roof of MI-60. The MI60 Yagi antenna is a directional antenna that is pointed at single Yagi antennas on the roofs of the F23 and F27 service buildings. The F23 and F27 roof antennas connect to Cisco Aironet wireless access points inside of the F23 and F27 service buildings. The MI60 wireless access point has a secure access list that only allows wireless network connections from the F23 and F27 wireless access points. The wireless access points at both F23 and F27 connect to Cisco Catalyst 2940 switches which provide Ethernet connectivity via the standard Cat 5 network cable.

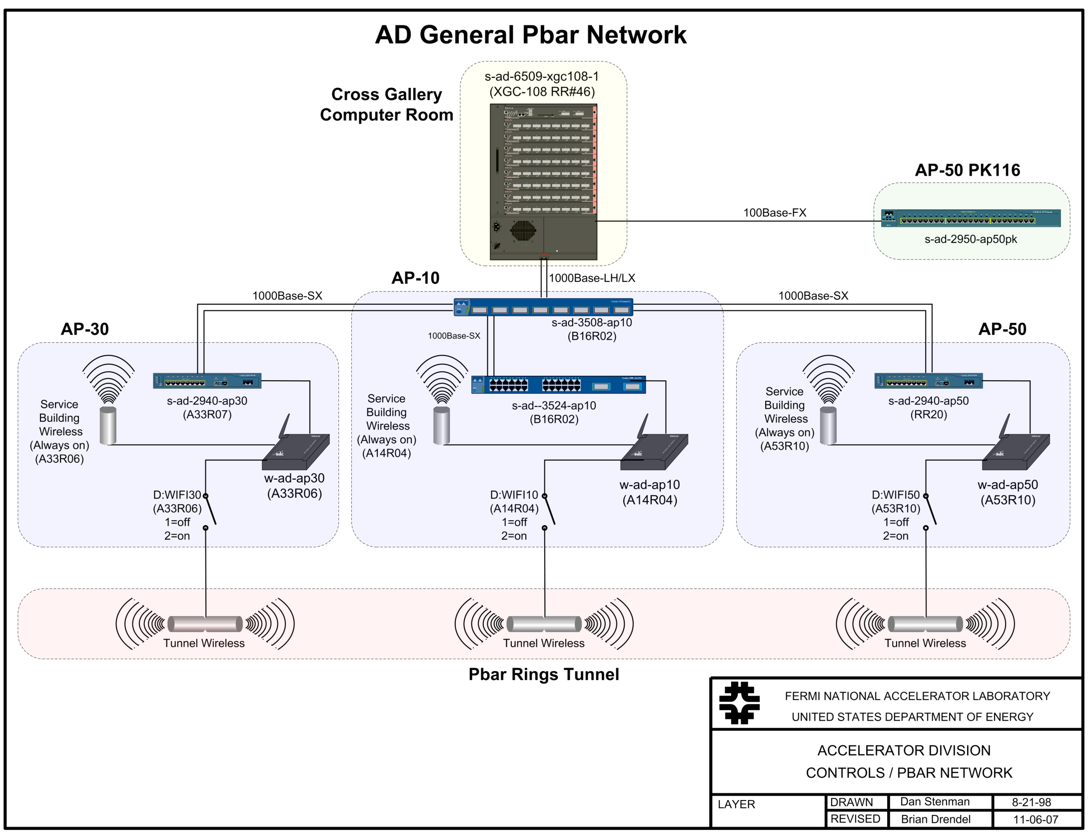

Figure 9.5: Pbar general network

Pbar General Network:

The Pbar general network is used for desktop computers and other devices that are not part of the control system. Computers on this network are outside of the firewall. This means they have access to the Internet and most Fermilab networks such as the Fermilab mail, but are restricted from access inside of the controls firewall. To gain access to nodes inside the firewall, these computers need to use additional security tools such as SSH tunnels or the Controls VPN. When a computer is connected via the Controls VPN, it becomes a part of the controls network and no longer has outside network access until the VPN connection is disconnected.

Figure 9.5 shows an overview of the Pbar general network. 1000Base-LH/LX gigabit Ethernet is run over multi-mode fiber optic cable from the general Cisco 6509 router/switch in the Cross Gallery computer to a Cisco Catalyst 3508 switch at AP10. From the Cisco Catalyst 3508, we branch out with 1000Base-SX gigabit over multi-mode fiber optic cable to a Cisco Catalyst 3524 at AP10, a Cisco Catalyst 2940 at AP30, and a Cisco Catalyst 2940 at AP50. These three Cisco network switches provide 100Mbit/s FastEthernet and 10Mbit/s Ethernet connections over the standard Cat 5 network cable. It should be pointed out that the AP50 network rack is in the AP50 counting room.

At all three service buildings, the Cisco network switch connects to a Cisco Aironet 802.11 wireless access point, which provides Pbar general, network to both the service building and to the tunnel. One unique concern is the potential for unwanted interaction between the 802.11 wireless, which runs at 2.4 GHz, and our 2-4 GHz stochastic cooling systems. As a result, switches were installed at each service building to allow disabling or enabling the wireless antennas in the tunnel. When the ACNET parameters D:WIFI## (where ## is 10, 30 or 50) is set to 1, the switch is open and the tunnel wireless is disabled. When set to 2, the switch is closed in and the tunnel wireless is active. The wireless in the upstairs service building is always on.

Figure 9.6 shows a more detailed view of the Pbar tunnel wireless system. It is of note that each antenna line going to the tunnel is split into three antennas and a corner reflector. This allows wireless coverage all the way around the Pbar rings.

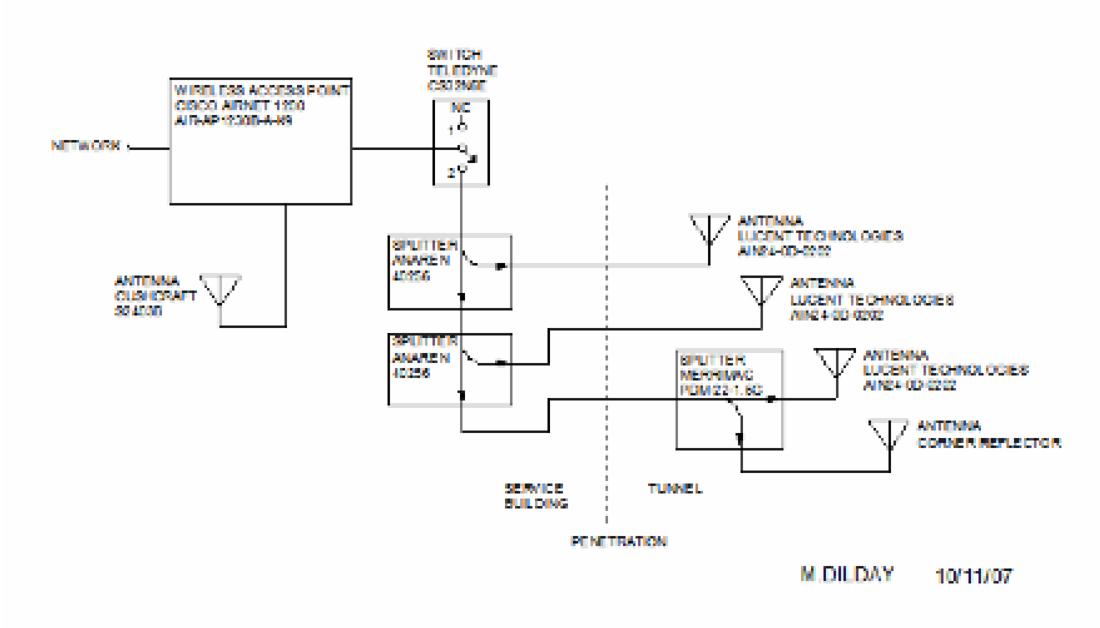

Figure 9.6: Pbar tunnel wireless details

References

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2) Conversations with Greg Brown

3) Conversations with Dave Peterson

4) Input from Greg Vogel

5) Dan Stenman, AD/Controls Pbar Controls and General Network Map (March 2007). Expanded and broken into two drawings for this chapter.

6) Mark Dilday, Pbar Wireless Diagram (October 2007)

7) Dave Peterson, PLC Troubleshooting and Programming Instructions, www-bdnew.fnal.gov/pbar/documents/Eng_Info/PLC%20Instructions.html (June 2007)

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Notes:

10 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.

Antiproton 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

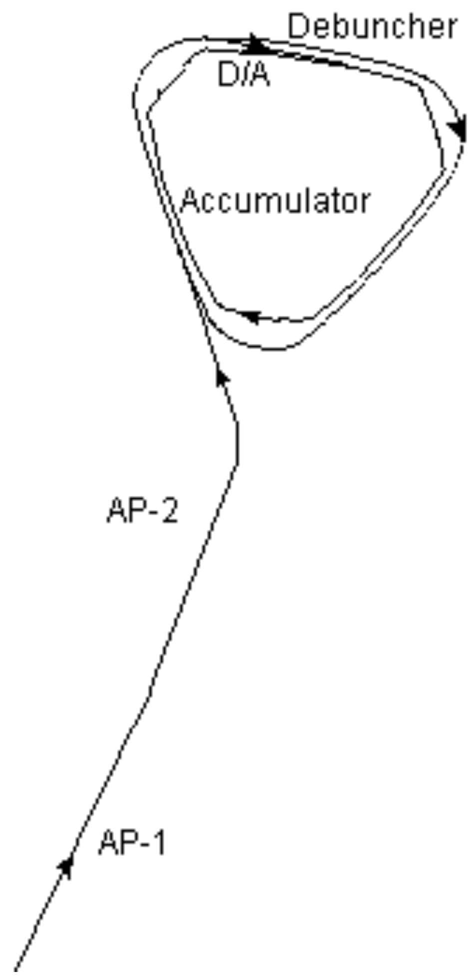

Figure 10.1: Stacking

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.

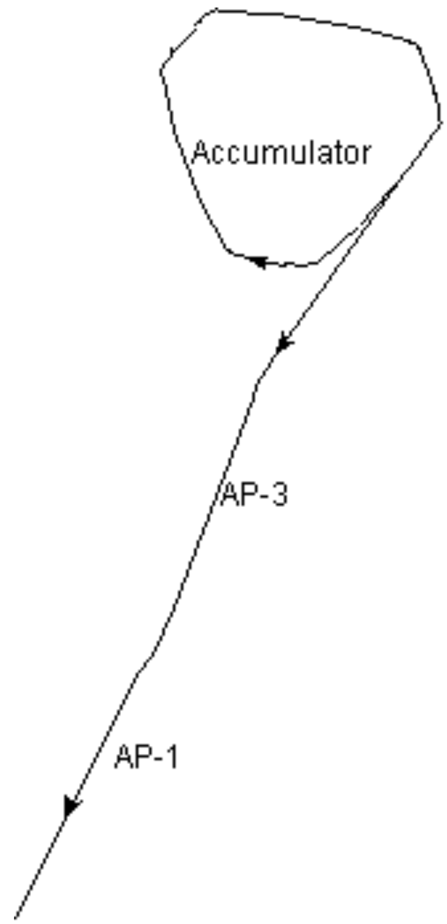

Figure 10.2: Pbar transfers to Main Injector

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.

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) that 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.

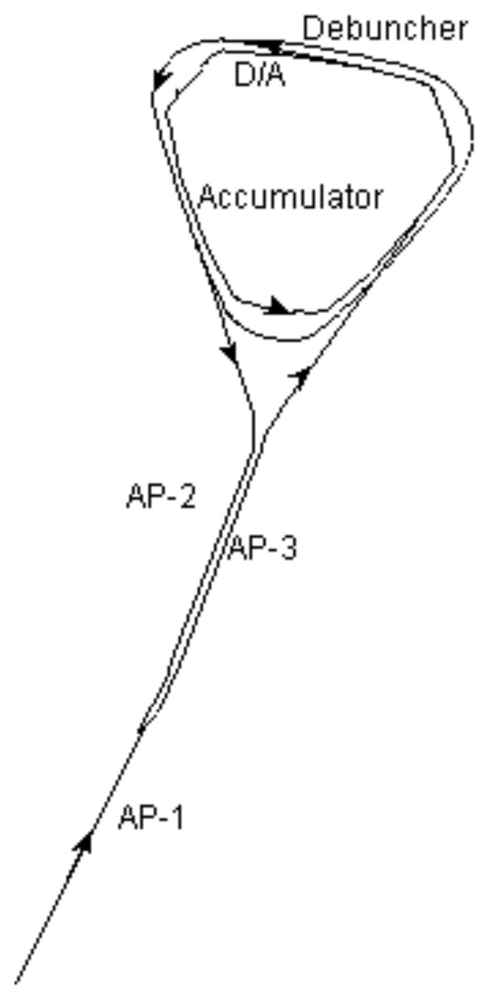

Figure 10.3: Reverse Protons

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.

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.

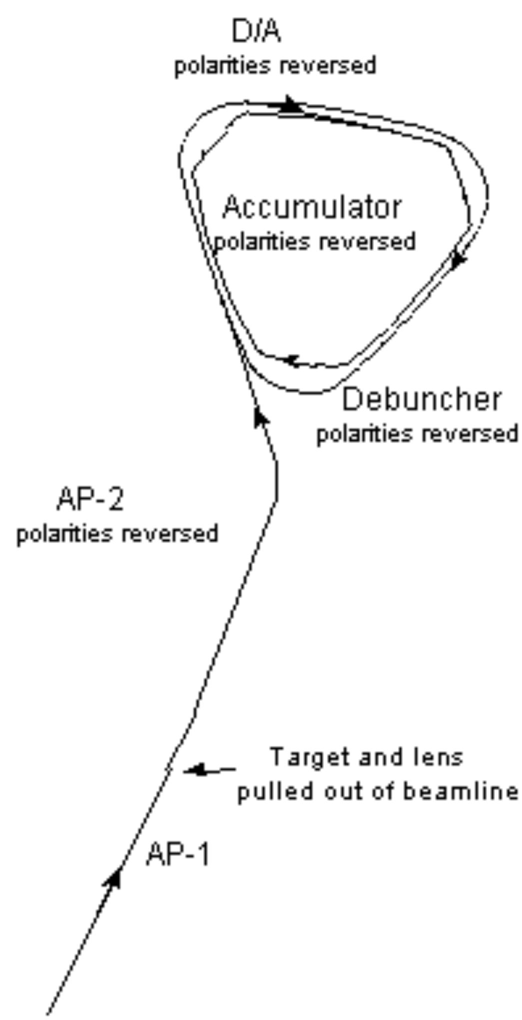

Figure 10.4: Forward Protons

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.

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.

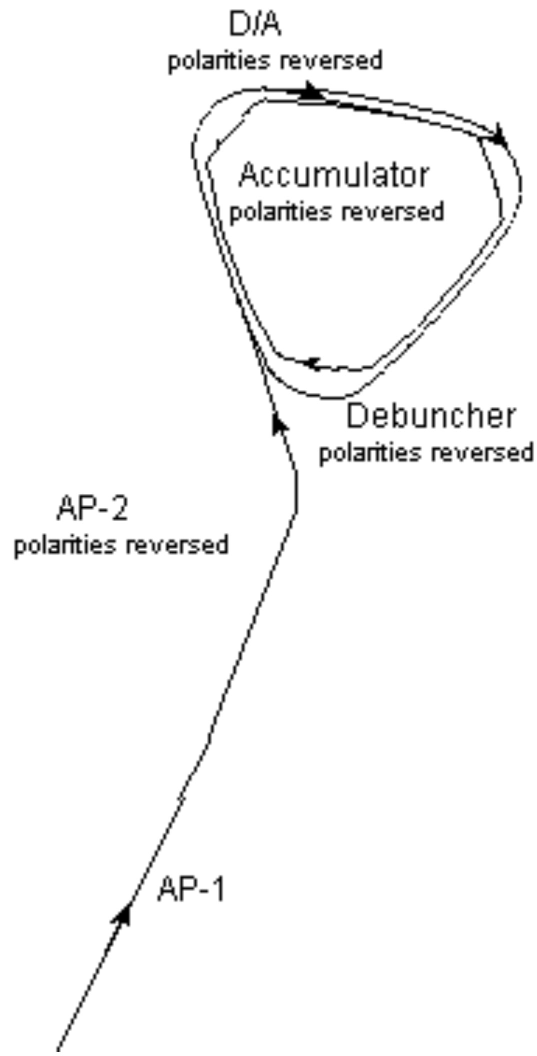

Figure 10.5: Proton Stacking

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.

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 (charmed quark and charmed antiquark) 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.

Notes: