VII. 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).

A. 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.

1. DCCT's

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 DCCT's 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 DCCT's 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:

$$1\ mA = 1 \times 10^{10}\ particles.$$

because

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

For 10^{10} circulating particles, the current is: 1×10^{-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 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 heatsinked 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

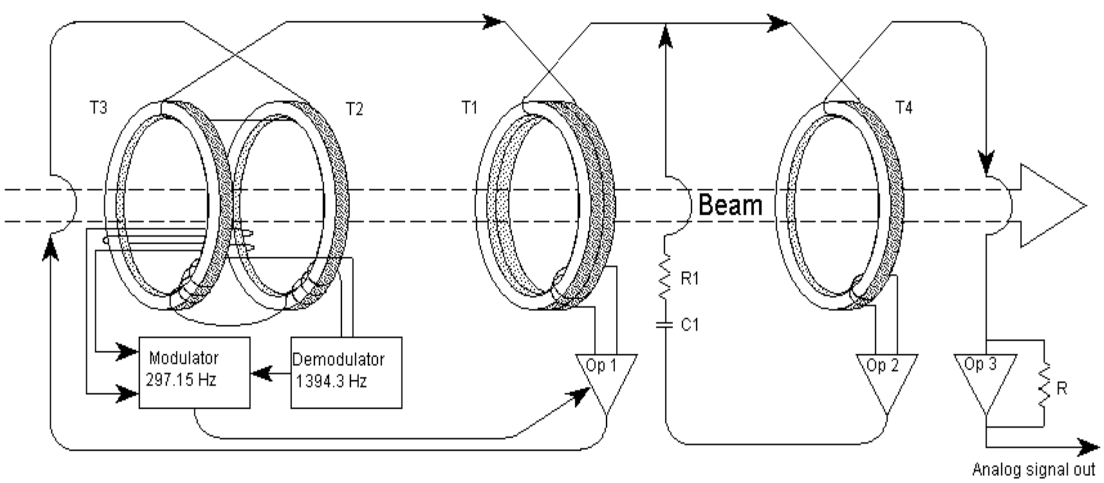

Figure 7.1 DCCT electronics

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 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.

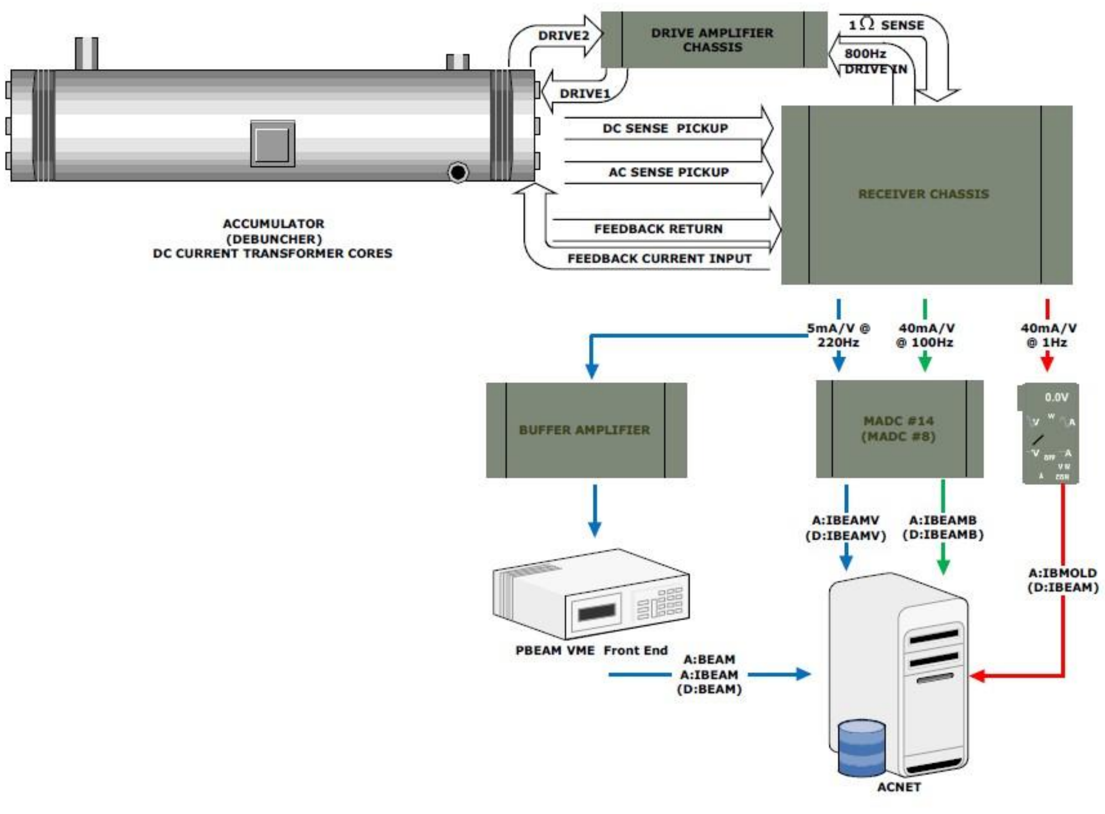

Figure 7.2 Accumulator and Debuncher DCCT layouts[27]

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 oversamples 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 which 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 oversamples 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

2. 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 can add an offset to this toroid signal. 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.

3. 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

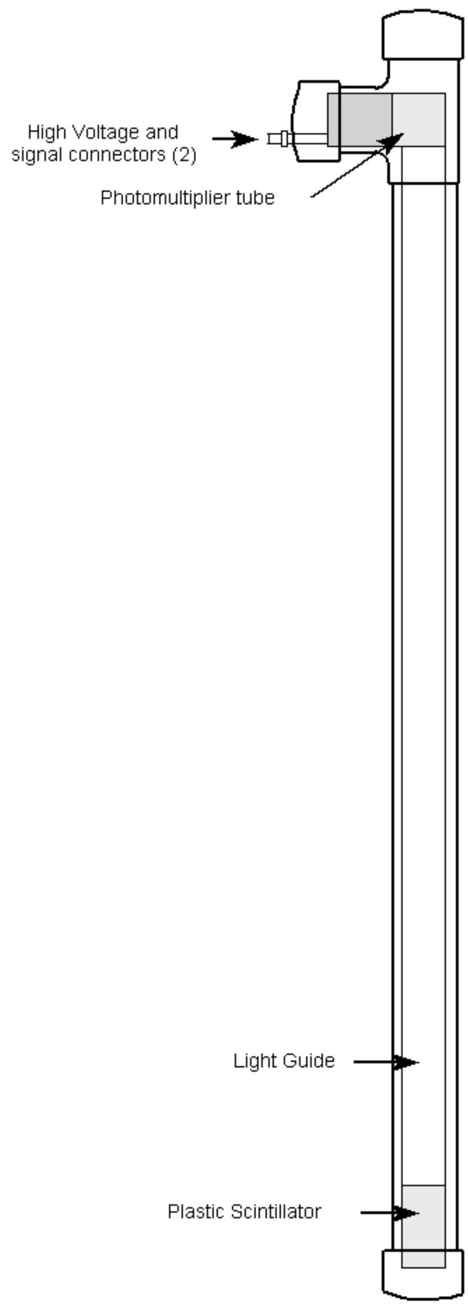

Figure 7.3 Accumulator and Debuncher BLM's

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"x1/2" 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 PMT's 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.

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 which allows the gains of all the PMT's 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 BLM's. 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}>).

B. 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.

1. 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 BPM's 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 BPM's 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 BPM's are 10 x 30 cm rectangles, Accumulator low dispersion BPM's are cylindrical and have a 13 cm diameter, Debuncher BPM's are cylindrical with an 18 cm diameter. BPM's can also be found in the AP1, 2 and 3 beamlines. The AP-1 line has 7.6 cm diameter combined horizontal and vertical BPM's 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.

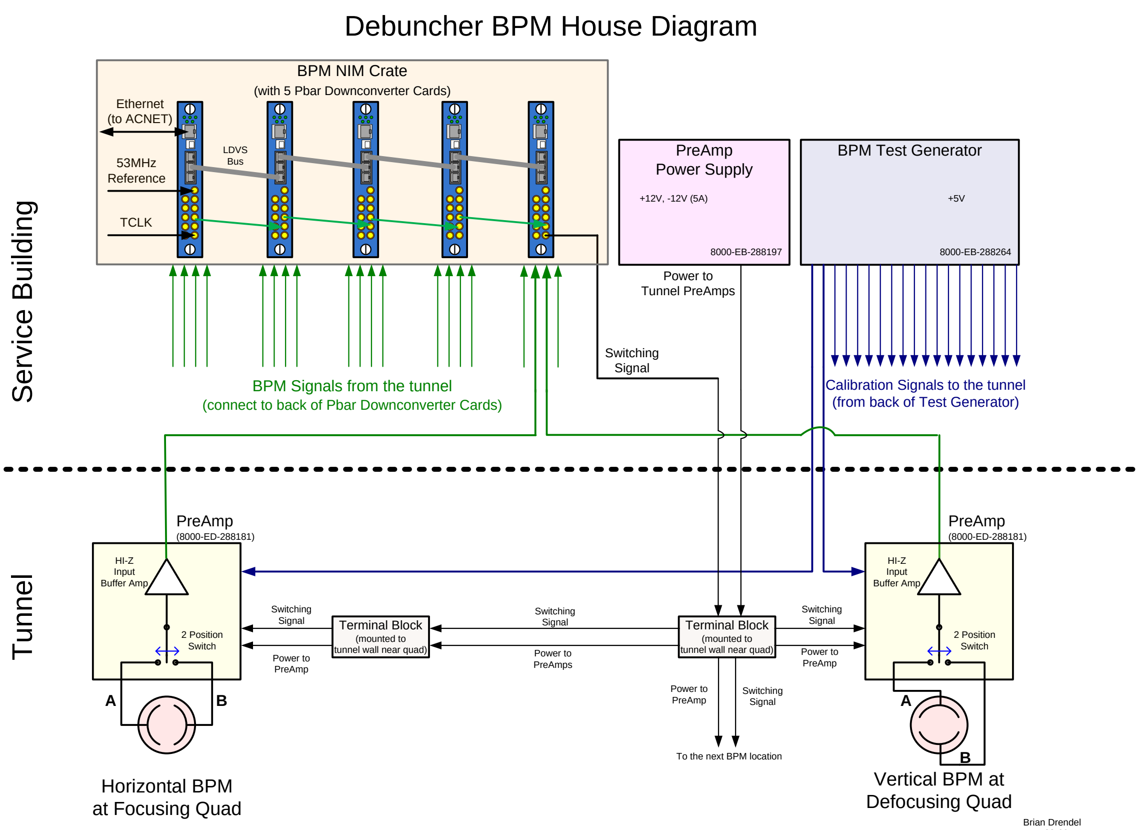

Figure 7.4 Debuncher BPM layout for one house
(only two of twenty BPM's are shown)

a. 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:

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 Downconverter cards in a 5U NIM crate. The Pbar Downconverter 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 Downconverter Card based system in November 2008. This upgrade allows the use of Debuncher BPM's for both reverse protons and stacked pbars.

Each downconverter 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 downconverter card serves as the "master" and the other downconverter cards act as "targets." The "master" downconverter 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" downconverter card also receives a

53.1MHz reference signal which is sourced and fanned out from the A10 BPM house. Each downconverter 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 downconverter module can decode signals from four BPM units.

The "master" downconverter card connects to the "target" downconverter 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 Downconverter 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" downconverter 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 AP2BPM Java Open Access Client (OAC) pseudo front end which 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.

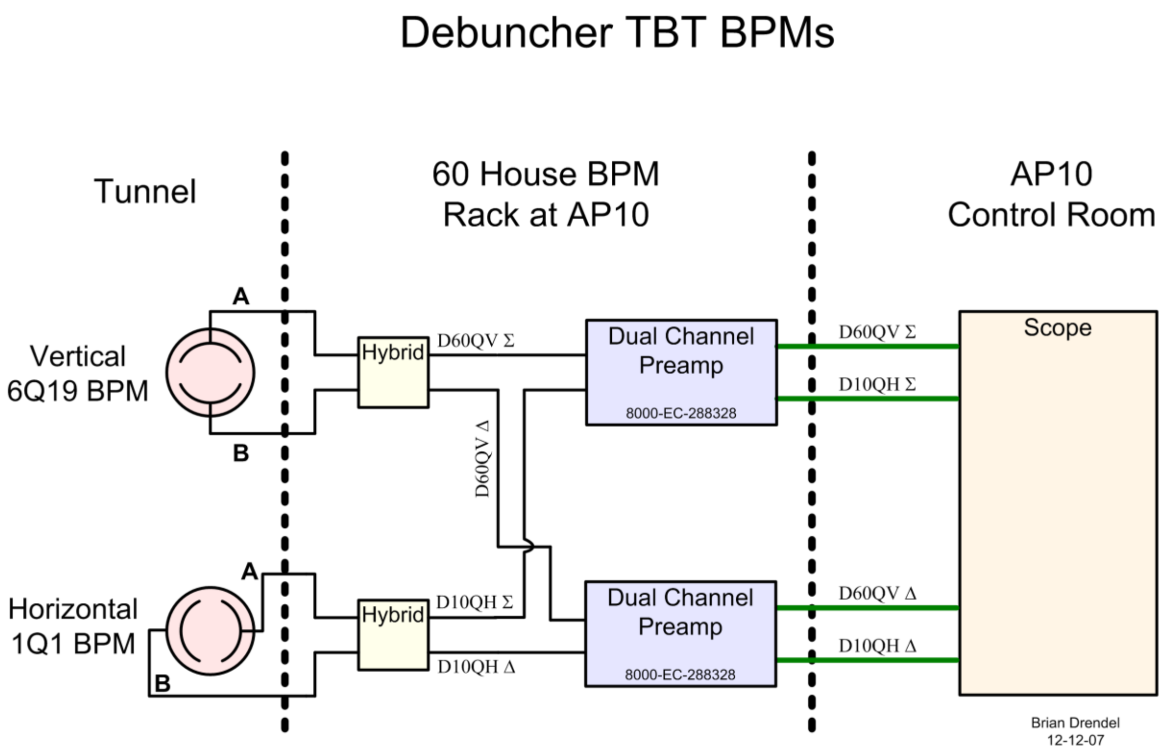

Figure 7.5 Debuncher TBT BPM's

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.

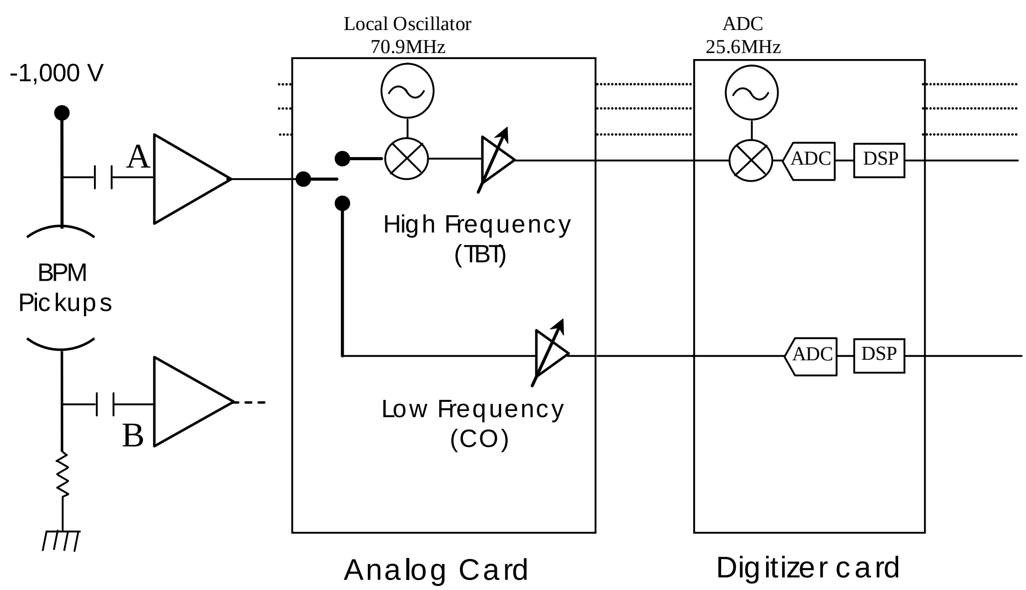

Figure 7.6 Accumulator BPM block diagram

b. Accumulator

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) which 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 which allows the VXI crate to communicate with ACNET and an Ethernet interface which 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 which 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).

c. 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.

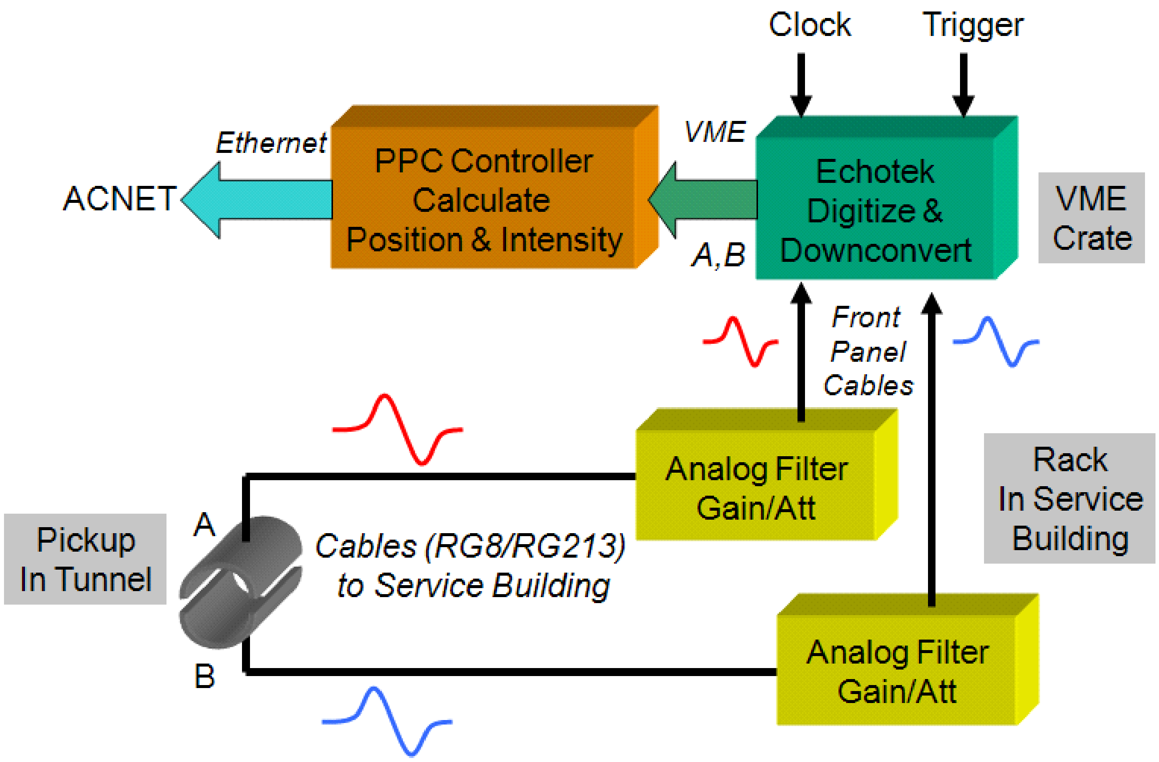

Figure 7.7 Echotek Beamline BPM's
(diagram courtesy of Beams Document Database #1849)

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) which 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 Tuneup application (currently P150).

d. 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 BPM's 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 downconverter 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 which 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).

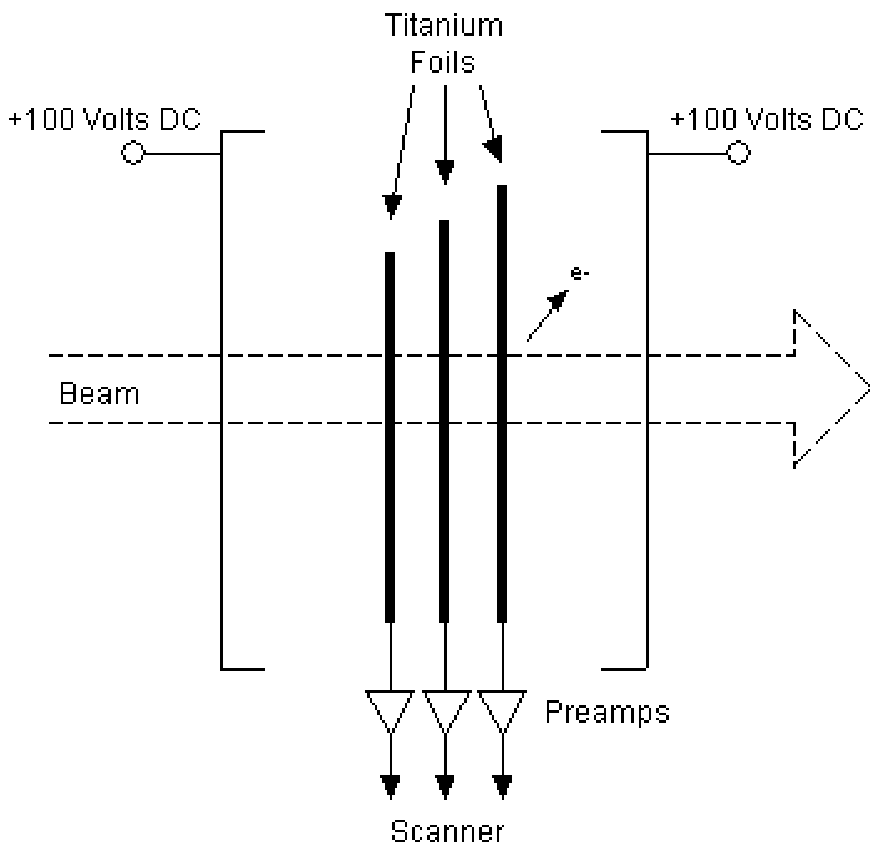

Figure 7.8 SEM grid

2. 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.

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.

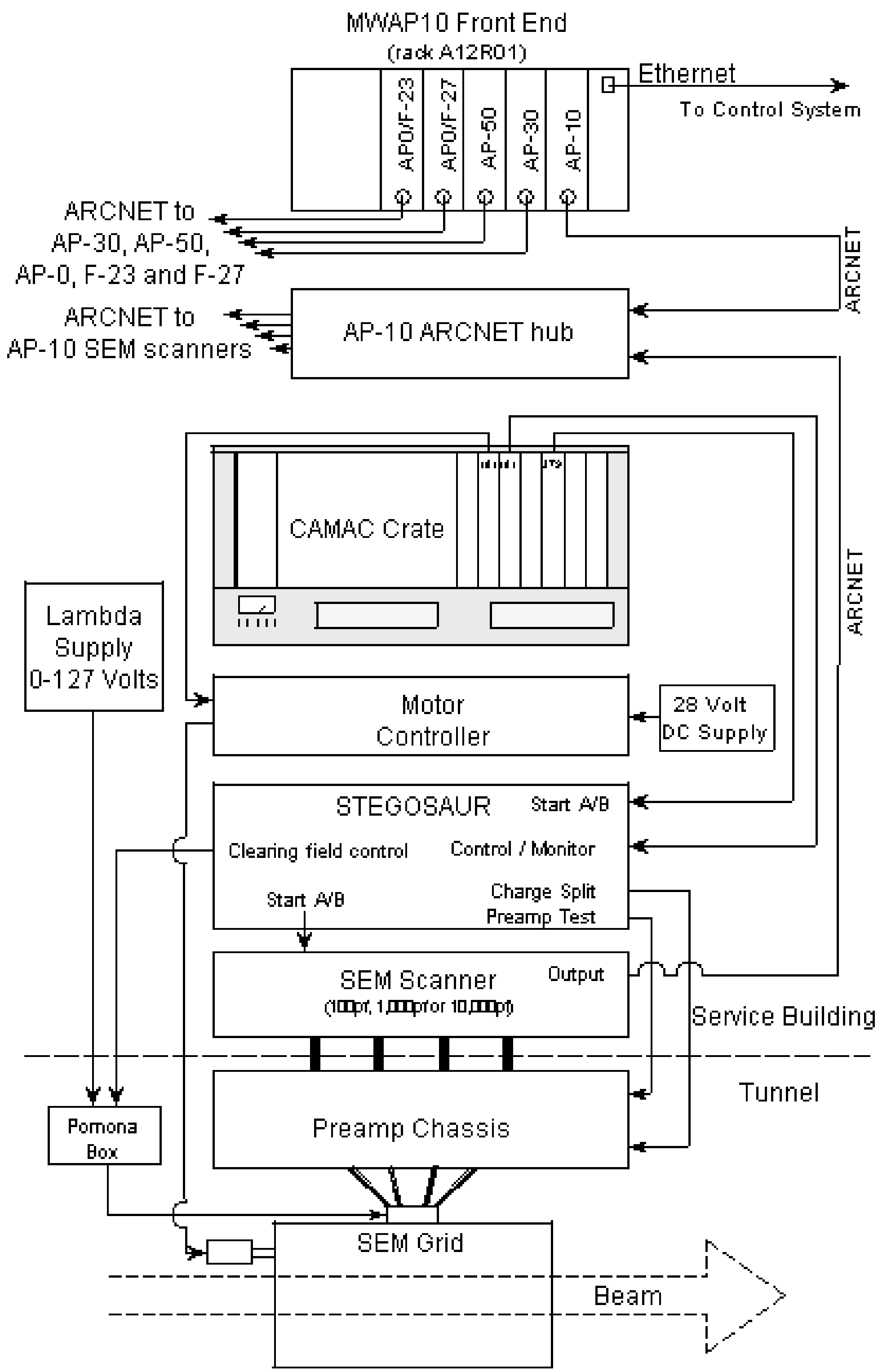

Figure 7.9 SEM electronics and control

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.

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 which 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 SEM’s in and out, display SEM profiles and adjust timing.

3. 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. 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 which 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.

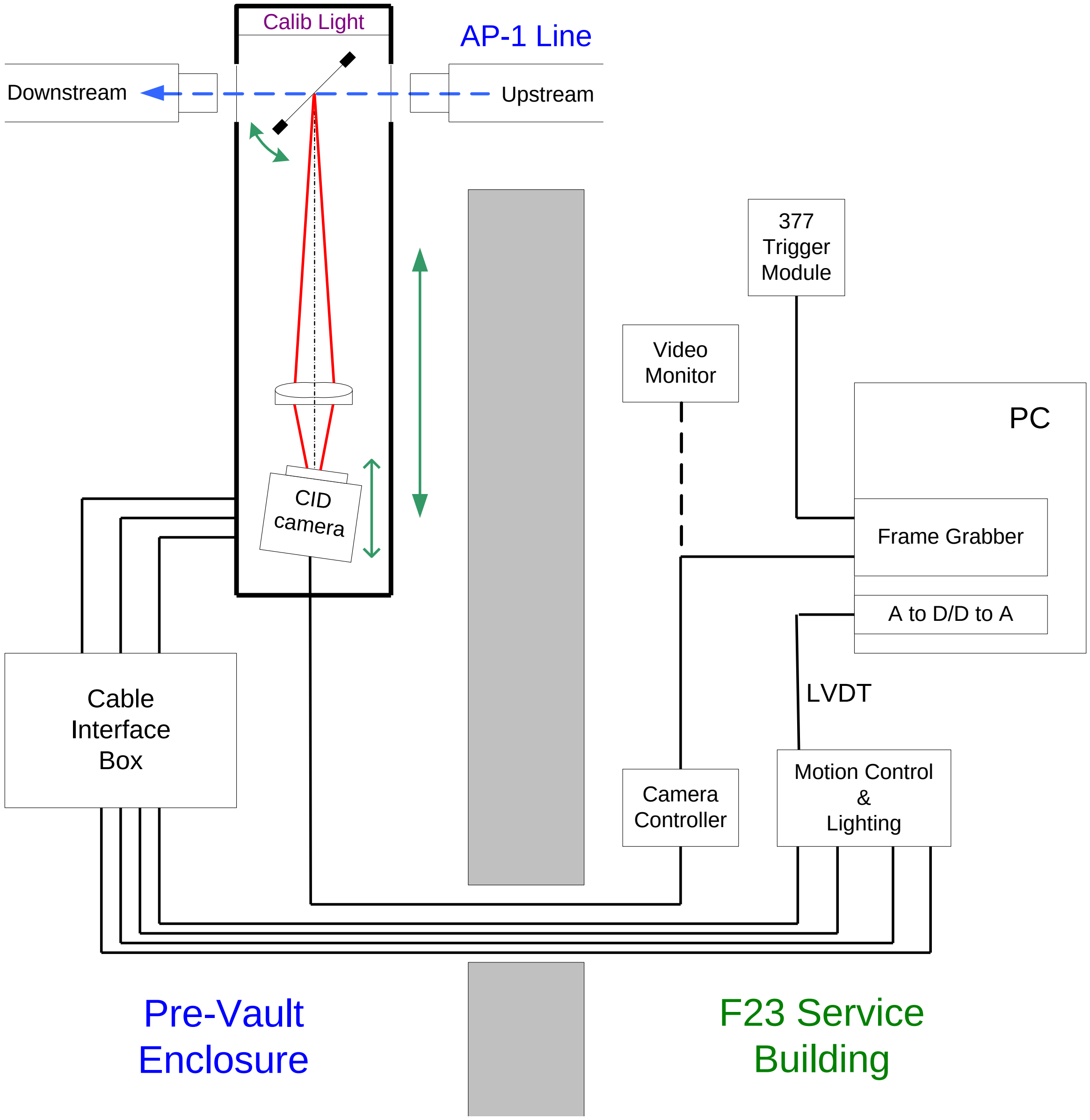

Figure 7.10 OTR Block Diagram
(diagram courtesy of Beams Document Database #2110)

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.

4. 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.

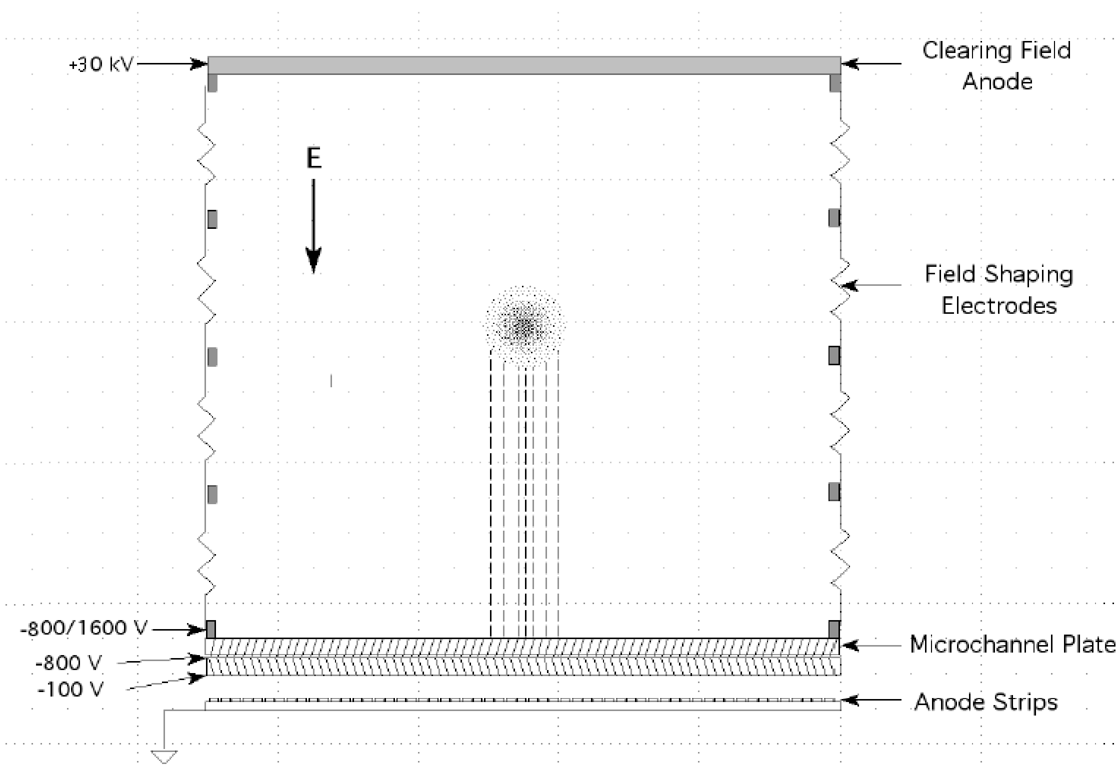

Figure 7.11 IPM components

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 IPMViewer.

5. 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 which 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.

6. 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 decohere very quickly. Although the skew quad pickup is currently not used, it is available for use as a fast broadband pickup.

C. 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.

1. 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.

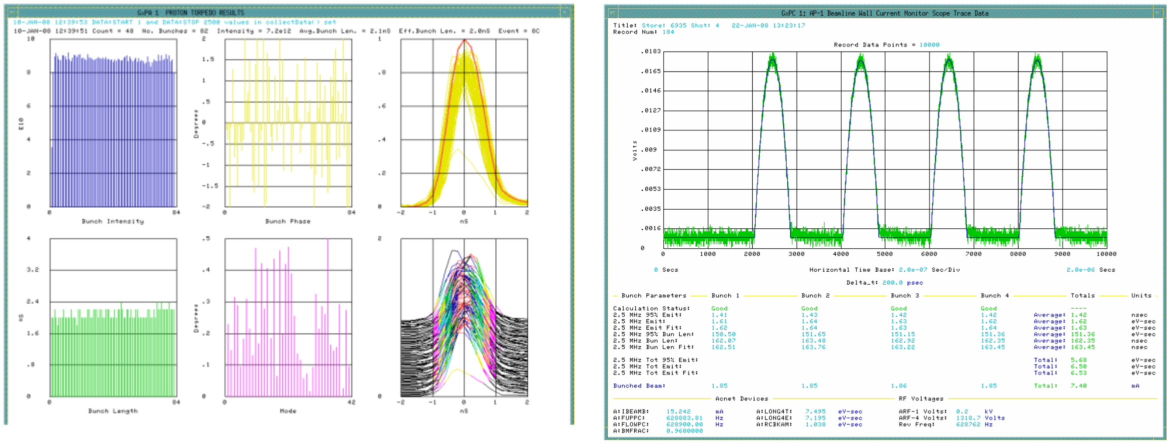

Figure 7.12 AP-1 Wall current monitor displays for
120 GeV protons (left) and 8 GeV unstacked pbars (right)

2. 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. It is used by three diagnostic tools: the Debucher 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 bullseye plot that can be used to reduce Debuncher Injection turn by turn oscillations.

D. 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.

1. 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	F_{rev} (Hz)	Momentum (MeV/c)
Debuncher	0.006	590,018	8886
Accumulator (Injection Orbit)	0.0159	628,767	8886
Accumlator (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.

Schottky 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

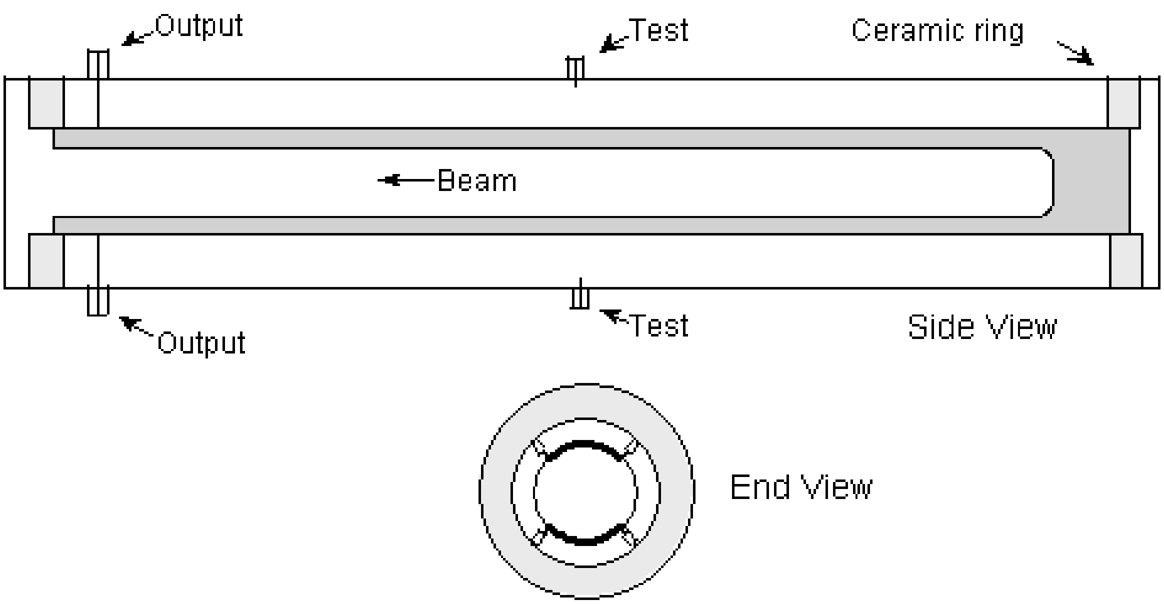

Figure 7.13 Vertical Schottky detector

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 schottkys 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.

2. 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.

E. 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.

1. 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).

1. Network Analyzer

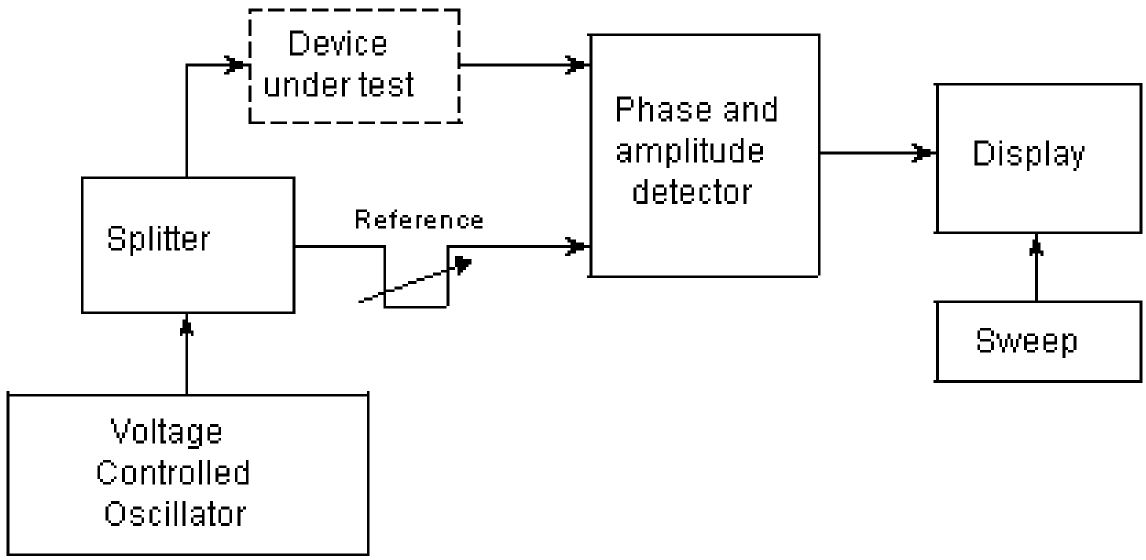

Figure 7.14 Network Analyzer block diagram

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.

2. 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 VSA's used in Pbar. The first VSA is the D to A VSA which is used in the Accumulator/Debuncher energy alignment procedure. This VSA displays two traces as shown in Figure 7.15. 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).

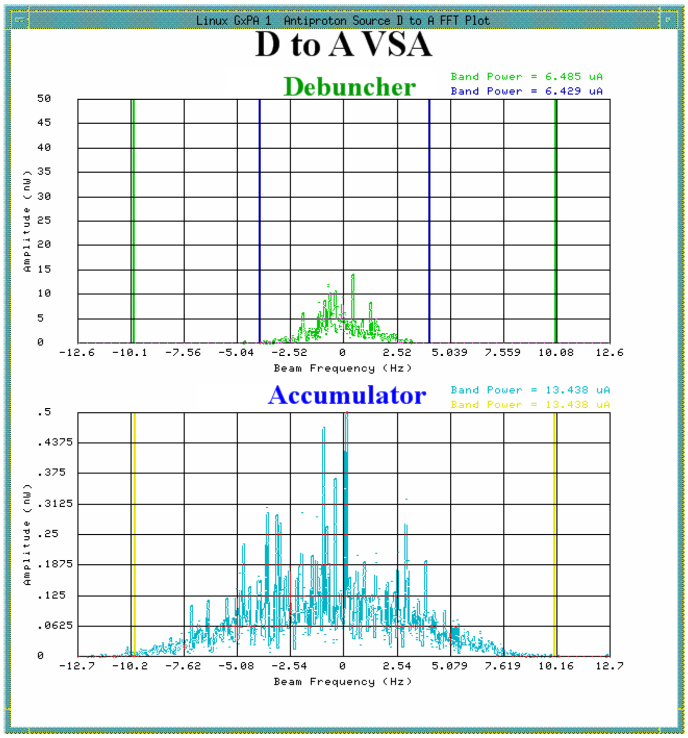

Figure 7.15 D to A VSA display

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 which 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 which is launched from the VSA ACC LONG PROF application (currently P142). In this mode, the VSA display updates every stacking cycle. 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.

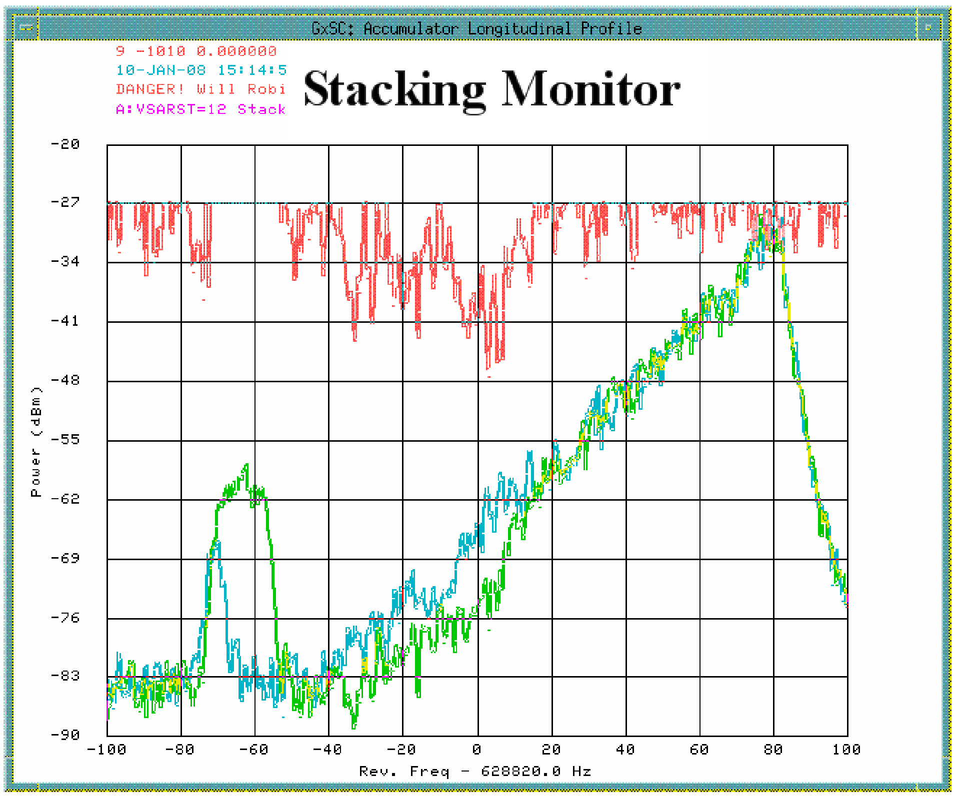

Figure 7.16 Stacking Monitor display

The stacking VSA outputs a number of parameters which 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 "backstreaming". 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 backstreaming. Lastly, the core calculations are done around 20dB of the maximum density. A:CENFRQ is the mean frequency of the core.

F. 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.

1. 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), that 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.

2. 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 outgasses 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 BPM's 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 at small stack sizes and as much as 100 volts or more at 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.

G. Beam Shaping Devices

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

1. 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).

2. 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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