IV. Accumulator

A. 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

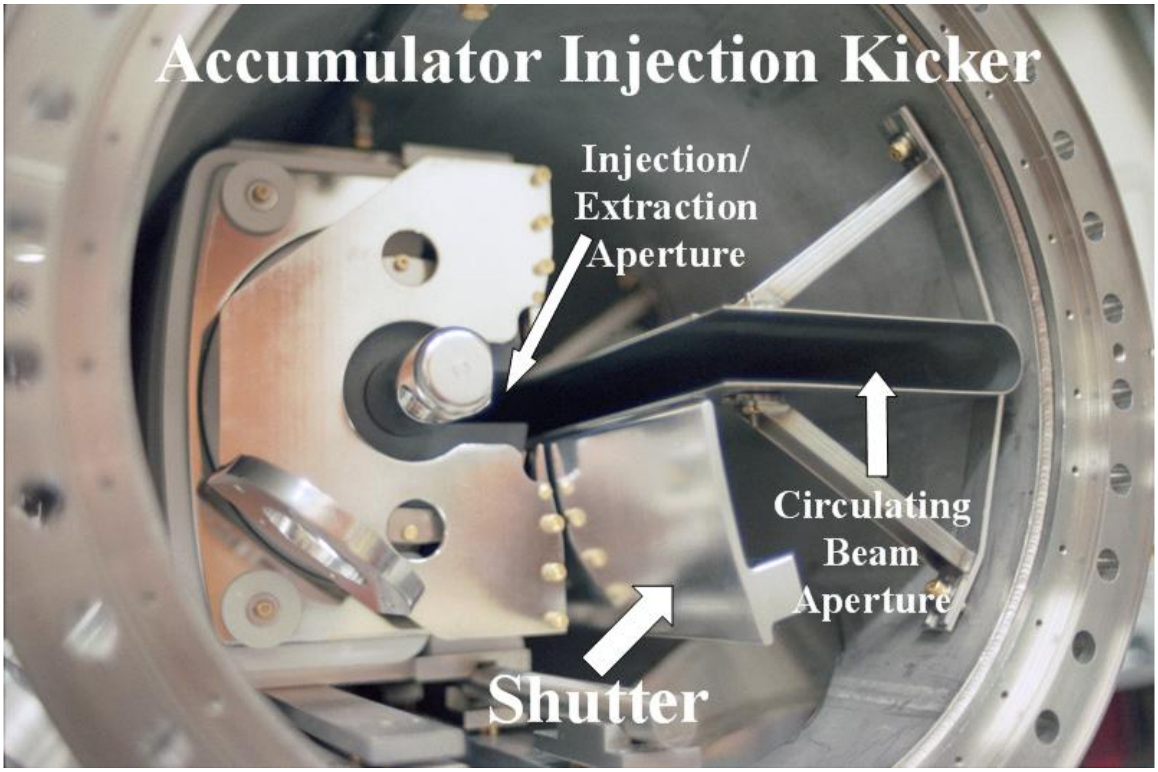

Figure 4.1 Accumulator Injection Kicker

injection orbit to the deposition orbit. Operationally 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.

4) The stacktail momentum cooling system now acts on the pbars. This system decelerates the beam towards the core, which is

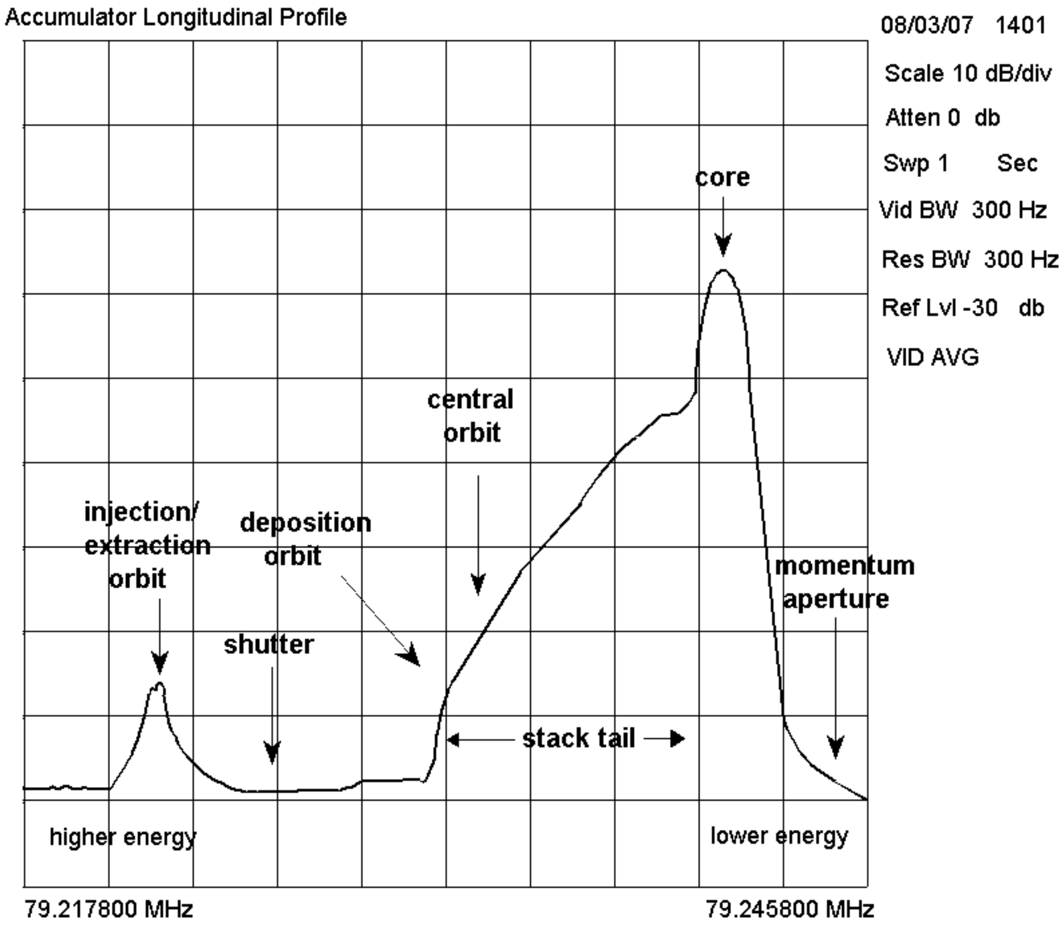

Figure 4.2 Accumulator stack profile

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.

B. 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 π/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.

Low dispersion regions can be used by cooling systems 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 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

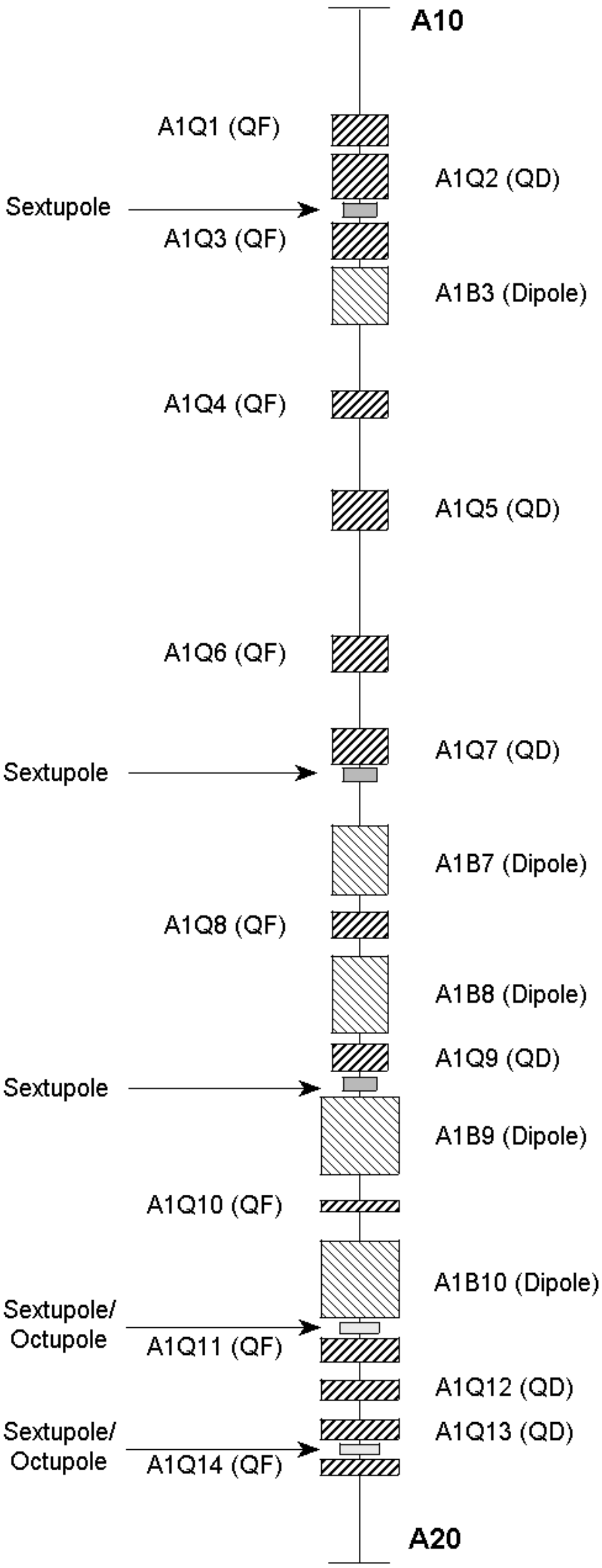

Figure 4.3 Accumulator lattice

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.

C. Power supplies

The main dipoles and quadrupoles in the Accumulator are powered by four different power supplies, 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 A 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 ν_x = 6.683 and ν_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 ν_x = .66 and ν_y = .66 are 3rd, 6th or 9th order resonance lines; the lines the intersect ν_x = .7 and ν_y = .7 are 10th order resonances lines; the lines that intersect ν_x = .714 and ν_y = .714 are 7th order resonances. By far the strongest of the resonance lines, the main 2/3rd resonances are shown in bold.

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

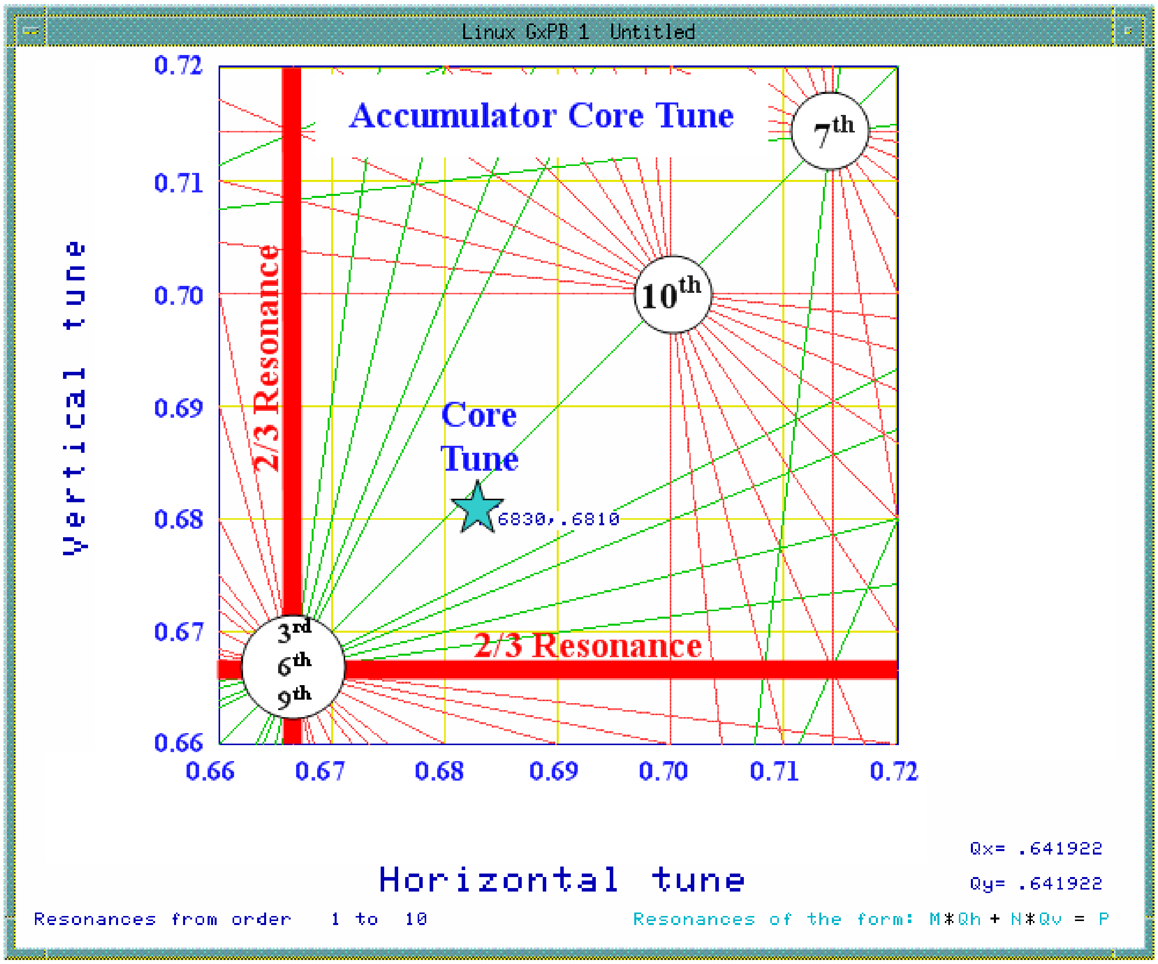

Figure 4.4 Nominal Accumulator tune

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.

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

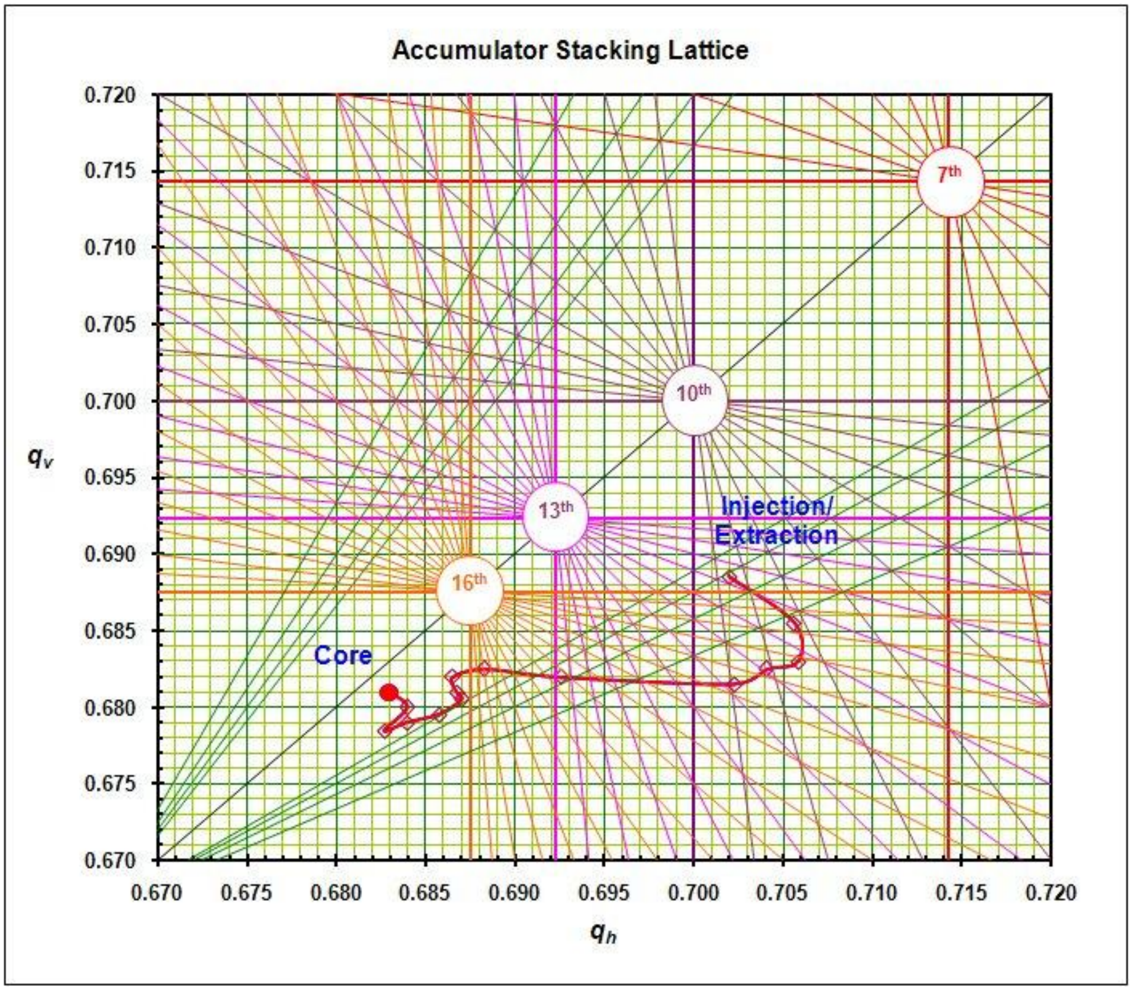

Figure 4.5 Accumulator tunes across the momentum aperture

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 which 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 LQF's 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

D. RF systems

1. 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

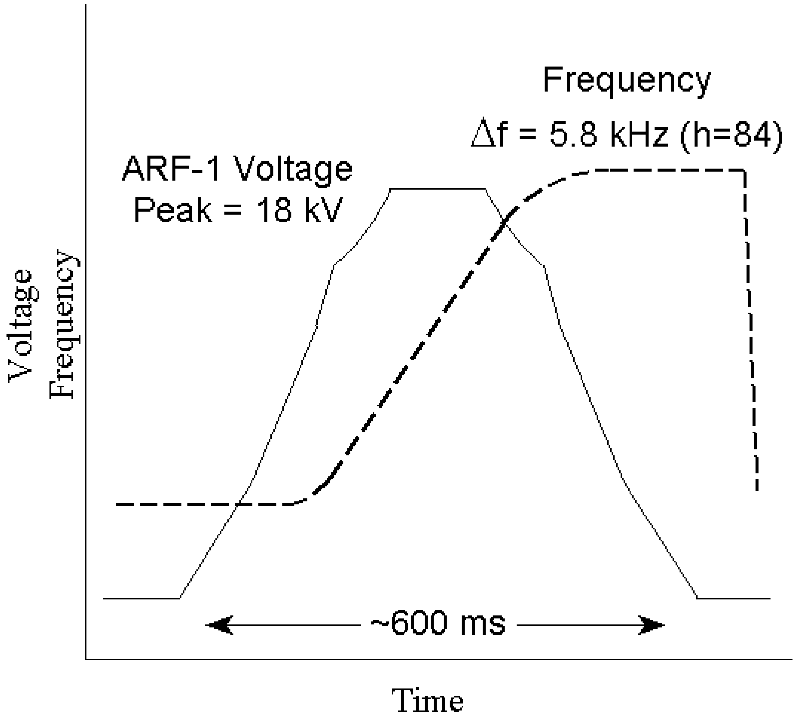

Figure 4.6 ARF-1 voltage and frequency waveforms

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.

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 both a DAC (A:R1LLFR) or a 164 card (A:R164FR).

2. 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.

Amplitude control of ARF-2 can be switched to either a DAC (A:R2LLAM)

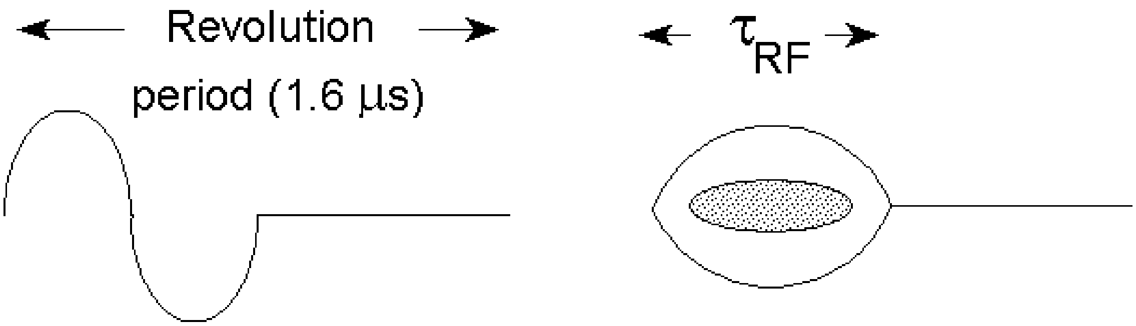

Figure 4.7 ARF-2 structure

or a 164 card (A:R264AM). The frequency inputs are provided by a DDS which can be set to a DC level or ramped (A:R2DDS1).

3. 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.

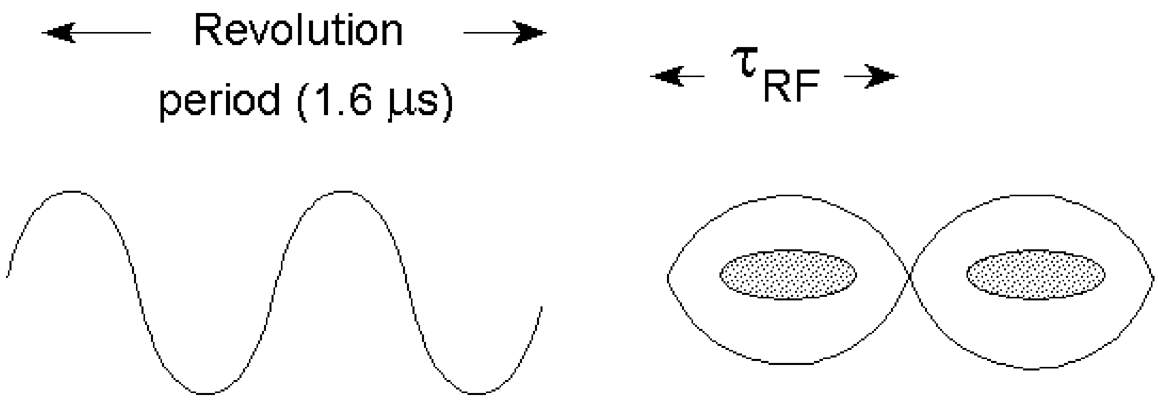

Figure 4.8 ARF-3 structure

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).

3. 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).

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

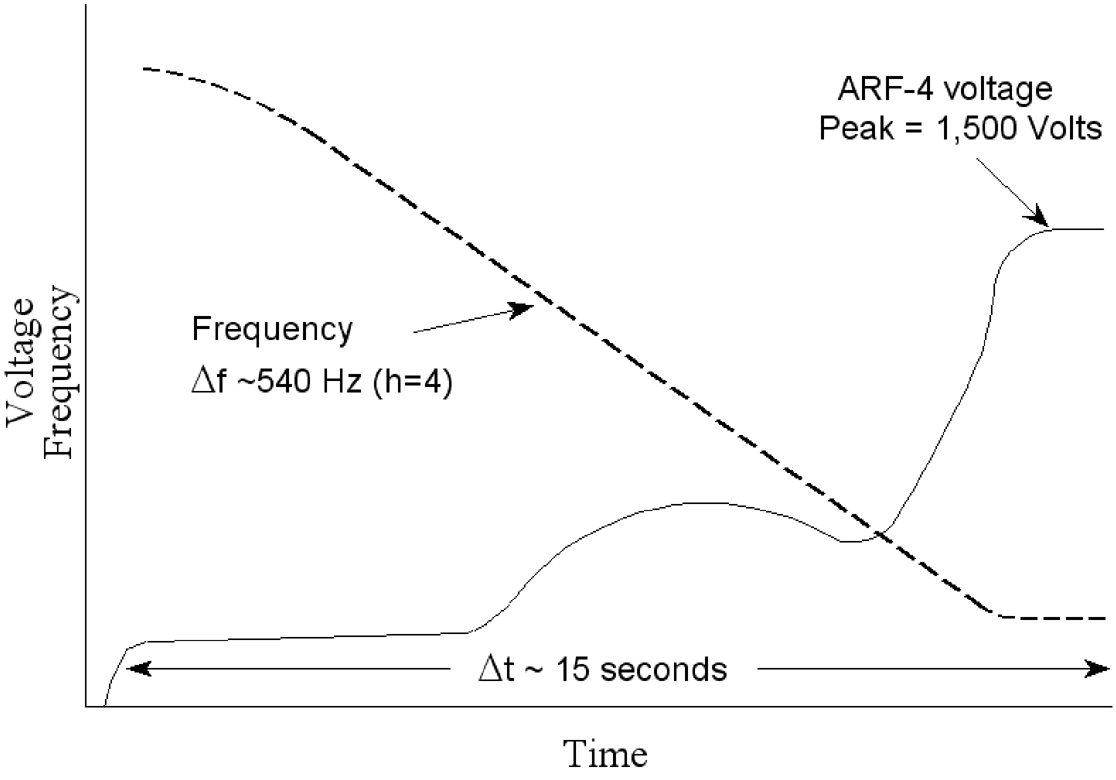

Figure 4.9 ARF-4 waveforms during extraction

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.