III. Debuncher

A. Function

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

B. Lattice

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

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

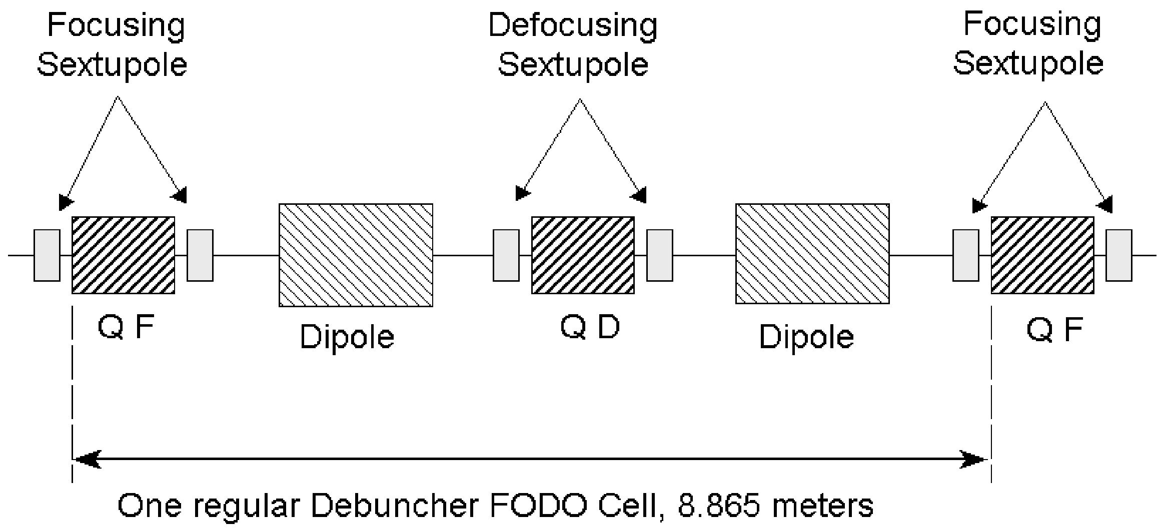

Figure 3.1 Debuncher lattice in the arcs

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

C. Power supplies

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

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

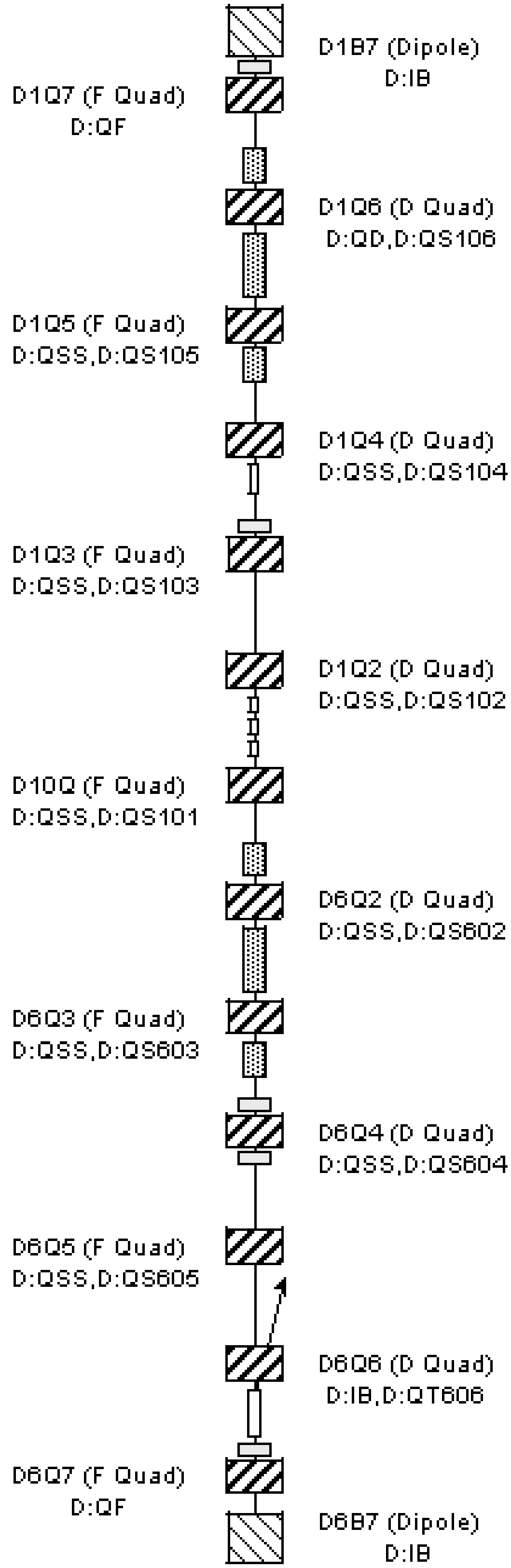

Figure 3.2 D10 straight section

trim supplies produces about 1,500A.

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

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

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

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

D. RF systems

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

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

Table 3.1 Debuncher RF systems

1. DRF-1

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

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

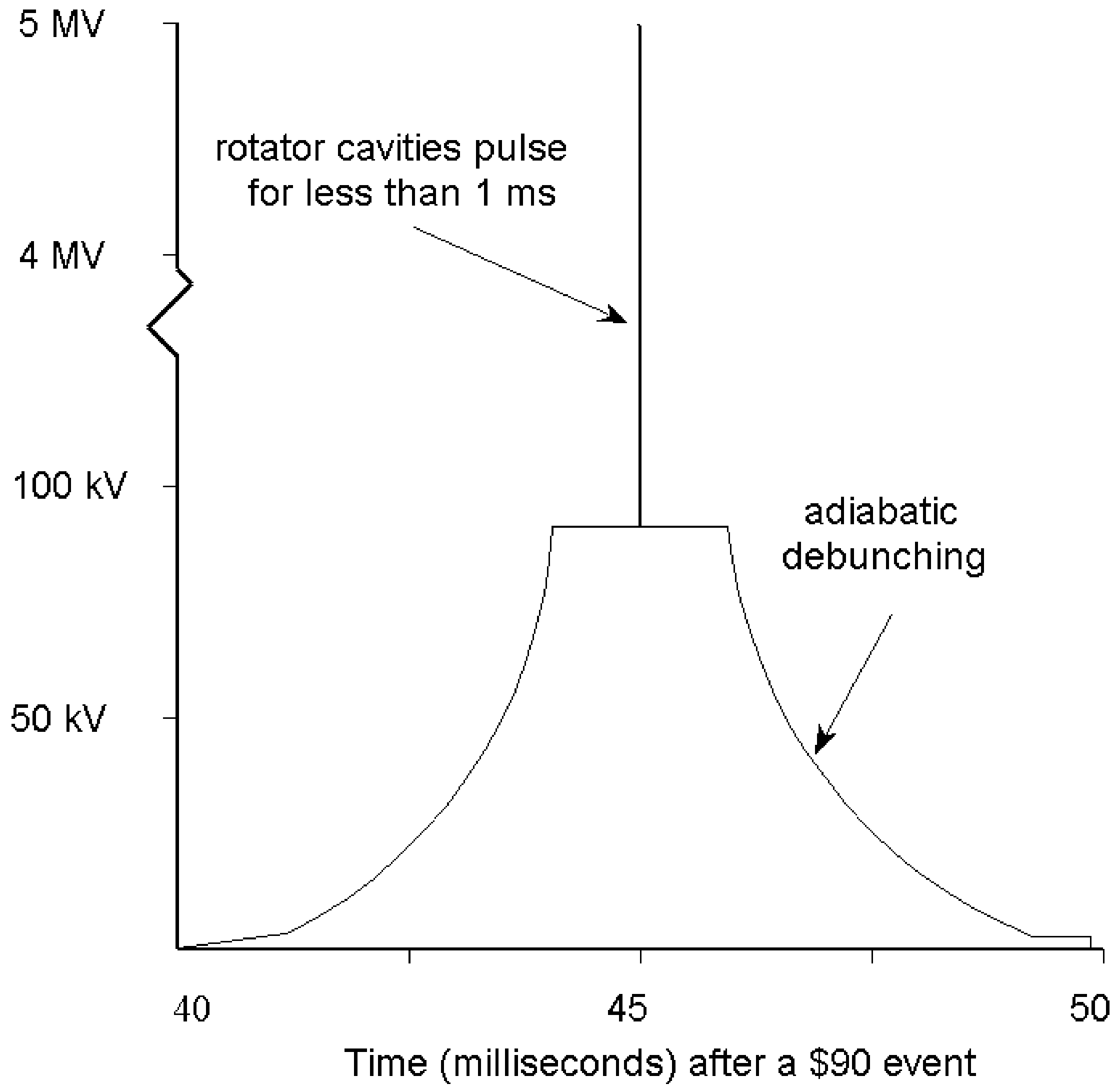

Figure 3.3 DRF-1 cavity voltage during bunch rotation

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

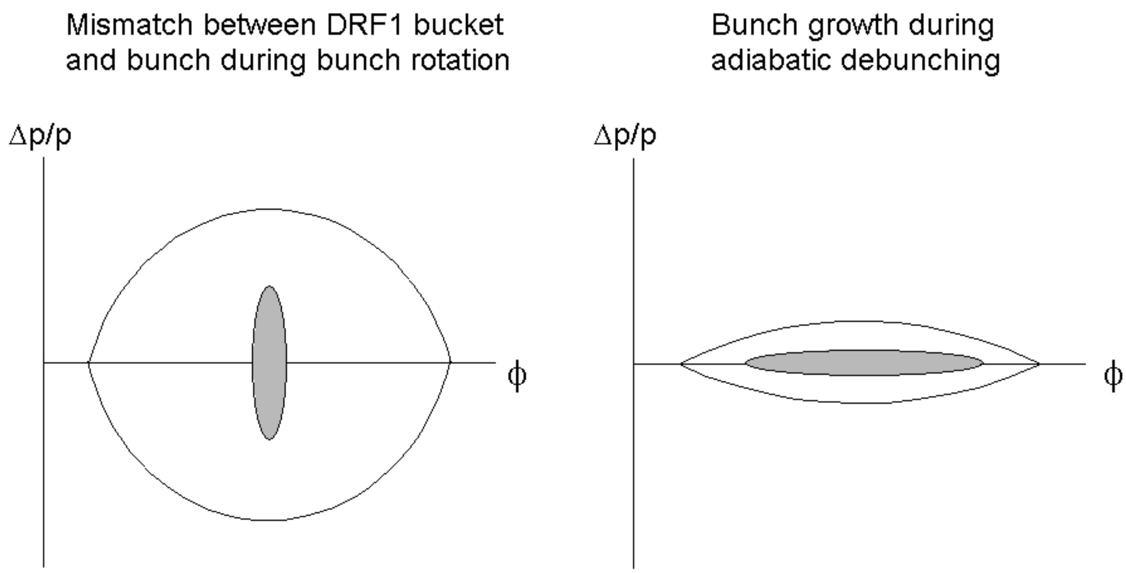

Figure 3.4 Bunch rotation in the Debuncher

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

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

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

There presently isn't a good quantitative way to determine how efficient the bunch rotation process is. Figure 3.5 shows a typical spectrum analyzer

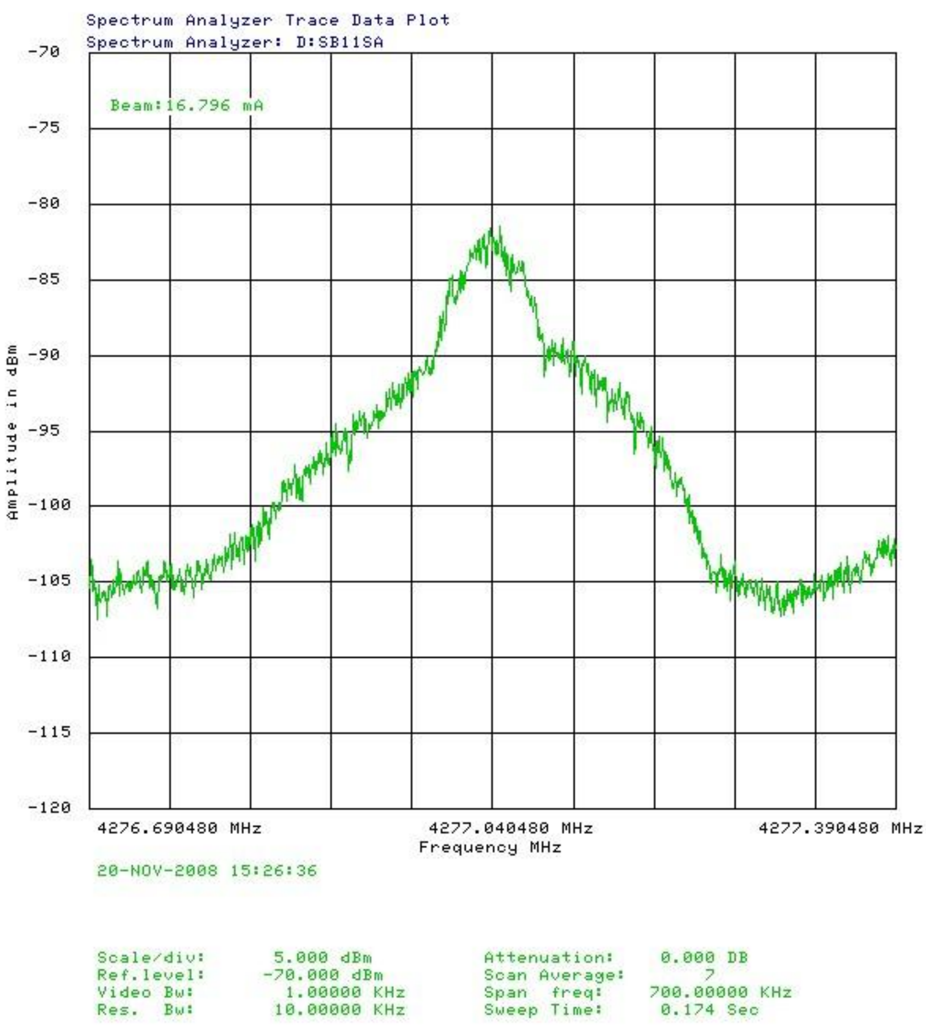

Figure 3.5 Debuncher bunch rotation spectrum analyzer display

display of the frequency distribution of the Debuncher beam. The signal comes from a cooling pickup, so the frequencies displayed are harmonics of the revolution frequency in the microwave range. This display can be used as a qualitative measure of how well the bunch rotation process is working. Two DRF-1 parameters can be tuned to maximize the bunch rotation efficiency. D:R1LLPS is the phase offset between the Main Injector and Debuncher low level RF and is tuned to optimize bucket to bucket transfer. D:R1LLMT is the master trigger time and controls when the DRF-1 rotator cavities are pulsed. By synchronizing the peak RF voltage (and bucket area) to the arrival of the beam, capture can be maximized. A narrower distribution on the spectrum analyzer display, available on Cable Television (CATV) Pbar channel 20, indicates more efficient bunch rotation. Beam quality in the Main Injector is also important. A program called the "Proton Torpedo" on page P194 is used to check Main Injector longitudinal beam quality.

2. DRF-2

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

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

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

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

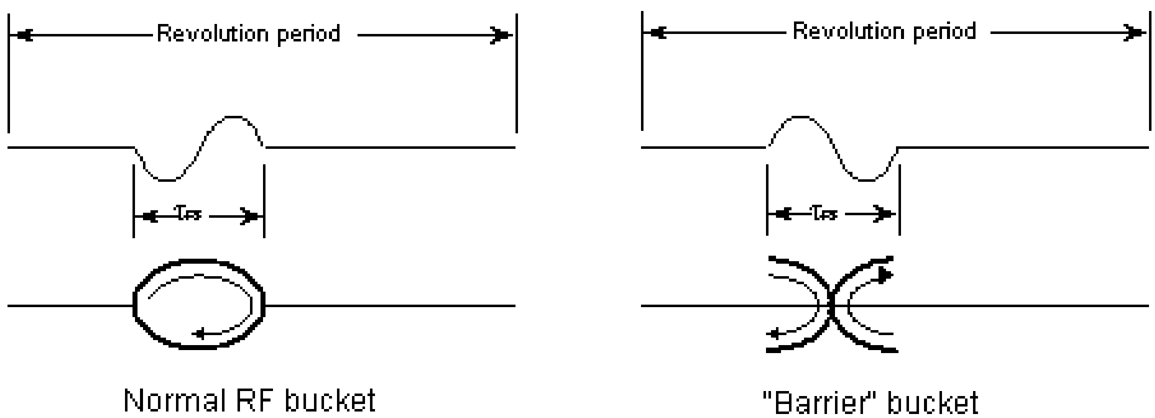

Figure 3.6 DRF-2 barrier bucket

3. DRF-3

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

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