2. Accelerator Physics

The purpose of the Recycler ring is to improve the luminosity performance of the Tevatron Collider during Run II. The design luminosity of $2x10^{32}$ cm^{-2} sec^{-1} is accomplished by creating more antiprotons at a faster rate, storing existing antiprotons in a more reliable fashion, and recycling antiprotons remaining in the Tevatron at the end of stores. The Recycler ring plays a major role in each of these three areas of improvement.

In this chapter the role of accelerator physics and novel technologies in the Recycler are reviewed. This discussion starts with a detailed overview of the operational role of the Recycler during Run II. Next, the beam manipulations and accelerator technology crucial to the Recycler are described.

2.1. Operational Overview

In order to describe the operational role of the Recycler ring, it is necessary to explain the intricately interweaved operation of all of the particle accelerators in the entire accelerator complex. It is convenient to start this discussion when the Tevatron has just started a new store.

2.1.1. Operational Goals

The purpose of the Fermi III accelerator upgrades is to maximize the luminosity of the Tevatron Collider. In the absence of a crossing angle the luminosity per interaction region L is determined by the equation

$$L = \frac{N_p(N_a B) f_o (6\beta_r\gamma_r)}{2\pi\, \beta^*(\varepsilon_{np}+\varepsilon_{na})} H\left(\frac{\beta^*}{\sqrt{\frac{1}{2}\left(\sigma_{sp}^2+\sigma_{sa}^2\right)}}\right) \quad , \qquad (2.1.1)$$

in which $N_{p,a}$ is the number of protons and antiprotons per bunch, B is the number of bunches per beam, f_o is the revolution frequency of the Tevatron, β_r and γ_r are the relativistic velocity and energy of the beam, β^* is the value of the beta function at the interaction points, $\varepsilon_{np,na}$ are the proton and antiproton 95% normalized transverse emittances, σ_s is the rms bunch length, and the hour-glass luminosity form factor has the form

$$H(x) = \sqrt{\pi}\, x[1-\Phi(x)]\, e^{x^2} \quad , \qquad (2.1.2)$$

where $\Phi(x)$ is the error function. The transverse emittance is defined so that the transverse rms bunch widths are calculated using the equation

$$\sigma_{a,p}^2 = \beta^* \frac{\varepsilon_{na,np}}{(6\beta_r\gamma_r)} \quad . \qquad (2.1.3)$$

The values for all of these parameters at the beginning of a store for Run I operations, anticipated after completion of the original Main Injector project, and after commissioning of the Recycler ring are listed in table 2.1.1.

Table 2.1.1: Initial Beam conditions for Run I (recently completed), originally anticipated post-Main Injector Run II, and Run II in which the Recycler ring is operational.

Initial Store Parameters	Run I	MI only	Recycler
N_p Proton Intensity/Bunch (10^9)	250	330	270
N_a Antiproton Intensity/Bunch (10^9)	60	36	66
B Number of Bunches/Beam	6	36	36
Minimum Time between Bunches (ns)	3500	395	395 (132)
E_o Beam Energy (GeV)	900	1000	1000
β^* Interaction Point Beta (cm)	35	35	35
ε_{np} Proton 95% Emittance (π mmmr)	24	30	18
ε_{na} Antiproton 95% Emittance (π mmmr)	15	15	15
σ_{sp} Rms Proton Bunch Length (cm)	50	45	45
σ_{sa} Rms Antiproton Bunch Length (cm)	50	45	33
f_o Revolution Frequency (kHz)	47.7	47.7	47.7
(N_aB) Total Antiproton Intensity (10^{10})	36	130	238
($\beta_r\gamma_r$) Relativistic Momentum	959	1066	1066
H Hour Glass Form Factor	0.65	0.69	0.72
L Peak Luminosity (10^{32} cm^{-2} sec^{-1})	0.19	0.8	2.0
$\int L$ Integrated Luminosity (pb^{-1}/week)	3.8	17	40
N_{IR} Number of interaction Regions	2	2	2

The quantity N_aB (called the stack size) in equation (2.1.1) is just the total antiproton intensity injected into the Tevatron Collider, independent of the number of bunches that charge is divided into. Note that the luminosity grows proportionally with this number, the fact which is the basis of the luminosity improvement generated by the Recycler ring. This relationship between luminosity and antiproton availability is due to the fact that the proton intensity is limited.

The limit on the proton intensity comes from the observation that the maximum allowable total antiproton linear beam-beam tune shift from all bunch crossings with the proton bunches is approximately 0.026. The equation relating this maximum antiproton total tune shift ξ_{max} and the proton intensity is

$$\xi_{max} = \frac{r_o}{4\pi} \frac{N_p}{\varepsilon_{np}} N_{IR} \quad . \qquad (2.1.4)$$

The quantity r_o is the classical radius of the proton (1.53×10^{-18} m). The number of interaction regions N_{IR} is at a minimum equal to the number of high energy physics detectors operating in the collider. Plugging this equation for the tune shift into the equation for luminosity per interaction region (2.1.1) yields the result

$$L = \frac{(N_a B)}{N_{IR}\,\beta^*}\,\frac{2\xi_{max}\,f_o(6\beta_r\gamma_r)}{r_o\left(1+\frac{\varepsilon_{na}}{\varepsilon_{np}}\right)}\,H\left(\frac{\beta^*}{\sqrt{\frac{1}{2}\left(\sigma_{sp}^2+\sigma_{sa}^2\right)}}\right) \quad , \qquad (2.1.5)$$

where the factors whose values can be significantly modified appear in the left fraction on the right hand side of the equation. The emittances of the protons and antiprotons can be changed, but the ratio of the proton to antiproton emittances is always near unity due to nonlinear beam dynamics concerns. Therefore, reducing the emittances of the beams is not helpful once the beam-beam limit has been reached.

Even though β^* can be changed, eventually the length of the bunch and the sensitivity of the lattice to errors in low-β quadrupole strengths limits the extent to which β^* can be reduced. The number of interaction regions is chosen by the high energy physics community. Note that for a uniform β^* in all detectors, the sum of the luminosity available in the Tevatron Collider at all interaction regions is conserved as the number of interaction regions is changed.

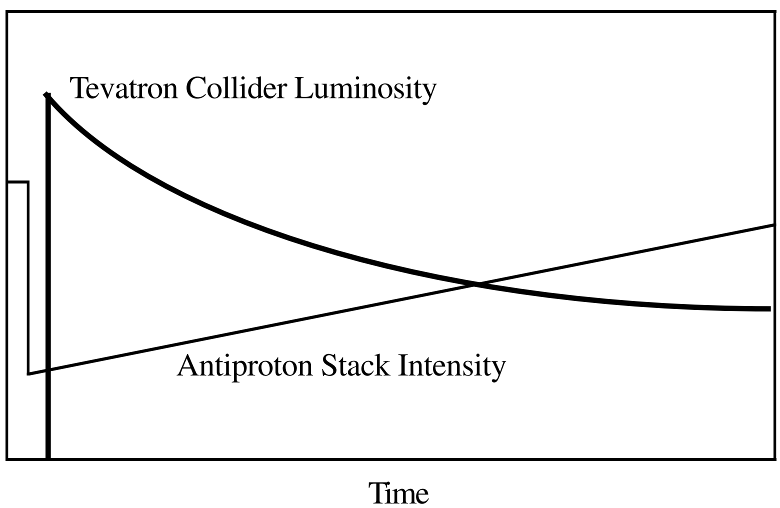

Figure 2.1.1: Sketch of antiproton stacking during Tevatron Collider stores. At the beginning of each store some of the stacked antiprotons are delivered to the Tevatron. During the store those antiprotons are replenished via continuous Main Injector operations.

2.1.2. Antiproton Stacking

As demonstrated in the previous section, the dominant limitation to high luminosity operations in proton-antiproton colliders is the availability of bright (high current and low emittance) antiproton beams. Antiprotons are produced by aiming 120 GeV protons from the Main Injector onto a metallic target. For every million protons, approximately 15 antiprotons are captured, cooled, and stored for future use. Because of this very small yield, antiproton production must occur continuously while the Tevatron is storing beam and creating proton-antiproton collisions for high energy physicists.

While the Tevatron is storing beam at an energy of 1 TeV, the Main Injector is continuously cycling. Every ~2 seconds the Main Injector accelerates protons from a kinetic energy of 8 GeV to the required 120 GeV for antiproton production. The 8 GeV kinetic energy antiprotons from the target are cooled and stored (stacked) in the Debuncher and Accumulator rings. As the Tevatron stores the beam the luminosity decreases due to particle loss and emittance growth. Therefore, a certain antiproton stacking rate is required to keep the Tevatron operating at a determined typical peak luminosity level. Figure 2.1.1 contains a sketch of the Tevatron luminosity and antiproton stack size during collider operations.

2.1.3. Luminosity Evolution

The evolution of the luminosity and antiproton intensity during a Tevatron Collider store is determined by the luminosity itself, intrabeam scattering, external transverse and longitudinal emittance growth mechanisms, and the length of the store. The parameters which depend on luminosity itself are the proton and antiproton intensity lifetimes. The central purpose of the Tevatron Collider is to collide protons and antiprotons, using them up at the rate of

$$R_{lost} = N_{IR}\, L\, \sigma_{lost} \quad , \qquad (2.1.6)$$

where σ_{lost} is the 78 mb cross-section [E811 collaboration] for losing protons and antiprotons due to both inelastic and large elastic interactions and N_{IR} is the number of interaction regions in the Collider. The proton and antiproton intensity lifetimes due to this mechanism are calculated using the equation

$$\tau_{Lp,La} = \frac{N_{p,a}\, B}{R_{lost}} \quad . \qquad (2.1.7)$$

Another limit to beam intensity lifetime is the residual vacuum in the Tevatron. The vacuum intensity lifetime τ_{vac} is approximately 200 hours at the present time.

The other parameters which vary during a store are the bunch length and the transverse emittance. One mechanism observed to induce emittance growth during a store was external noise. When noise driven coherent betatron and synchrotron oscillations decohere due to nonlinearities, a constant emittance growth rate is established. Over the years this emittance growth rate has been lowered to a fairly insignificant level of 0.3 π mmmr/hr 95% normalized transversely and 0.01 eV-sec/hr 95% normalized longitudinally. Another mechanism is multiple Coulomb scattering against the residual molecules in the vacuum chamber.

The growth times of the transverse and longitudinal emittances due to intrabeam scattering in the Tevatron are described by the equations [D. Finley, TM-1646 (1989)]

$$\tau_{\varepsilon_P} = 0.054\left(\frac{6\text{x}10^{10}}{N_P}\right)\varepsilon_{nP}^{2.24}\ A_P^{0.68} \quad , \quad (2.1.8)$$

$$\tau_{A_P} = 0.103\left(\frac{6\text{x}10^{10}}{N_P}\right)\varepsilon_{nP}^{1.24}\ A_P^{1.68} \quad , \quad (2.1.9)$$

where ε_{np} and A_p are the normalized 95% transverse (π mmmr) and longitudinal (eV-sec) emittances of the protons and the times are in hours. The antiproton growth times are calculated similarly. This equation assumes the Tevatron Collider lattice and an RF voltage of 1 MV/turn.

By including all of the above effects into a calculation of the evolution of the luminosity and beam properties during a collider beam store, predictions can be made. In order to confirm that the factors affecting luminosity evolution are understood, these calculations were applied to the recently completed collider Run I. This model is quantitatively in agreement in all beam parameters in all measured stores in which comparisons have been performed. Therefore, it is with confidence that predictions of Run II performance are presented below.

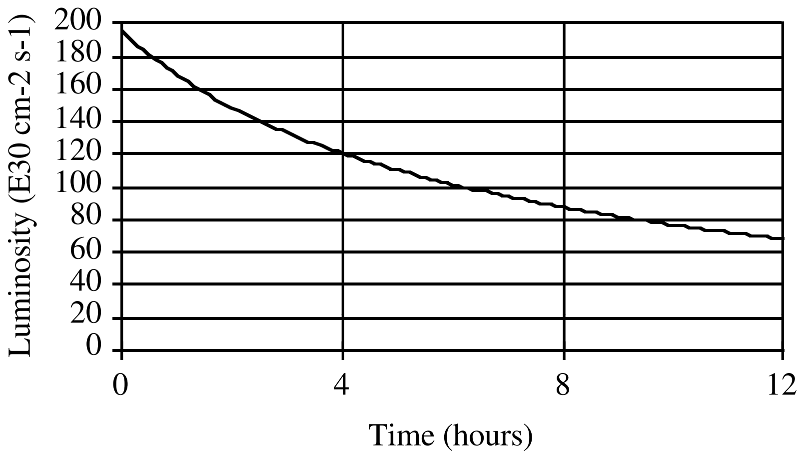

Figure 2.1.2: Prediction of the time evolution of luminosity during a Tevatron Collider store during Run II with the Recycler ring.

The prediction of Run II luminosity evolution appears in figure 2.1.2. The luminosity drops by a factor of two in about six hours. The next factor of two drop requires more than an additional 12 hours. The principal reason for this increase in the luminosity lifetime with elapsed time in the store is intrabeam scattering. The transverse emittance time evolution of both the protons and antiprotons are shown in figure 2.1.3. The emittance growth rates are initially steep and decrease with time in the store. In addition, the longitudinal emittance of the protons and antiprotons also grow during a store due to intrabeam scattering. The predictions for this effect of intrabeam scattering are displayed in figure 2.1.4.

The longitudinal emittance of the antiproton bunches in figure 2.1.4 start out small due to the fact that the Recycler ring is capable of forming the required intensity bunches without the use of coalescing. The 11 proton and antiproton bunches before coalescing in the present collider run have a longitudinal emittance of approximately 0.2 eV-s each. Instead of the expected longitudinal emittance of 2.2 eV-s for the coalesced bunch, the initial emittance ends up as ~3 eV-sec. The process of coalescing dilutes the longitudinal emittance by approximately 50%.

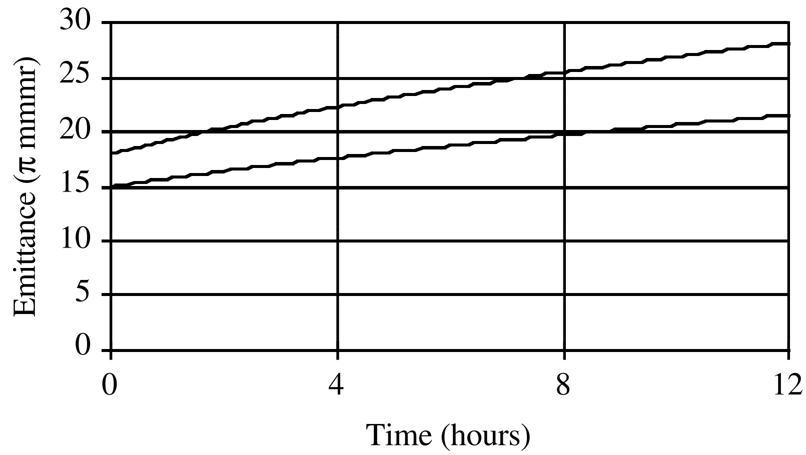

Figure 2.1.3: Predictions of the proton (upper) and antiproton (lower) transverse 95% invariant emittances as a function of time during Run II with the Recycler ring.

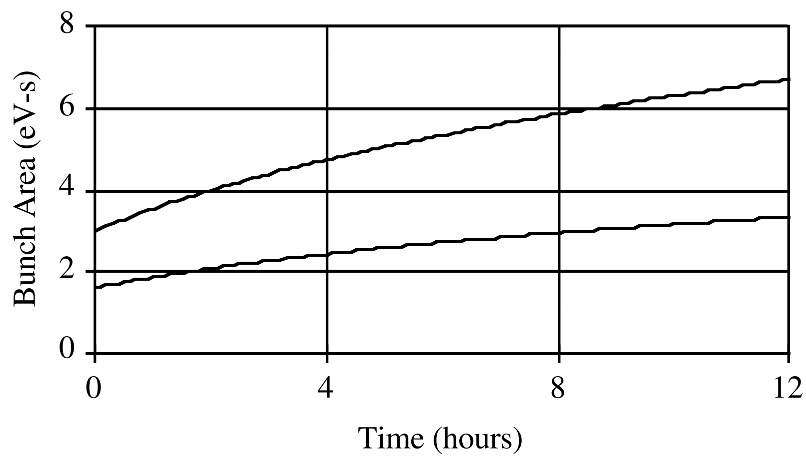

Figure 2.1.4: Predictions of the proton (upper) and antiproton (lower) longitudinal 95% invariant emittances as a function of time during Run II with the Recycler ring.

For 36x36 bunch operations, the total longitudinal emittance of the antiprotons stored in the Recycler ring must be partitioned into 36 equal portions. The total invariant 95% longitudinal emittance of the Recycler ring A_r is

$$A_r = 4\, T_o\, \sigma_e \qquad , \quad (2.1.10)$$

where T_o is the revolution period of the Recycler and σ_e is the rms energy spread. Given the Main Injector longitudinal admittance of 0.5 eV-s (at transition crossing) for a single bunch in a 53 MHz RF bucket, the total Recycler longitudinal emittance must be less than 18 eV-sec. For reference, this 18 eV-sec emittance corresponds to an rms energy spread of 0.4 MeV, or a fractional energy spread of approximately 5×10^{-5}. Because the stochastic cooling system cannot generate such small longitudinal emittances in the presence of the expected intrabeam scattering growth rates, the 2.5 MHz RF system normally used for coalescing will be used to accelerate and decelerate the beam through transition. The backup plan is to use the traditional coalescing manipulation, which has the disadvantages of larger final longitudinal emittance and lower charge efficiency.

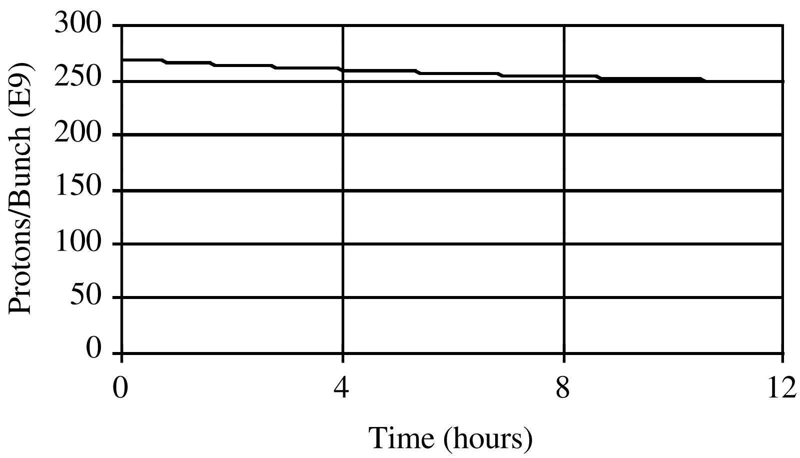

Figure 2.1.5: Prediction of the proton bunch intensity as a function of time during Run II with the Recycler ring.

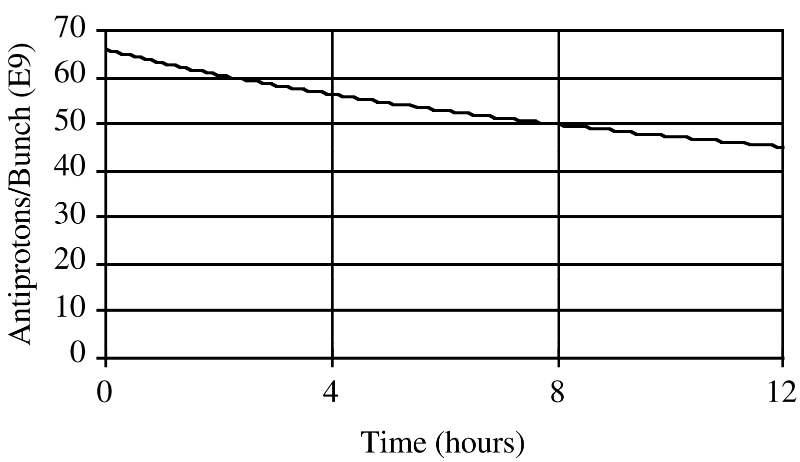

Figure 2.1.6: Prediction of the antiproton bunch intensity as a function of time during Run II with the Recycler.

The time evolution of the proton and antiproton bunch intensities are shown in figures 2.1.5 and 2.1.6. As expected, because the rate of particle loss for both beams is equal and the antiproton total intensity is much lower than that of the protons, the proton intensity lifetime is much longer than the antiproton lifetime. The third major benefit of the Recycler ring is the ability to recycle antiprotons remaining at the end of a store. In order to assess the benefit of antiproton recycling, the percentage of the original antiproton intensity remaining at the end of the store is critical. The next task is to consider the optimum length of a store.

2.1.4. Optimum Store Length

The goal of the Tevatron Collider is to integrate luminosity at the highest rate possible. In order to achieve this goal, high initial luminosities, long luminosity lifetimes, and high stacking rates are required. The store length T_s is also equal to the time available for stacking between injections. The filling time T_f is determined by a number of factors not relevant to this discussion. In present operations using the Accumulator to stack antiprotons the time evolution of the luminosity and antiproton stack size have the dependencies sketched in figure 2.1.7. The total Tevatron Collider cycle time T_c is the sum of the store time and the fill time.

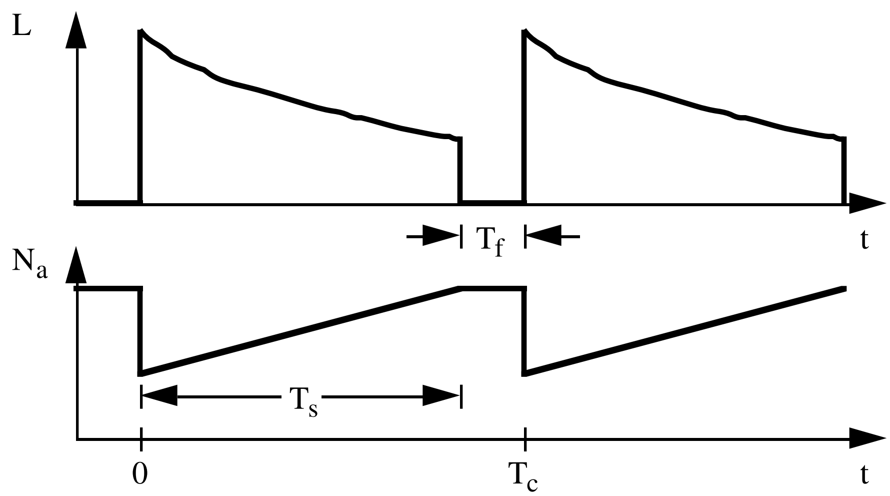

Figure 2.1.7: Sketch of the time dependence of luminosity and accumulated antiproton stack intensity during Collider Run I. The store time T_s plus the fill time T_f equals the total collider cycle time of T_c.

To maximize the rate at which integrated luminosity is delivered, it is necessary to maximize the average luminosity <L>, which is defined as

$$\langle L \rangle = \frac{1}{T_s + T_f} \int_0^{T_s} L(t)\,dt \quad . \qquad (2.1.11)$$

Because antiproton recycling is assumed, T_S plus the deceleration efficiency partially determine the initial number of available antiprotons. The recycled antiprotons are not immediately recooled, but stored and cooled for an entire Tevatron Collider store. The model used to predict the luminosity and other beam parameters during Run II operations also generates the integrated luminosity vs. time during a store. It assumes steady state operations with no Collider failures. By allowing the store duration to be the independent variable, the dependence of the average luminosity on store length for a number of choices for the fill time is plotted in figure 2.1.8. As expected, shorter fill times correspond to high average luminosities and shorter optimum store lengths. Even though fill times of one half hour are possible, it is more likely that fill times around 1 hour will be operationally feasible. At that choice of fill time, there is only a 10% difference in average luminosity between the optimum of 3.5 hours and 8 hours. A store length of 7 hours will be used as the reference store length for discussions below.

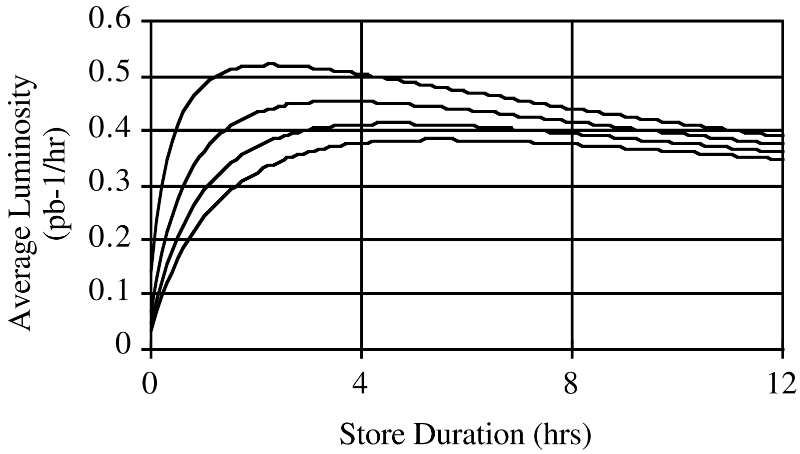

Figure 2.1.8: Prediction of the average luminosity vs. store duration for fill times of 0.5 (top), 1.0, 1.5, and 2.0 (bottom) hours. The longer the fill time, the longer is the optimum store duration. The above calculation assumes the existence of the Recycler during Run II.

The main impact of the store length is the antiproton stacking rate required to maintain the design luminosity of $2\text{x}10^{32}$ cm^{-2} sec^{-1} during Run II. In order to understand how the curve in figure 2.1.9 describing the required stacking rate vs. store duration was generated, refer to table 2.1.2.

The values in the rows labeled "Antiprotons at End of Store" and "Integrated Luminosity" were generated by the luminosity evolution calculations described above. The fill time for the MI and the MI with the Recycler ring are estimates. The Main Injector fill time is longer since without recycling the optimum store length is longer, making fill time less critical to average luminosity and putting less pressure on efforts aimed at shortening the injection time. The acceleration efficiency is the same as the value of 90% chosen in the original Main Injector design. The deceleration efficiency of 80% is basically the acceleration efficiency plus a factor due to the initially novel nature of this operation. Plugging in all of these parameter values, one can generate the subsequent numbers.

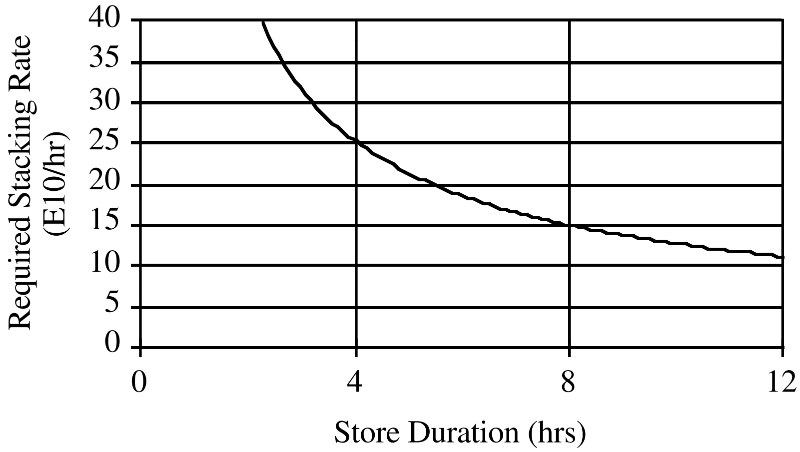

Figure 2.1.9: Prediction of the stacking rate required to achieve repeated stores at the peak luminosity of $2x10^{32}$ cm^{-2} s^{-1}.

Table 2.1.2: Parameters which describe the effect of recycling antiprotons on antiproton stacking and average luminosity during Run II. Comparisons are made with Run I operations (without both the Main Injector and the Recycler).

Parameter	Run I	MI only	Recycler
Store Duration T_s (hr)	12	12	7
Injection Time T_f (hr)	2.5	1	1
Antiprotons at End of Store	73%	65%	78%
Deceleration Efficiency	0%	0%	80%
Acceleration Efficiency	75%	90%	90%
Integrated Luminosity (pb^{-1}/store)	0.56	2.9	3.4
Required Usable Stack (10^{10})	48	144	264
Antiprotons Recycled (10^{10})	0	0	148
New Antiprotons Stacked (10^{10})	48	144	116
Required Stacking Rate (10^{10}/hr)	4	12	17
Average Luminosity (pb-1/hr)	0.04	0.21	0.43
Store Hours Needed to Achieve the Snowmass Criterion Between Integrated and Peak Luminosity	98 (typical)	101	93

The required usable stack is simply the initial total antiproton intensity in the Tevatron divided by the acceleration efficiency. In other words, it is the number of antiprotons which must be extracted from the Accumulator now or the Recycler in the future in order to attain the number of antiprotons called for in table 2.1.1. The number of antiprotons recycled is the initial antiproton intensity times the fraction of antiprotons remaining at the end of the store times the deceleration efficiency. The number of antiprotons stacked is simply the difference between the required stack size and the number of antiprotons recycled. In the case of Run II with the Recycler, recycling contributes more than a factor of two to the luminosity. The stacking rate is just the number of stacked antiprotons divided by the store duration.

2.1.5. Luminosity Leveling

At a given luminosity, the maximum number of interactions per crossing which the HEP detectors can absorb while still performing physics research determines the number of bunches per beam. Table 2.1.3 contains a summary of the average number of interaction per crossing for Run I and anticipated with the Main Injector alone and with the addition of the Recycler. The purpose of the Tevatron Collider is to record useful HEP interactions on tape at the fastest possible rate. From the perspective of an accelerator physicist, this requires the delivery of integrated luminosity at the fastest rate possible. In other words, the average luminosity in equation 2.1.11 must be maximized. From the perspective of an HEP physicist, a high average luminosity is desired only if the number of interactions per crossing is at a "reasonable" level. Too many interactions in a given crossing increases the chances of mistaking tracks associated with a given vertex, thereby decreasing trigger and off-line analysis efficiencies. The problem is that the word "reasonable' is very soft, depending on the type of particle tracking and identification required for a given class of measurements. The general consensus is an average number of interactions per crossing below 5-6 are probably reasonable for Run II.

Table 2.1.3: Average number of interactions per crossing at each HEP detectors at the beginning of stores for the same three scenarios summarized in tables 2.1.1 and 2.1.2. These rates occur at the peak luminosities listed in table 2.1.1.

Parameter	Run I	MI only	Recycler
Average Number of Interactions per Crossing (@ 49 mb)	3.2	2.4	5.7

One method for controlling the interactions per crossing problem while still delivering a high average luminosity is called luminosity leveling. In this plan the peak luminosity at the beginning of a store is sacrificed in order to maintain a stable average luminosity for a longer period of time. The method for achieving this luminosity profile calls for slowly decreasing the β^* at the interaction period, starting at a larger initial value. For example, in figure 2.1.2 a constant value of β^* = 35 cm was assumed. Using the same simulation of Tevatron Collider performance, the time dependence for β^* shown in figure 2.1.10 was assumed.

Of course the primary effect of this continuous low beta squeeze is on the luminosity, shown in figure 2.1.11. In this example the peak luminosity was decrease by almost a factor of two, bringing the average number of interactions per crossing down to the peak value experienced in Run I. The β^* is decreased until the minimum value of 35 cm is reached. Because the low beta squeeze has no effect on the beam sizes around the ring, the emittance growth mechanisms are not affected. In addition, with the exception of particle losses due to these interaction region collisions, the beam intensity evolution is also unaffected. In fact, for the luminosity leveling example investigated here the evolution of emittances and intensities are identical to those shown in figures 2.1.3 through 2.1.5.

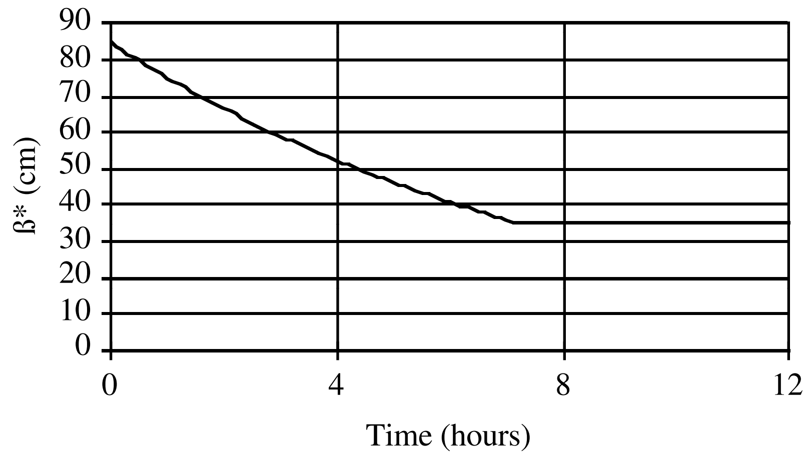

Figure 2.1.10: Continuous low beta squeeze during a Tevatron Collider store which produces a constant luminosity. The squeeze ends at 35 cm, which is considered the minimum for Run II.

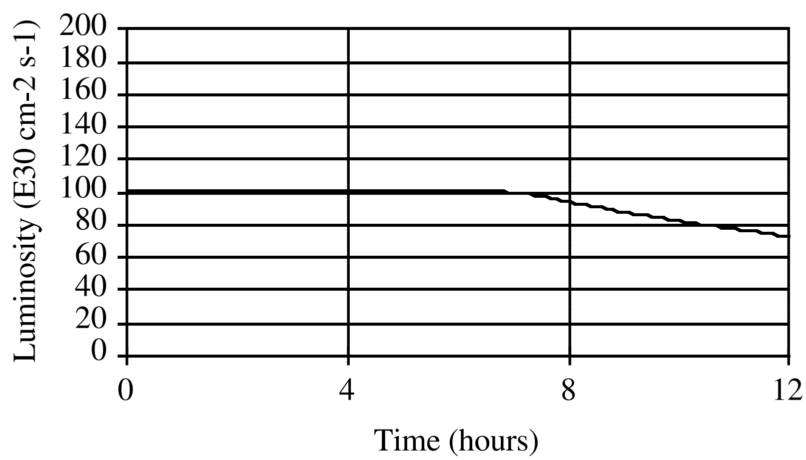

Figure 2.1.11: Luminosity as a function of time for the same initial values of beam intensity and emittance, but employing the continuous low beta squeeze to level the luminosity.

The only noticeable change is in the antiproton intensity lifetime, which is dominated by the rate of proton-antiproton collisions. The antiproton intensity evolution with time is shown in figure 2.1.12. It is this improvement in antiproton lifetime which explains why the luminosity curve in figure 2.1.10 is higher than the constant β^* curve in figure 2.1.1 after 6 hours.

Since the luminosity lifetime is improved, the loss in average luminosity is not as severe as might at first be expected. As shown in figure 2.1.13, the biggest impact is to push the optimum store length out by 2-3x to values which were typical in Run I. In fact, assuming a 1 hour injection time, the optimum store length is 10-11 hours. On the other hand, comparing with figure 2.1.8, the optimum average luminosity decreased by 25%.

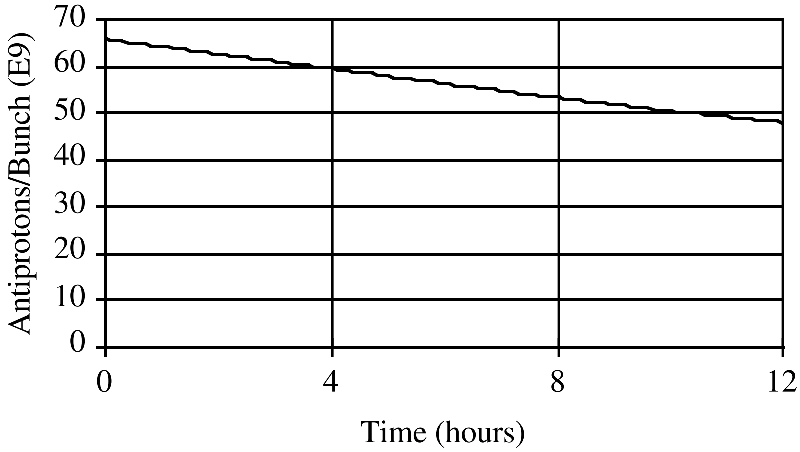

Figure 2.1.12: Time evolution of the antiproton intensity per bunch when luminosity leveling is employed. At the end of 8 hours there are approximately 10% more antiprotons in the Tevatron as compared with the case of constant β^*.

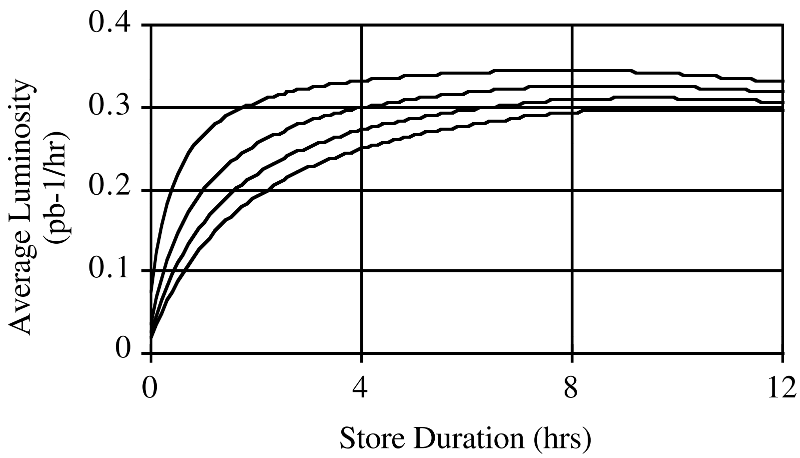

Figure 2.1.13: Prediction of the average luminosity as a function of store duration for fill times of 0.5 (top), 1.0, 1.5, and 2.0 (bottom) hours. In this example luminosity leveling in which the peak luminosity is decreased by a factor of 2 is assumed.

The impact of luminosity leveling on the stacking rate required to achieve a steady state condition of repetitive stores is small but positive. Displayed in figure 2.1.14, the required stacking rate is slightly smaller for all choices of store length. But what if the stacking rate does reach it's design goal of $16x10^{10}$ antiprotons/hour?

Figure 2.1.14: Prediction of the stacking rate required to achieve steady state luminosity performance assuming luminosity leveling. As found in the case of constant β^*, longer store lengths mean that a lower antiproton stacking rate still produces the same peak luminosity.

This was the stacking rate needed to achieve the 7 hour store lengths assumed in the case of constant β^*, so it is a reasonable assumption. At the same time, relax the interaction per crossing criterion and require that the optimum average luminosity be the same as the constant β^* case. In this case the initial antiproton intensity per bunch in the Tevatron increases from 66×10^9 to 100×10^9, the initial luminosity is 1.3×10^{32} cm^{-2} sec^{-1}, and the peak average number of interactions per crossing is the manageable value of 3.7!

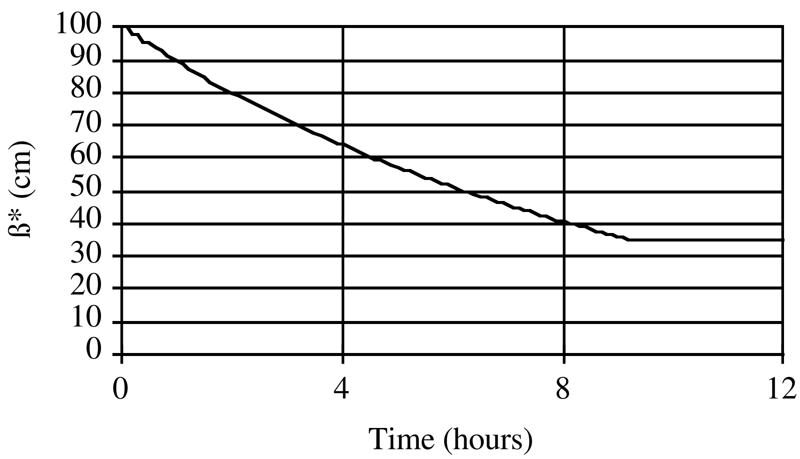

Figure 2.1.15: Continuous low beta squeeze which generates a constant luminosity at 65% of peak with an antiproton stacking rate of 16×10^{10} antiprotons/hour.

Figure 2.1.15 shows the continuous low beta squeeze needed to maintain a constant luminosity at the higher initial antiproton intensity. Since the goal is to end up with the same optimum average luminosity, the peak luminosity shown in figure 2.1.6 is 65% of the peak design luminosity of $2x10^{30}$ cm^{-2} sec^{-1} in the absence of luminosity leveling.

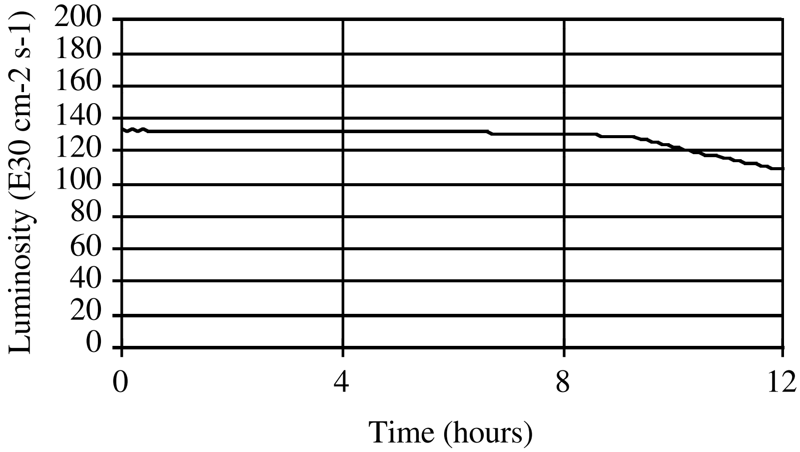

Figure 2.1.16: Prediction of the time dependence of Run II luminosity assuming luminosity leveling at 65% of peak with an antiproton stacking rate of $16x10^{10}$ antiprotons/hour at an optimum store length of 11 hours.

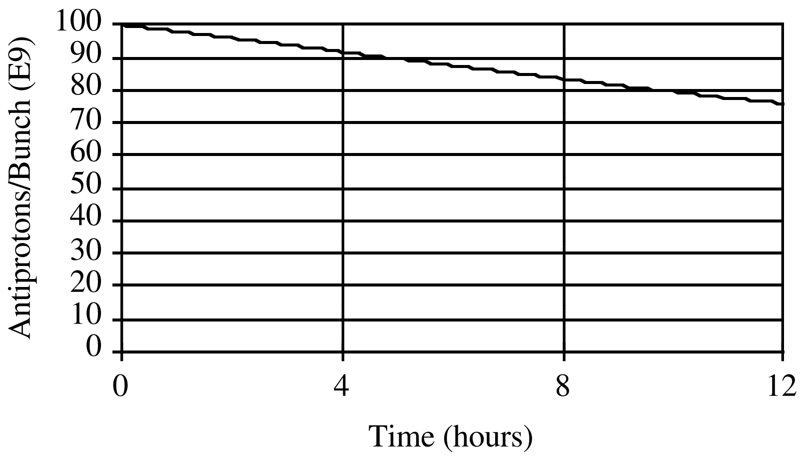

Figure 2.1.17: Prediction of the time dependence of the antiproton intensity/bunch assuming luminosity leveling at 65% of peak with an antiproton stacking rate of $16x10^{10}$ antiprotons/hour at an optimum store length of 11 hours.

Because there are more antiprotons and a lower peak luminosity, the antiproton intensity lifetime is considerably longer than in the case of no luminosity leveling (see figure 2.1.17). So even for double the store length the percentage of antiprotons left at the end of the store is the same. But because the antiproton intensity is higher for longer, the transverse and longitudinal emittance growth of the antiprotons are also larger. The updated emittance evolution curves are displayed in figure 2.1.18 and 2.1.19. Note that because of the greater growth rates and the longer stores, the recycled antiprotons will have transverse emittances approaching 25 π mmmr and longitudinal emittances of 4 eV-sec.

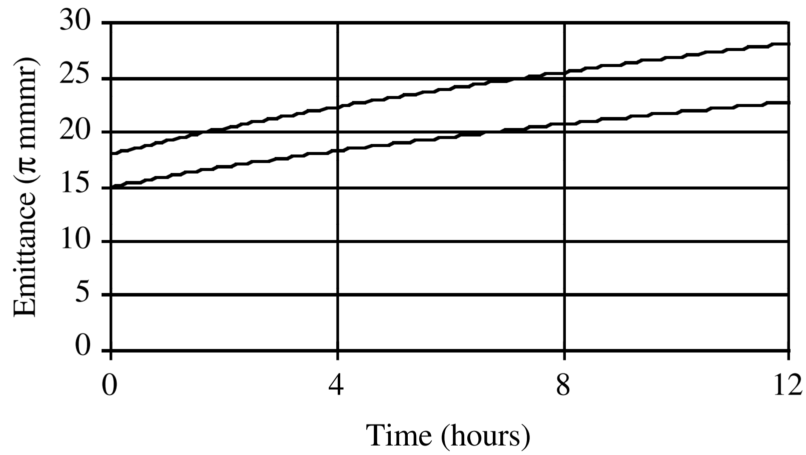

Figure 2.1.18: Prediction of the time dependence of the proton (top) and antiproton (bottom) transverse normalized 95% emittance assuming luminosity leveling at 65% of peak with an antiproton stacking rate of 16×10^{10} antiprotons/hour at an optimum store length of 11 hours.

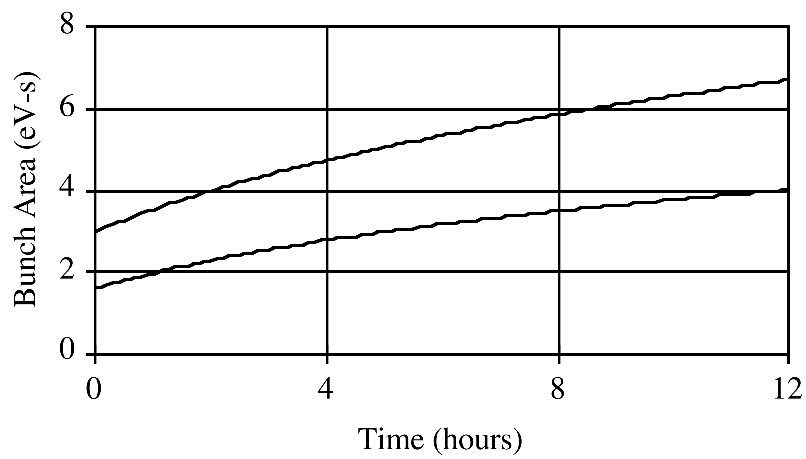

Figure 2.1.19: Prediction of the time dependence of the proton (top) and antiproton (bottom) longitudinal normalized 95% emittance assuming luminosity leveling at 65% of peak with an antiproton stacking rate of 16×10^{10} antiprotons/hour at an optimum store length of 11 hours.

By design, the average luminosity (figure 2.1.20) and stacking rate (figure 2.1.21) at a store length of 11 hours is equal to the constant β^* case at a store length of 7 hours. There are some advantages with this luminosity leveling scenario beyond the arguments concerning interactions per crossing. For example, the longer store lengths reduces the sensitivity to unanticipated increases in the fill time. It also gives the Recycler more time to cool the recycled antiprotons.

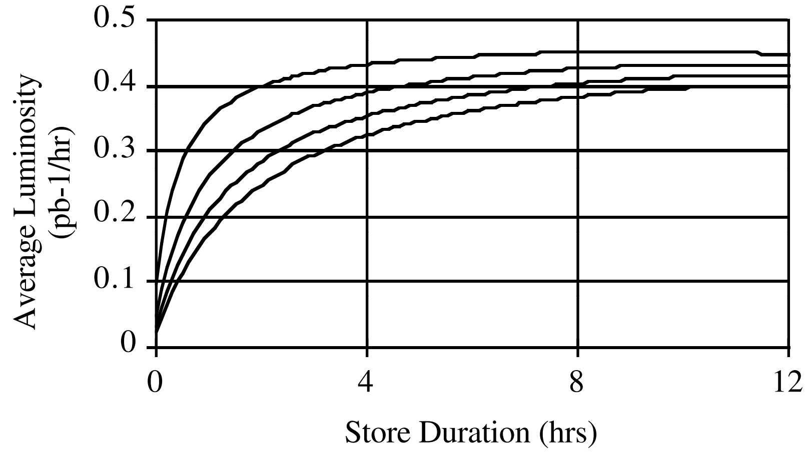

Figure 2.1.20: Average luminosity assuming luminosity leveling at 65% of peak with an antiproton stacking rate of 16×10^{10} antiprotons/hour at an optimum store length of 11 hours. The four curves are for injection times of 0.5 (top), 1.0, 1.5, and 2.0 (bottom) hours.

Figure 2.1.21: Required antiproton stacking rate to support luminosity leveling at 65% of peak with an antiproton stacking rate of 16×10^{10} antiprotons/hour at an optimum store length of 11 hours.

2.1.6. Antiproton Recycling

In order to achieve the luminosity goal of Fermi III with the Recycler, the proton and antiproton beams will have to be extracted from the Tevatron. This section is a review of the beam parameter values and issues associated with the transfers from Tevatron Collider end-of-store to storage in the Recycler.

The process of recycling starts in the Tevatron at 1 TeV in the low-β lattice configuration. The first step is to eliminate the protons. Computer controlled collimators are used to scrape away the protons (which are on one strand of the separated orbit helix) without intercepting antiprotons and without quenching Tevatron magnets. It is anticipated that once some experience has been gain that this operation can take as little time as 5 minutes.

Once the protons are eliminated, the electrostatic separators can be turned off, dramatically increasing the available aperture for the larger emittance antiprotons. The antiprotons can then be decelerated while remaining in the low-β lattice, or the low-β lattice can be unsqueezed back into the injection lattice. Changing β^* from its injection value to 35 cm and back to its injection value has already been performed at 900 GeV. The resulting tune change was only 0.004 from the value before reducing β^*. The decision of whether or not to unsqueeze from the low-β lattice should depend on which approach provides the brightest antiproton bunches to the Main Injector.

The maximum deceleration rate expected is 16 GeV/sec which is the acceleration rate used for Collider Run I. This acceleration rate was chosen so that acceleration would still be possible with a single RF station non-operational. If the deceleration ramp is constructed to be a mirror image of the acceleration ramp from Collider Run I, the RF system can still produce a 3 eV-sec bucket with a missing station. The regulation of the main power supply and low beta quadrupole systems is not a problem. The current main power supply regulation error coming out of flattop is about 100 mA, about a factor of 2 higher than the error at the start of ramp. Regulation parameters can be adjusted to try to improve this regulation. With a single beam in the machine, this regulation error is not a problem. With a deceleration ramp that mirrors the acceleration ramp, the low-β quadrupole power supplies will need no modification. If the rate of deceleration is increased near the injection energy, four of the power supplies will need to be given the ability to invert.

The waveform generators used to control most Tevatron power supplies have enough capability to produce the additional ramps needed. The correction dipoles, however, have an older waveform generator that may need to be reloaded for the deceleration process. This will be operationally awkward, but is not technically difficult. Replacement of these generators with newer models is under present consideration.

The biggest challenge will be correctly compensating for the changing sextupole component in the main dipoles. Some magnet measurements have been made to analyze these fields so that compensation ramps can be calculated. The expected current needed from the chromaticity sextupoles is well within the capabilities of the existing circuits. The exact shape of the deceleration ramp will be finalized after all results of the magnet measurements are available.

The antiprotons will be decelerated to a DC energy of 150 GeV. The exact number of bunches transferred at a time will depend on the proton injection kicker used. It is likely that this kicker will have a flattop long enough to transfer 4 bunches at a time. Nine Main Injector cycles would then be needed to transfer all antiproton bunches to the Recycler. The Tevatron needs to be at 150 GeV for no more than 3 minutes to complete the transfers to the Main Injector. The main issue at this point will be compensating the time varying sextupole fields in the Tevatron during this period. The exact scheme for this will be determined after more Tevatron magnet measurements are complete.

The transverse aperture in the Tevatron at 150 GeV is approximately 25 π mmmr with the electrostatic separators turned on. Since the separators are off during recycling, the transverse aperture is even larger and once measured at approximately 40 π mmmr.

Therefore, since the antiprotons are expected to increase in emittance to less than 25 π mmmr, no problems with transverse aperture are anticipated. In table 2.1.4 the longitudinal aperture of the Tevatron is explored. At 150 GeV the maximum RF voltage is 1 MV. This is also the maximum voltage at the flattop energy of 1 TeV. Note that the bucket area decreases from 11 eV-sec to 4.2 eV-sec as the antiprotons are decelerated. This bucket area is sufficient to accommodate the 4 eV-sec bunches expected at the end of a store, even if luminosity leveling is employed.

Table 2.1.4: Longitudinal parameters relevant to antiproton deceleration in the Tevatron during the recycling process.

Parameter	Tevatron FT	Tevatron Inj
Beam Kinetic Energy (GeV)	1000	150
RF Voltage (MV)	1	1
RF Frequency (MHz)	53	53
Momentum Compaction Factor	0.0028	0.0028
RF Bucket Half Length (nsec)	9.4	9.4
RF Bucket Half Height (MeV)	450	175
Invariant RF Bucket Area (eV-sec)	11	4.2
Synchrotron Frequency (Hz)	34	87
Invariant 95% Longitudinal Emittance (eV-sec)	3	3
Matched RMS Bunch Length (nsec)	1.5	2.3
Matched RMS Energy Spread (MeV)	110	68
Fractional RMS Momentum Spread (%)	0.011	0.045
Ratio of Emittance to Bucket Area	0.28	0.71

The Main Injector has a design transverse aperture of 40 π mmmr. The Recycler ring has been chosen to have the same aperture. Therefore, at no point in the remainder of the recycling process is transverse aperture envisioned to cause any difficulties, even assuming 1-2 π mmmr of invariant emittance growth per transfer between accelerators.

Since the Tevatron and the Main Injector have different circumferences, the RF voltage in each ring at Tevatron to Main Injector transfer must be different in order to generate matched RF buckets. Otherwise, longitudinal emittance growth will occur just after the transfer. As can be seen in table 2.1.5, a Main Injector RF voltage of 0.4 MV generates a bucket height and area equal to a Tevatron voltage of 1.0 MV. Based on present operational experience, the transfer between the Tevatron and Main Injector should only increase the already large bunch area by approximately 0.1-0.2 eV-sec.

The maximum 53 MHz RF voltage in the Main Injector is approximately 4 MV. This voltage is required for fast deceleration when the synchronous phase must be limited in order to maintain bucket area. In table 2.1.5 deceleration in the Main Injector to 25 GeV using the standard 53 MHz RF system is described. The energy of 25 GeV is far enough above transition that longitudinal beam dynamics are not distorted by the strong energy dependence of the momentum compaction factor near transition.

Table 2.1.5: Longitudinal parameters relevant to antiproton deceleration in the Main Injector during the recycling process. This table describes the standard deceleration phase from Tevatron transfer down to 25 GeV, just before transition crossing.

Parameter	MI Flattop	MI 25 GeV
Beam Kinetic Energy (GeV)	150	25
RF Voltage (MV)	0.4	1.2
RF Frequency (MHz)	53	53
Momentum Compaction Factor	0.0021	0.0008
RF Bucket Half Length (nsec)	9.4	9.4
RF Bucket Half Height (MeV)	178	206
Invariant RF Bucket Area (eV-sec)	4.2	4.9
Synchrotron Frequency (Hz)	65	168
Invariant 95% Longitudinal Emittance (eV-sec)	4	4
Matched RMS Bunch Length (nsec)	2.7	2.5
Matched RMS Energy Spread (MeV)	80	85
Fractional RMS Momentum Spread (%)	0.053	0.33
Ratio of Emittance to Bucket Area	0.93	0.81

The problem with transition crossing is that the longitudinal admittance hits its minimum at 0.5 eV-sec. This aperture limitation is caused by the normal increase in momentum spread (and conjugate decrease in the bunch length) during transition crossing. Assuming a nominal longitudinal emittance of 4 eV-sec, it is clear that antiproton recycling via the 53 MHz RF system alone is not possible. But if the RF frequency were decreased by a factor of 8 or more, then the matched bunch length would be longer and momentum spread decreased correspondingly. Since the Main Injector contains a 2.5 MHz RF system, it is natural to investigate using that system for transition crossing and the remaining deceleration to the base kinetic energy of 8 GeV.

The transition from one RF system to the other can take place relatively easily by turning on the 2.5 MHz system and then adiabatically lowering the 53 MHz voltage to zero. The maximum sustainable voltage in the 2.5 MHz system is 60 kV. Table 2.1.6 contains the parameter values for transfer to the 2.5 MHz system. Once the transfer has taken place, the antiprotons can be decelerated at a rate of the peak voltage times the sine of the synchronous phase angle. Assuming a phase angle of 53°, the beam can be decelerated at a rate of 48 keV/turn, or 4.25 GeV/sec. At this rate it takes 4 seconds to decelerate the beam down to a kinetic energy of 8 GeV.

In order to deliver the smallest possible momentum spread beam to the Recycler, at 8 GeV the RF voltage is reduced adiabatically until the bunch longitudinal emittance equals the bucket area. Table 2.1.7 contains the longitudinal parameters just before transfer to the Recycler. The beam delivered to the Recycler has an energy spread less than 4 MeV, even for the large longitudinal emittance of 4 eV-sec.

The act of transition crossing has been simulated using the ESME program. Figure 2.1.22 contains the resultant phase space distribution of a 3 eV-sec bunch after crossing transition with only an instantaneous RF phase change. No special RF or gamma-t jump manipulations are involved. Note that the longitudinal emittance grew by approximately 10%, and no test particles out of the original 1000 were lost. The case of 4 eV-sec transition crossing was also studied with ESME. The result is that for an identical deceleration as in the previous 3 eV-sec case, the longitudinal emittance is diluted to 5.1 eV-sec, which represents a 25% growth. On the other hand, no beam loss was observed. Repeating the 4 eV-sec transition crossing simulation but this time with a gamma-t jump, the longitudinal emittance dilution was reduced to less than 10%.

Table 2.1.6: Longitudinal parameters relevant to antiproton deceleration in the Main Injector during the recycling process. This table documents the transfer of RF systems to the 2.5 MHz system for deceleration through transition to a kinetic energy of 8 GeV.

Parameter	RF Handoff
Beam Kinetic Energy (GeV)	25
RF Voltage (kV)	60
RF Frequency (MHz)	2.5
Momentum Compaction Factor	0.0008
RF Bucket Half Length (nsec)	198
RF Bucket Half Height (MeV)	211
Invariant RF Bucket Area (eV-sec)	106
Synchrotron Frequency (Hz)	8.2
Invariant 95% Longitudinal Emittance (eV-sec)	4
Matched RMS Bunch Length (nsec)	11.2
Matched RMS Energy Spread (MeV)	18.8
Fractional RMS Momentum Spread (%)	0.073
Ratio of Emittance to Bucket Area	0.037

Table 2.1.7: Longitudinal parameters relevant to antiproton deceleration in the Main Injector during the recycling process. This table documents the remaining deceleration to the kinetic energy of 8 GeV and transfer into the rectangular barrier bucket RF system of the Recycler ring, where the energy spread must be minimized.

Parameter	MI @ 8 GeV
Beam Kinetic Energy (GeV)	8
RF Voltage (kV)	2.8
RF Frequency (MHz)	2.5
Momentum Compaction Factor	-0.0089
RF Bucket Half Length (nsec)	198
RF Bucket Half Height (MeV)	8.0
Invariant RF Bucket Area (eV-sec)	4.04
Synchrotron Frequency (Hz)	10
Invariant 95% Longitudinal Emittance (eV-sec)	4
Matched RMS Bunch Length (nsec)	58
Matched RMS Energy Spread (MeV)	3.7
Fractional RMS Momentum Spread (%)	0.041
Ratio of Emittance to Bucket Area	0.99

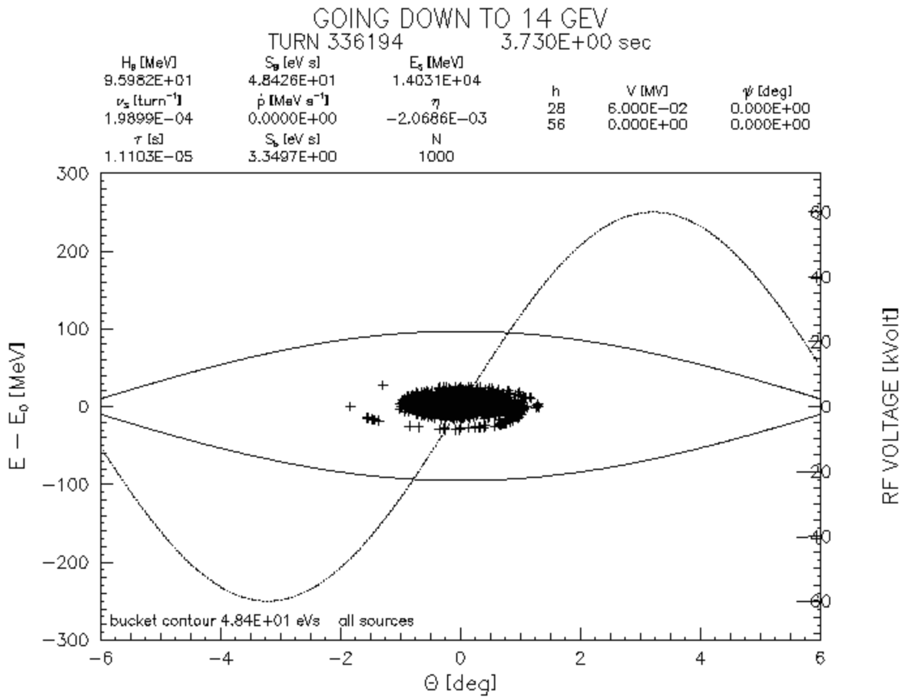

Figure 2.1.22:Simulation of longitudinal phase space of a 3 eV-sec bunch after crossing transition with a simple RF phase change and no gamma-t jump.

The recycled antiproton beam in the Tevatron are handled as 9 batches each composed of 4 bunches spaced at a 2.5 MHz frequency. The entire recycling process repeats the Main Injector deceleration and transfer process 9 times, once per batch. The next issue to address is how the transfers and RF manipulations are handled during the recycling process between the Main Injector and the Recycler.

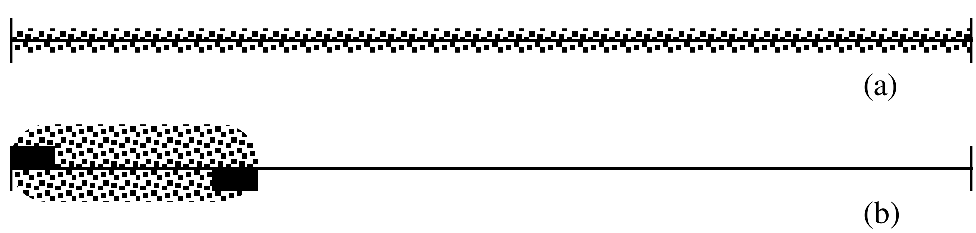

Figure 2.1.23: Full ring phase space sketches of the initial steps of antiproton recycling in the Recycler. In the top drawing (a) the cooled beam starts off basically unbunched (unless an azimuthal gap is necessary for ion clearing reasons). In the bottom drawing (b) a rectangular barrier voltage system adiabatically squeezes the beam into a small fraction of the circumference.

In the remainder of this discussion luminosity leveling is not assumed. When luminosity leveling is included some quantitative values may change, but the qualitative flavor of the operations and concerns remains unchanged.

When the entire recycling process starts, the Recycler already contains $264\text{x}10^{10}$ antiprotons ($116\text{x}10^{10}$ newly stacked, $148\text{x}10^{10}$ from the recycling process of the previous store). Given calculations of intrabeam scattering and the choice of stochastic momentum cooling system, the longitudinal emittance is cooled to approximately 54 eV-sec, which according to equation (2.1.10) corresponds to a fully occupied ring with an rms energy spread of 1.2 MeV (see figure 2.1.23a). The first step is to generate a barrier bucket [J.E. Griffin, C. Ankenbrandt, J.A. MacLachlan, and A. Moretti, "Isolated Bucket RF Systems in the Fermilab Antiproton Facility", IEEE Trans. Nucl. Sci. **NS-30**, 3502 (1983)] voltage waveform which constrains the cooled beam distribution to one quarter of the circumference, as shown in figure 2.1.23b. In figure 2.1.24 the phase space capture bucket generated by a pair of rectangular voltage pulses is shown. Because of the intrinsic wide bandwidth of modern power amplifiers, rectangular pulses are desirable for generating the largest bucket height for the smallest pulse width and voltage. The bucket half height $\Delta E_{1/2}$ given a pulse voltage of V_o, a beam total energy of E_o, a pulse width of T, a revolution period of T_o, and a momentum compaction factor η is

$$\Delta E_{1/2} = \sqrt{\frac{T}{T_o}\frac{2\beta_r^2}{\eta} eV_o E_o} \quad . \quad (2.1.12)$$

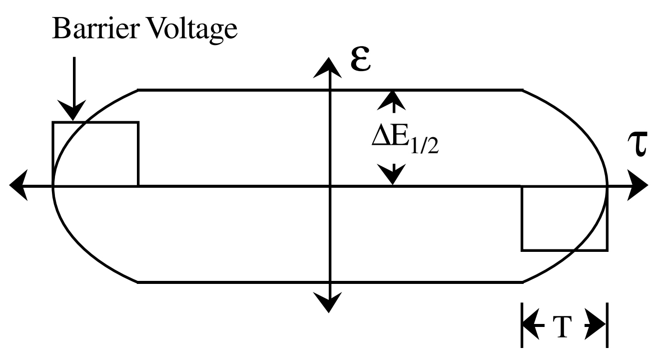

Figure 2.1.24: Phase space sketch associated with a rectangular barrier bucket accelerating voltage system. Inside the voltage pulse the trajectory of energy vs. longitudinal position is quadratic.

Assuming that one wants to longitudinally compress this beam distribution so that the momentum span of the bunch grows out to the momentum aperture of the stochastic cooling systems, the rms momentum spread has grown to approximately 4.8 MeV and charge length has been compressed into 1/4 of the ring circumference. Assuming $\pm 2\ \sigma_e$ of bucket height to constrain most of the beam to that portion of the circumference, table 2.1.8 describes the required voltage and pulse length necessary to produce the minimum bucket height. The final beam distribution length is approximately 2.8 μsec out of 11.2 μsec, so 8.4 μsec of free circumference is available for the recycling process.

Table 2.1.8: Parameters which produce the minimum bucket height necessary to constrain a beam distribution with an rms energy spread of 4.5 MeV.

Parameter	σ_e=4.5 MeV
Beam Total Energy (GeV)	8.938
Relativistic Velocity	0.9945
RF Voltage (kV)	1.2
RF Pulse Length (µsec)	0.5
Momentum Compaction Factor	-0.008683
Revolution Period (µsec)	11.2
RF Bucket Half Height (MeV)	10

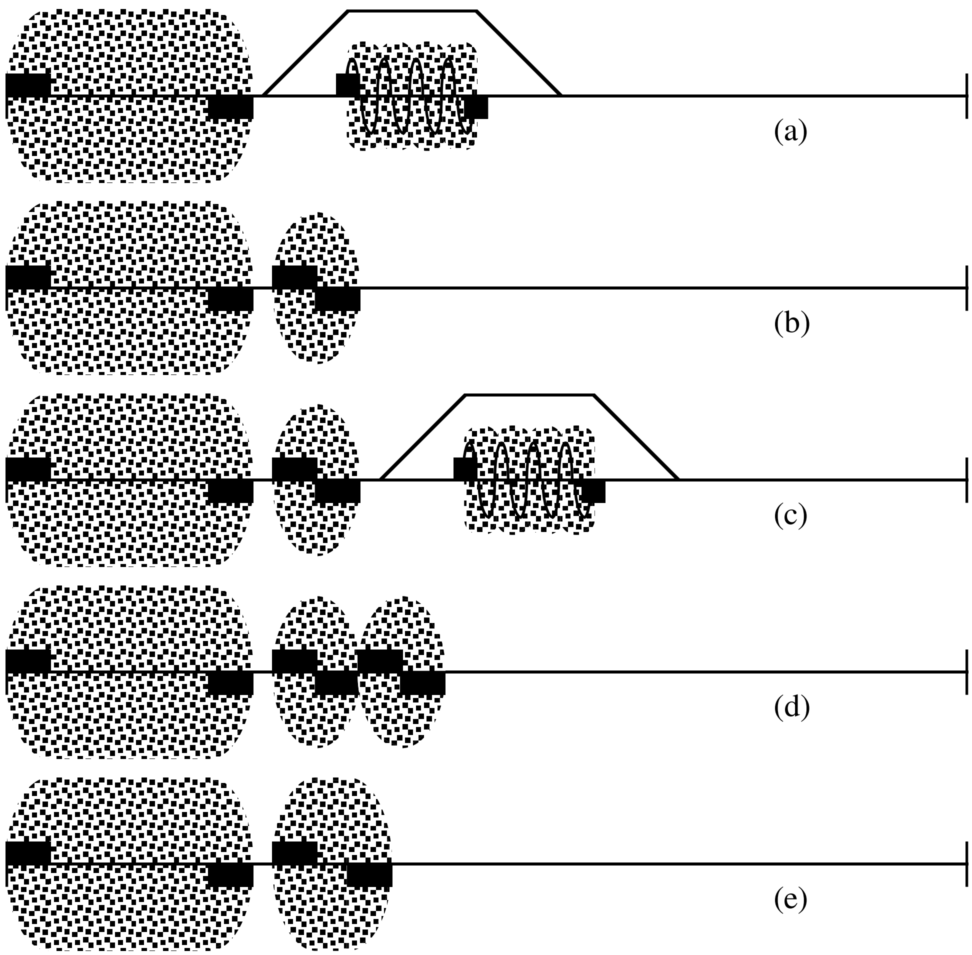

Figure 2.1.25: Recycling of antiproton batches from the Main Injector. The leftmost charge distribution is always the cooled antiprotons. The shown Recycler injection kicker waveform has a rise-time and fall-time of 1 µsec. The recycling process never requires more than 3 pairs of barrier voltage pulses.

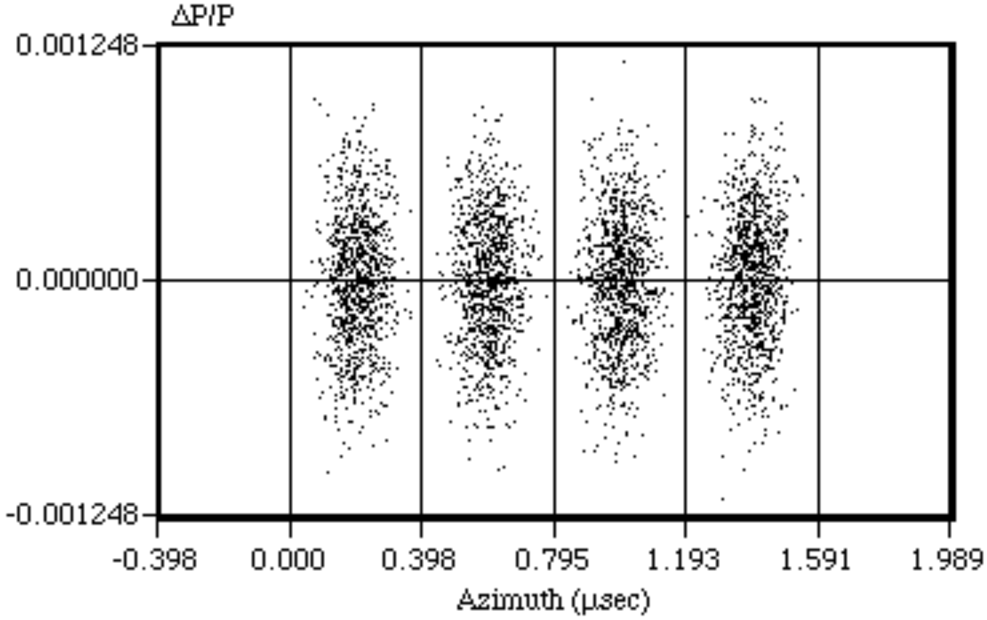

Figure 2.1.26: Simulation result of the adiabatic debunching of the 2.5 MHz bunch structure into a barrier bucket. In this figure the initial distribution with an rms fractional momentum spread of 0.00033 is shown.

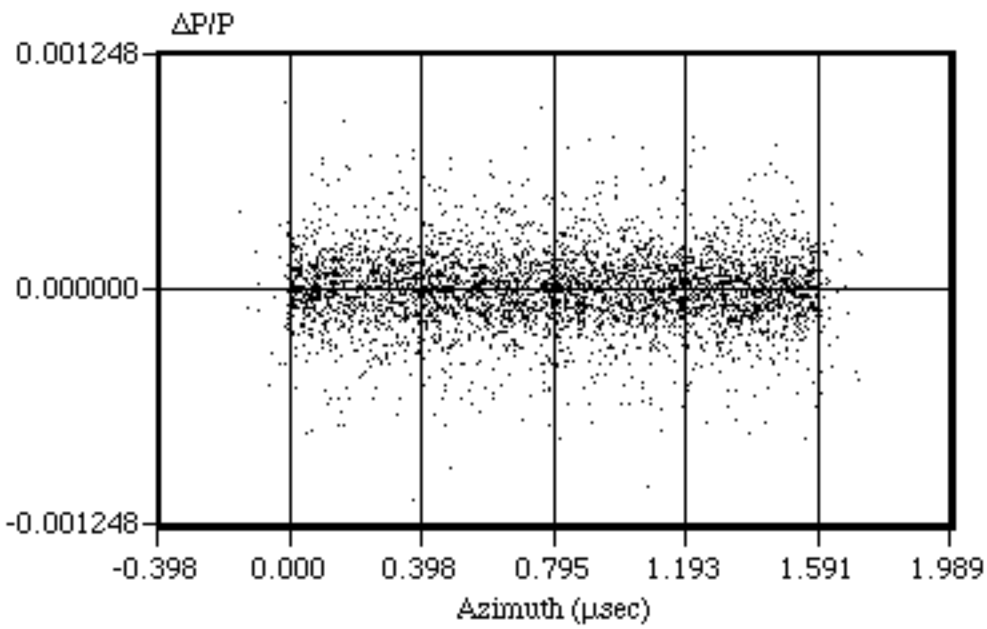

Figure 2.1.26: Simulation result of the adiabatic debunching of the 2.5 MHz bunch structure into a barrier bucket. In this figure the final distribution with an rms fractional momentum spread of 0.00020 is shown. The 2.5 MHz sinusoidal matching waveform was reduced in voltage linearly in 1 second.

The transfers of bunches from each batch from the Main Injector to the Recycler ring is performed 4 bunches at a time. The length of a series of 4 recycled collider bunches in the Recycler ring just after transfer is 1.6 µsec. According to table 2.1.7 the rms energy spread of this distribution at 3 eV-sec per bunch is 2.8 MeV. A sketch of this injection in longitudinal phase space is shown in figure 2.1.25a.

At the time of beam transfer the Recycler RF system is generating a pair of constraining barrier voltage pulses. In addition, between these pulses 4 wavelengths of 2.5 MHz with a matching voltage of 1.6 kV (matched to the 3 eV-sec bucket in the Main Injector) provides bucket-to-bucket RF transfer. After adiabatically turning the 2.5 MHz sinusoidal waveform to zero, the transferred charge is cogged azimuthally to its storage position (see figure 2.1.13b) and compressed. Figures 2.1.26 and 2.1.27 show the results of a ESME-like simulation of this operation, where the entire process takes approximately 1 second with no measurable longitudinal emittance growth..

The second antiproton batch transfer occurs similarly (see figure 2.1.25c). When the batch is moved to the left, it is merged with the first recycled batch. As shown in figure 2.1.25d and 2.1.25e, this merger is accomplished by adiabatically reducing the voltage of the inner voltage pulses to zero. At this point the distribution of recycled antiprotons can be compressed by moving the right barrier pulse to the left. This process was also simulated with an ESME-like computer program. The results are shown in figures 2.1.28 and 2.1.29. Reducing the middle pair of voltage pulses separating the 12 eV-sec distributions in 2 seconds with an emittance growth of less than 5%.

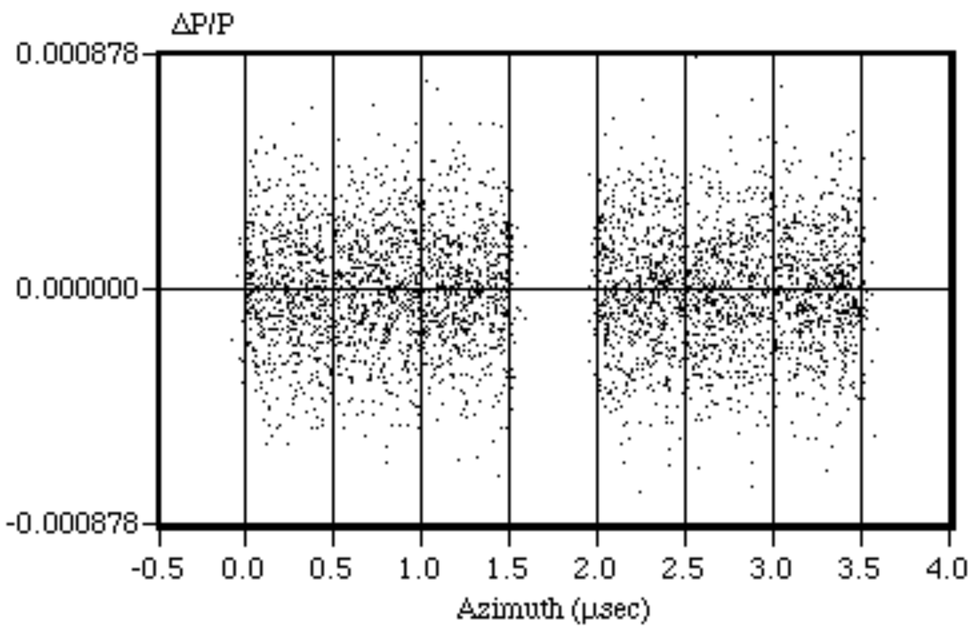

Figure 2.1.28: Initial distribution in which two 12 eV-sec distributions are constrained by a pair of 250 nsec long barrier RF pulse sets (not shown).

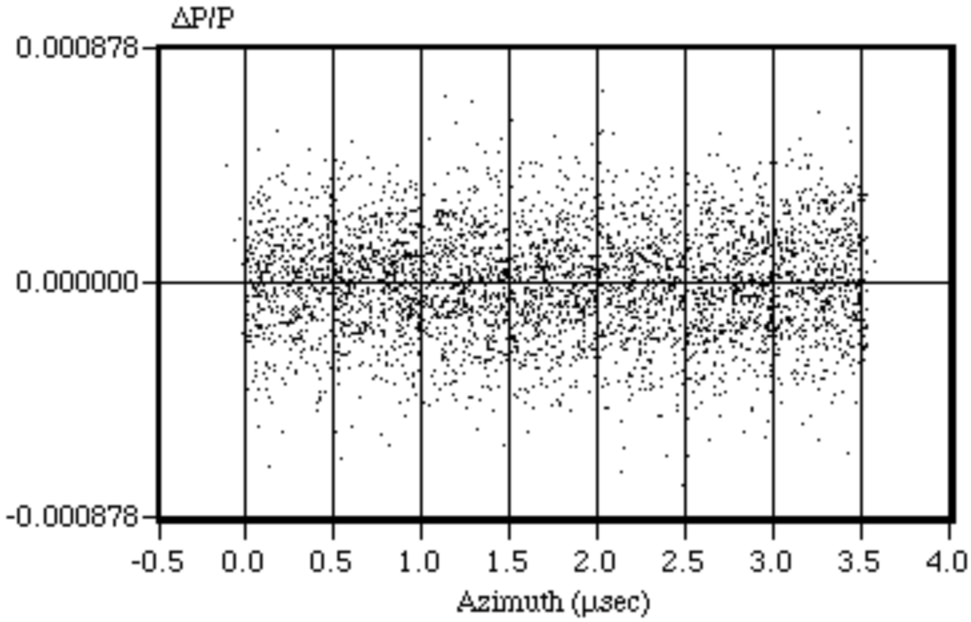

Figure 2.1.29: Final distribution in which the two 12 eV-sec distributions are merged by linearly reducing the voltage of the intermediate barrier pulses in 2 seconds. Less than 5% emittance growth is observed in the simulation.

This process of beam transfer continues until the last of 9 batches are injected. Figure 2.1.30a shows the compression of the previous 8 batches necessary to leave sufficient azimuthal aperture to fire the injection kicker. Note that a voltage of 2 kV and a pulse length of 1 μsec is now necessary to constrain the recycled beam. After merging the 9th batch (see figure 2.1.30b), the recycled beam is compressed into a pulse length of approximately 4 μsec, leaving sufficient room for the inverse operation of extracting the cooled antiprotons for injection into the next Tevatron Collider store (see figure 2.1.30c).

In a given allowed azimuthal time interval, the maximum bucket area is produced when the pair of barrier pulses have a total length equal to that interval. See figure 2.1.31 for a sketch of this situation. The equation for this bucket area A is

$$A = \frac{8}{3}\,\Delta E_{1/2}\,T \quad . \quad (2.1.13)$$

Table 2.1.9 contains parameters assuming storage of all of the recycled beam in 3.5 μsec assuming no emittance growth in any of the phase space manipulations above. By increasing the pulse width to 2 μsec each, equation (2.1.13) suggests that the bucket area would increase by a factor of 30%, enough to encompass a healthy emittance growth contingency.

It is anticipated that the minimum time between successive transfers of batches to the Recycler ring is approximately 20 sec. Therefore, the entire Main Injector deceleration cycle should be less than this time interval to keep the injection time as low as possible. Figure 2.1.32 contains a sketch of the timing of the Main Injector deceleration cycle.

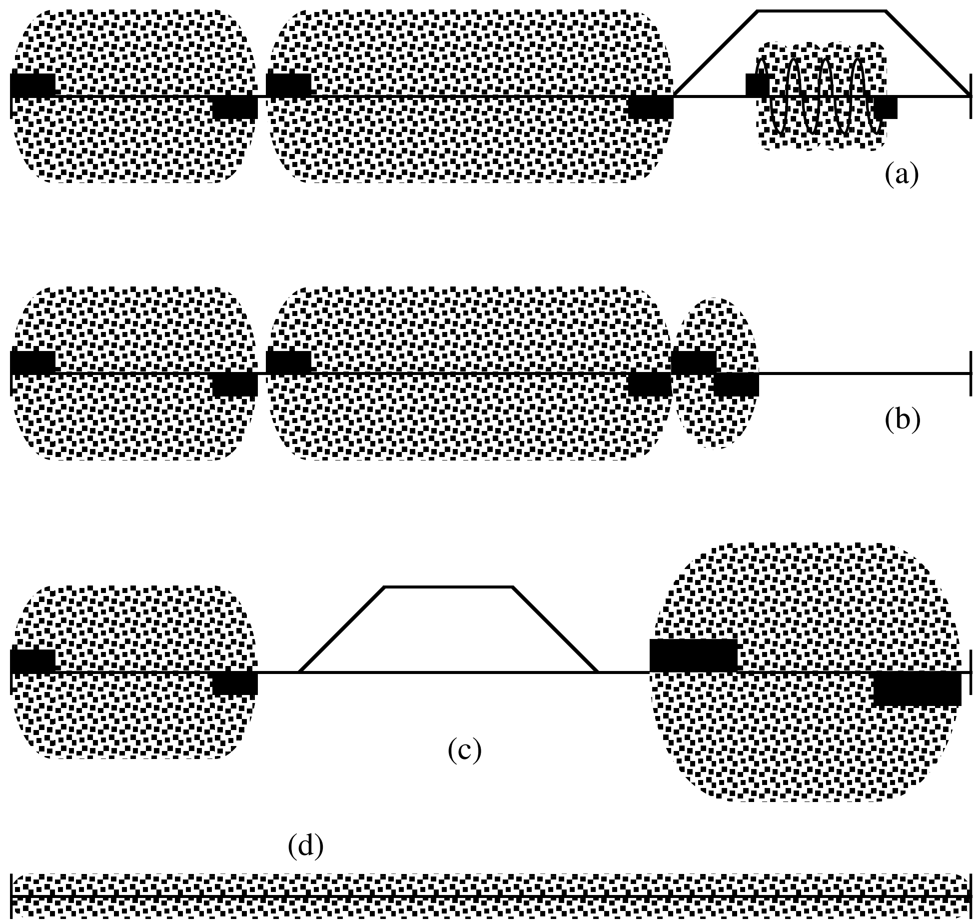

Figure 2.1.30: End of the process of antiproton recycling from the Main Injector. The leftmost charge distribution is always the cooled antiprotons. In (d) the cooled antiprotons have been injected into the Tevatron Collider and the recycled antiprotons have been debunched.

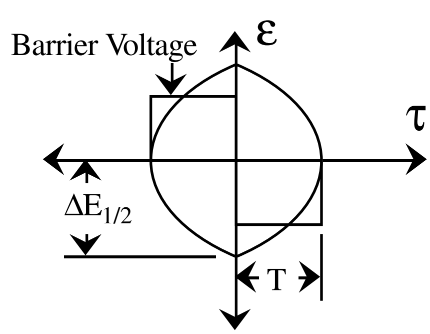

Figure 2.1.31: Sketch of the phase space configuration of the maximum bucket area generated in a given azimuthal time interval (=2T).

Table 2.1.9: Recycler and RF parameters which produce the maximum bucket area with a limited voltage inside a prescribed fraction of the circumference. The necessary RF bucket area is equal to the total invariant 95% longitudinal emittance of all the recycled antiprotons, which is equal to 36 x 3 eV-sec = 108 eV-sec.

Parameter	36 Bunches
Invariant 95% Longitudinal Emittance (eV-sec)	108
Beam Total Energy (GeV)	8.938
Relativistic Velocity	0.9945
RF Voltage (kV)	2
RF Pulse Length (μsec)	1.75
Momentum Compaction Factor	-0.008683
RF Bucket Length (μsec)	3.5
RF Bucket Half Height (MeV)	24
RF Bucket Area (eV-sec)	112
RMS Momentum Spread of the Beam (MeV)	12

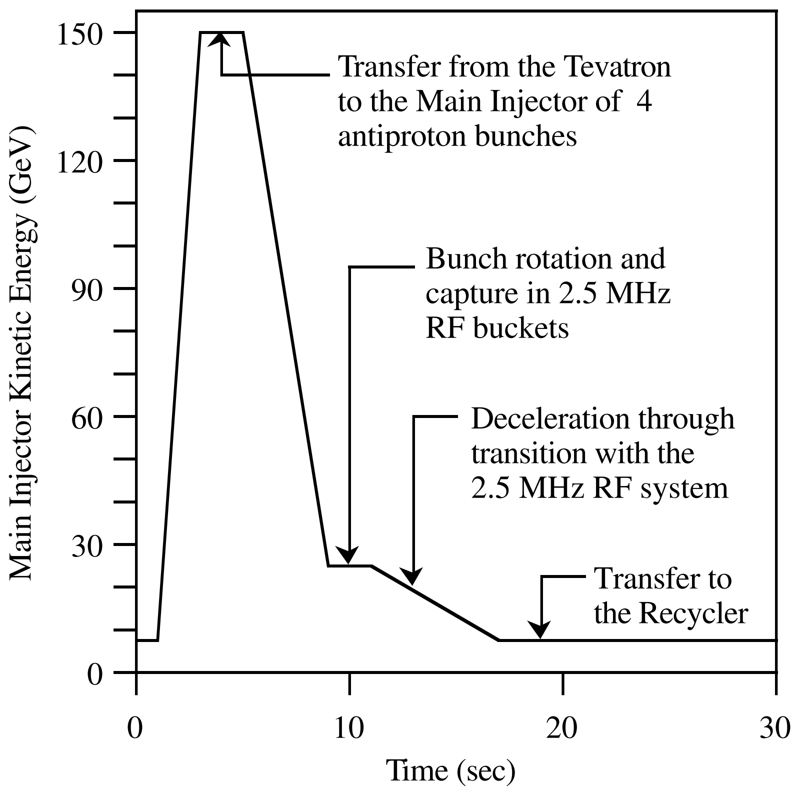

Figure 2.1.32: Sketch of the Main Injector deceleration cycle in which 4 recycled antiproton bunches are injected into the Recycler.

When all of the cooled antiprotons have been extracted, the recycled antiprotons can be adiabatically expanded to fill the ring. As shown in figure 2.1.30d, by slowly reducing the barrier pulse voltage to zero, the minimum momentum spread can be achieved.

Except for the portion of the azimuth carrying the overly compressed recycled antiprotons during extraction, the stochastic cooling is always turned on. In the above example calculations, assuming 3 eV-sec per recycled antiproton bunch and a healthy contingency of emittance growth through all of the RF manipulations, a maximum rms energy spread of approximately 3 MeV is expected.

2.1.7. Stacking from the Accumulator

In the Accumulator, a longitudinal emittance of 6.4 eV-sec is produced by the longitudinal stochastic cooling system at low stack intensities. This corresponds to an rms energy spread of 1 MeV. As the stack intensity increases, both the longitudinal emittance and rms energy spread increase linearly. Therefore, if short bunches are desired in the Tevatron Collider the Recycler ring acts as a necessary storage stage after the Accumulator.

It is anticipated that the optimum rate at which antiprotons are transferred from the Accumulator to the Recycler ring will be determined by a number of factors. First, as the stack size in the Accumulator increases the stacking rate eventually starts to decrease. Second, there will be considerable setup time preparing the transfer lines. This is because the 120 GeV proton transfer line to the antiproton target as an 8 GeV antiproton extraction line must be used. Changing the energy of the line and tuning up the steering between the Accumulator and the Main Injector could require up to 5 minutes for each transfer (in the mean time the Main Injector is not stacking, but still servicing other needs such as 120 GeV fixed target or NuMI beam delivery). Third, if the momentum spread of the Accumulator is large compared to the Recycler stack and/or the momentum acceptance of the stochastic cooling system, time will be required to cool the beam before the next transfer. At present the best estimate for the optimum transfer rate is once every 2 hours.

The actual transfer between the Accumulator and the Recycler should be quite straightforward. Once a gap of sufficient azimuth is opened in the Recycler beam distribution, the Accumulator beam can be injected via the Main Injector. According to data gathered from Accumulator operations, a 20×10^{10} antiproton/hour stacking rate and a 2 hour time between transfers generates an antiproton distribution each transfer with a pulse length of 1.5 μsec, an intensity of 40×10^{10} antiprotons, a transverse emittance of approximately 10 π mmmr, and a momentum spread of 1.6 MeV. This corresponds to a longitudinal emittance of 10 eV-sec.

Therefore, the overall intensity history of the Recycler should look like the sketch in figure 2.1.33. The peak current in the ring occurs after the recycled antiprotons are injected but before the cooled antiprotons are extracted. Since the transverse diffusion mechanisms are quite small and the Accumulator beam is already injected at the target invariant 95% transverse emittance of 10 π mmmr, transverse cooling times on the order of a few hours are sufficient. In order to understand the demands on the momentum cooling system, an integrated model of the entire time evolution of antiproton distributions shown in figure 2.1.33 must be synthesized.

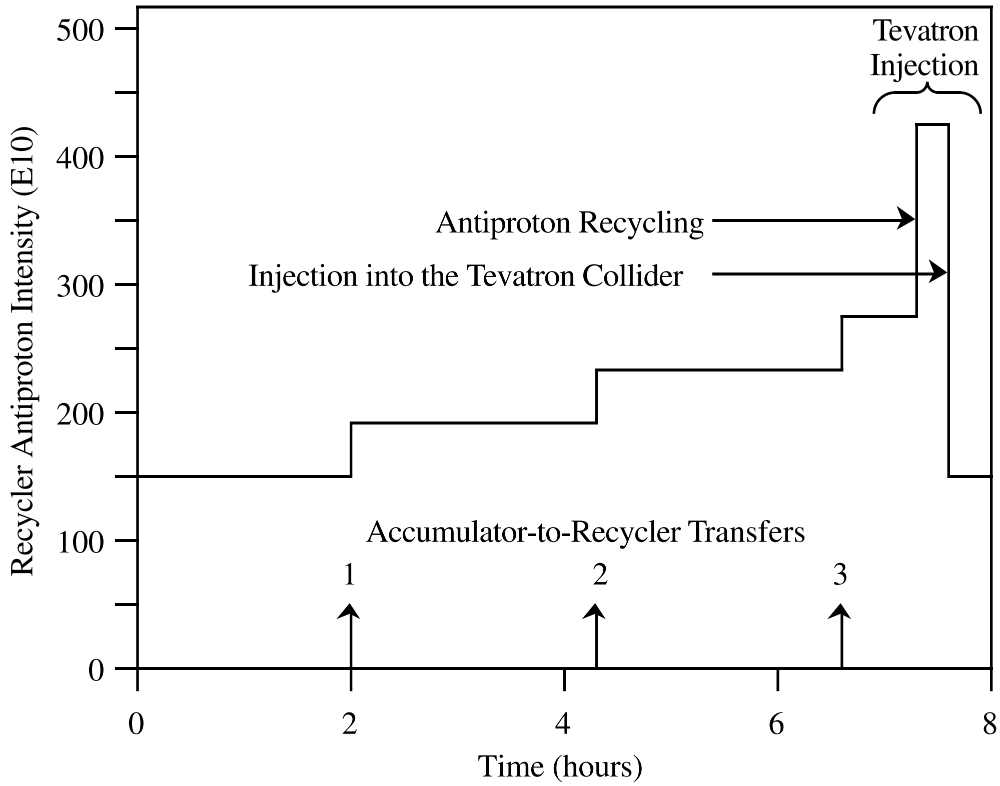

Figure 2.1.33: Anticipated time evolution of the intensity in the Recycler ring.

<u>2.1.8. *Antiproton Injection into the Tevatron Collider*</u>

In figure 2.1.30c the cooled antiprotons (left) and recycled antiprotons (right) are stored in the Recycler. At this point it is necessary to extract the cooled antiprotons. The empty space occupied in figure 2.1.30c by the extraction kicker waveform is the location where pulses of antiprotons are extracted into the Main Injector for injection into the Tevatron Collider.

A total of 36 collider bunches must be extracted in 9 batches of 4 bunches. Therefore, the 1/9th of the cooled distribution is extracted at a time. The extraction process for each batch starts with the formation of a pair of barrier pulses formed adiabatically inside of the cooled beam distribution. By placing the pulses at the correct azimuth, the correct fraction of antiprotons are segmented into a separate distribution. This separate distribution is then accelerated into the extraction azimuth.

Before the extraction kicker fires, the opposite adiabatic operation to that shown in figures 2.1.26 and 2.1.27 is implemented. The RF and beam parameters at this stage are summarized in table 2.1.10. In this way 4 bunches spaced into separate 2.5 MHz RF buckets are formed in the Recycler. When the extraction kicker is fired the Recycler and Main Injector 2.5 MHz waveforms are synchronized in amplitude and phase in order to avoid longitudinal emittance growth.

Once the transfer of 4 antiproton bunches into the Main Injector is accomplished, the 2.5 MHz RF system in the Main Injector then accelerates the beam through transition to

25 GeV. At 25 GeV the antiproton distribution is bunch rotated, similar to the operation performed on protons just before they are sent into the antiproton target. The purpose of this operation is to shorten the antiproton bunches sufficiently to allow capture into 53 MHz RF buckets. Once the RF handoff is complete, the beam is accelerated the rest of the way to 150 GeV and transferred into the Tevatron Collider. This entire process is summarized in figure 2.1.34.

Table 2.1.10: Recycler and RF parameters which produce the 2.5 MHz bucket just before injection of cooled antiprotons into the Main Injector.

Parameter	per Bunch
Invariant 95% Longitudinal Emittance (eV-sec)	1.5
Beam Total Energy (GeV)	8.938
Relativistic Velocity	0.9945
RF Voltage (kV)	2
RF Frequency (MHz)	2.5
Momentum Compaction Factor	-0.008683
RMS Bunch Length (μsec)	.038
RF Bucket Half Height (MeV)	6.9
RF Bucket Area (eV-sec)	3.5
Ratio of Bunch Area to Bucket Area	0.43

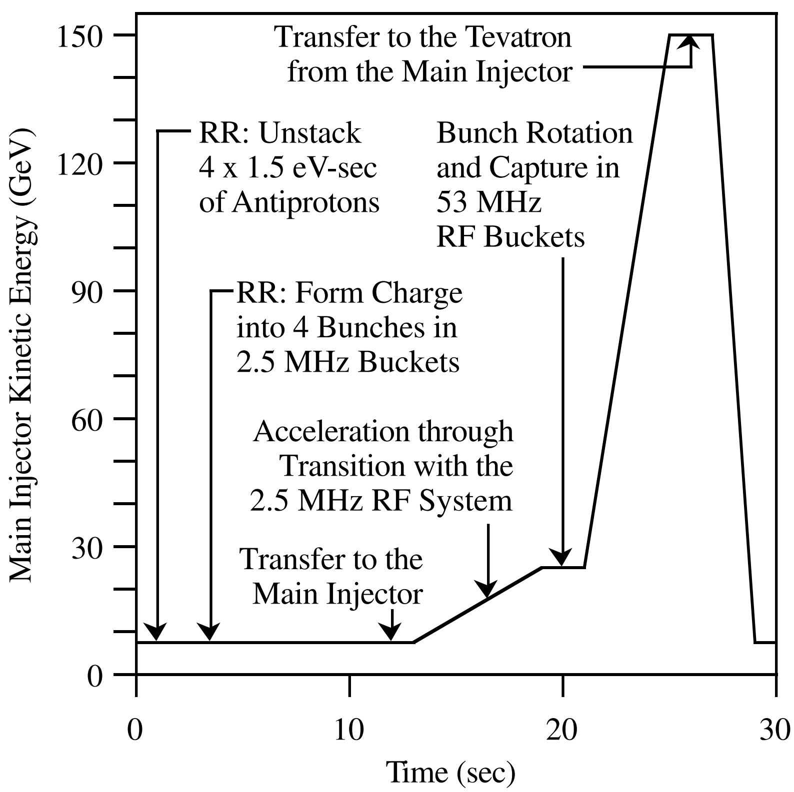

Figure 2.1.34: Sketch of the Recycler and Main Injector functions during each antiproton batch creation/extraction cycle.

2.1.9. Beam Cooling Requirements

In the above discussion the concept of stochastic cooling has been invoked but not explained. The requirements for beam cooling in the above Recycler operational scenario (where luminosity leveling is not invoked) are summarized below.

1. Produce a stacked beam of 2.6×10^{12} antiprotons in a longitudinal emittance of 54 eV-sec and a normalized transverse emittance of 10 π mmmr in an 8 hour cooling cycle (see table 2.1.2).

2. Accept recycled antiproton beams from the Tevatron at a nominal intensity of 1.5×10^{12} antiprotons, a maximum longitudinal emittance of 108 eV-sec and a maximum normalized transverse emittance of 30 π mmmr. This beam is the basis for forming the stacked beam for the next cooling cycle.

3. Accept beam from the Accumulator and add it to the stack at the rate of 0.2×10^{12} antiprotons per hour. The Accumulator beam has a longitudinal emittance of 10 eV-sec and a normalized transverse emittance of 10 π mmmr.

The design of the cooling systems to accomplish these functions is described in more detail in section 2.9.

2.1.10. Nominal Cooling/Recycling Cycle

In order to better understand the following discussion, refer to figure 2.1.33. The simulation begins at 0:00 (hours:minutes) with a beam of 1.5×10^{12} antiprotons that has been recycled from the Tevatron and is contained in a longitudinal emittance of 108 eV-sec. A remnant of the cold antiproton beam which was in the tails of the momentum distribution and not transferred to the Tevatron collider contains 0.3×10^{12} antiprotons in 85 eV-sec. The recycled and remnant antiprotons have been previously merged and are contained between a pair of 2 kV barrier bucket pulses 1 μsec wide and separated by 5.5 μsec. The recycled beam has a maximum normalized 95% transverse emittance of 30 π mmmr.

During the stacking cycle the barrier bucket holding the recycled beam is compressed to 2.3 μsec and beam is added from the Accumulator. Transfers from the Accumulator occur at 2:00, 4:20, and 6:40 in the stacking cycle. Each transfer contains 4.66×10^{12} antiprotons in 10 eV-sec longitudinally and 10 π mmmr transversely.

At 7:20 a new batch of recycled antiprotons are injected and stored in a separate barrier bucket in the Recycler. These antiprotons can be cooling, but for simplicity the simulation assumes that the recycled beam is neither cooled nor heated until the beginning of the next cycle. The cooling of the stacked beam continues until 7:40, when the outer (unusable) 85 eV-sec of the cooled antiproton momentum distribution are combined with the recycled beam and the central 54 eV-sec are transferred to the

Tevatron. At this point the stacked beam has a normalized 95% transverse emittance of 10 π mmmr. At 8:00, the cooling cycle repeats.

A technical description of the cooling system is given in section 2.9.

2.1.11. Effect of Failures

The average luminosity is calculated using equation (2.1.11) and the parameter values for the store duration, fill time, and integrated luminosity per store. In tables such as 2.1.1 there is typically a row which contains the predicted integrated luminosity per week or month. This number is usually the integrated luminosity assuming the store is always at the peak luminosity the entire time period, and then derated by a factor of 3. This is commonly referred to as the Snowmass criterion. Given the average luminosity, a certain number of store hours in a week are thus required in order to achieve the Snowmass criterion. It turns out that the recently completed Run I had a ratio of peak to integrated luminosity which was consistent with the Snowmass criterion. In the case of Run II with the Recycler ring the same number of store hours per week will insure that the accumulation rate of integrated luminosity predicted in table 2.1.1 will be achieved.

During Run II the dominant anticipated type of failure is unintended antiproton loss in the Tevatron (i.e. the store ends unintentionally). During Run I Tevatron stores ended unintentionally at an average rate of twice per week. The worst time for such a failure is just after injection, when the antiproton stack size is at its minimum. In the scenario with the Recycler, during the couple of hours in which the cause of the store loss is investigated and the Tevatron is returned to an operational state, the recycled antiprotons have been recooled and are ready for immediate injection into the Collider. Therefore, a store at approximately half of the nominal luminosity can occur almost immediately.

Using the same simulations as those shown above, this store would have an initial luminosity of 1.1×10^{32} cm^{-2} sec^{-1} and after 12 hours would have accumulated 2.8 pb-1 of integrated luminosity, almost identical to the MI case where a full store was underway. During this time the stack size has grown to 204×10^{10} antiprotons assuming a stacking rate of 17×10^{10}/hr. The number of antiprotons recycled at this point is 72×10^{10}, and the initial luminosity of the next store is only 25% below Recycler scenario nominal. Assuming a normal store duration for that store, the subsequent store will have an initial luminosity which is 99% of nominal. In the absence of the Recycler, where the Accumulator is emptied to 40% of peak current each transfer, that same 12 hour period would yield no integrated luminosity. Therefore, the Recycler adds a level of versatility which makes the Tevatron Collider complex much more tolerant of unintentional Tevatron store losses.