Plans for

TEVATRON Run IIB

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1 Introduction

It is recognized that an experimental program, in the course of which greater than 15 fb^{-1} of integrated luminosity is delivered by the Tevatron complex to each of the two collider experiments, CDF and D0, has considerable discovery potential.[1] Achieving this integrated luminosity requires an increase in the instantaneous luminosity of a factor of 2-3 beyond that anticipated during Run IIa (the current run). The robustness of the physics program would be enhanced if more integrated luminosity could be achieved. The window of opportunity is bounded in time by the start of operation of the Large Hadron Collider for physics, which is anticipated towards the end of the decade.

Considerable work was done to examine the potential of the Tevatron complex to achieve such a goal. An extensive report[2] was prepared by April 1997 but not completed nor published. The plan described in this report includes a subset of the possibilities suggested in that report.

We concentrate on justifying the approach currently proposed, and describe a plan of execution, which we feel is responsive to the imperatives of the physics. In Chapter 2, we outline the overall strategy and scope. The components of the project are distributed throughout the accelerator complex. The priorities and schedules have been developed by balancing the difficulty and cost of each sub-component versus its potential to enhance the performance of the overall complex as a function of time. In Chapter 3, we describe the scope and current status of each of the sub-projects. In Chapter 4, we provide a summary of the needed resources, the cost and schedule. Finally in Chapter 5, we summarize.

2 Project Strategy, Scope & Goal

2.1 Collider Luminosity

The luminosity of the Tevatron collider may be written as

$$L = \frac{3\gamma_r f_0}{\beta^*}\left(BN_{\bar{p}}\right)\left(\frac{N_p}{\varepsilon_p}\right)\frac{F\left(\beta^*,\theta_x,\theta_y,\varepsilon_p,\varepsilon_{\bar{p}},\sigma_z\right)}{\left(1+\varepsilon_{\bar{p}}/\varepsilon_p\right)} \qquad (2.1.1)$$

where $\gamma_r=E/mc^2$ is the relativistic energy factor, f_0 is the revolution frequency, and β^* is the beta function at s=0 (where it is assumed to attain the same minimum in each plane). The proton (antiproton) beam transverse emittance $\varepsilon_p\,(\varepsilon_{\bar{p}})$ is defined to be $\varepsilon = 6\pi\gamma_r\sigma^2/\beta$ for a bunch with a gaussian distribution and assumed to be the same in both transverse planes (throughout this document we use the 95% normalized emittance), B is the number of bunches, $N_p\,(N_{\bar{p}})$ is the number of protons (antiprotons) per bunch, θ_y and θ_y are the crossing half-angles, σ_z is obtained from the rms proton and antiproton bunch lengths $\sigma_z^2 = \left(\sigma_{zp}^2+\sigma_{z\bar{p}}^2\right)/2$ and $F\leq 1$ is a form-factor that accounts for the depth of focus (hourglass) and crossing angle effects on the luminosity caused by non-zero bunch lengths. The bunch lengths depend on the longitudinal emittance and the rf voltage, but the luminosity depends only on the bunch lengths. In Run IIa, the form-factor is dominated by the hourglass effect (the design crossing-angle is 0). For gaussian beams the hourglass effect may be written as:

$$F = \frac{\sqrt{\pi}\beta}{\sigma_z} e^{\frac{\beta^2}{\sigma_z^2}} \operatorname{erfc}\left[\frac{\beta}{\sigma_z}\right] \qquad (2.1.2)$$

where the complementary error function is related to the error function by $\operatorname{erfc}(z) = 1-\operatorname{erf}(z)$. For Run IIb the crossing angle effect is large and the luminosity comes mainly from the z=0 region where the hourglass effect is small. In this case the form-factor F may be written as

$$F = \frac{1}{\sqrt{1+\sigma_z^2\left(\theta_x^2/\sigma_x^2+\theta_y^2/\sigma_y^2\right)}} \qquad (2.1.3)$$

where $\sigma_x^2 = \left(\sigma_{xp}^2+\sigma_{x\bar{p}}^2\right)/2$ and similarly for y.

The luminosity formula Eq. (2.1.1) is written so as to emphasize the major issues in achieving high luminosity. The first quantity in parentheses is the total number of antiprotons. Under current and probably future operating conditions, the most important factor contributing to the achievable luminosity is the total number of antiprotons in the ring, $BN_{\bar{p}}$. The second most important factor is the proton phase space density, N_p/ε_p, which is constrained by the need to limit the beam-beam tune shift. The form-factor (F) and the emittance ratio $\varepsilon_p/\left(\varepsilon_p+\varepsilon_{\bar{p}}\right)$ are important, but they cannot exceed unity and the amount of luminosity that can be gained using these factors is limited.

2.1.1 Beam-Beam effect

The formula for the (linear) antiproton beam-beam tune shift with no crossing angle is:

$$\Delta\nu = 6\frac{r_p}{4\pi} n_c \frac{N_p}{\varepsilon_p}$$
$$= 0.0073\ (\pi\,\text{mm-mrad}/10^{10})\ n_c \frac{N_p}{\varepsilon_p}$$

(2.1.4)

where r_p is the classical proton radius (1.535x10^{-18} m) and n_c is the number of interaction points. Operating experience in the Tevatron suggests that the maximum tolerable beam-beam tune shift lies in the range 0.02 to 0.025.

When the beam-beam tune shift is caused primarily by head-on interactions at zero crossing-angle, the beam-beam tune shift determines the maximum value of the factor N_p/ε_p, which appears in Eq. (2.1.1). For Run IIb, the formula Eq. (2.1.4) does not apply. In Run IIb, the beams cross at an angle to avoid unwanted beam-beam interactions near the interaction region. The crossing angle at the interaction region dramatically reduces the beam-beam tune shift (some higher order effects increase), and the sum of the long range interactions cause tune shifts comparable to those at the interaction points. These crossing angle and long range effects depend on both N_p and ε_p separately, and may partially cancel depending on the detailed geometry of the beams and their orbits. These issues are discussed in considerably more detail elsewhere[3]. With a naive application of Eq. (2.1.4) as a guide and considering the complicated nature of the beam-beam interaction, increasing N_p/ε_p in order to increase the collider luminosity is probably severely limited·

2.1.2 Antiproton Production

Of the many technical issues involved with high luminosity proton-antiproton colliders, there is probably no more fundamental limitation than the requirement that antiprotons must be produced at least as rapidly as they are consumed in beam-beam collisions. The minimum production rate is

$$\Phi_{\bar{p}}^{(\min)} = n_c \sigma_a L$$

(2.1.5)

where n_c is the number of collision points and L is the luminosity. The cross-section is the cross-section for scattering outside the acceptance of the Tevatron. This cross-section is only slightly less than the total cross-section. We assume that σ_a is 70 mb at 1000 GeV. With 2 collision points a luminosity of 4.0x10^{32} cm^{-2}-sec^{-1} is sustained with a minimum antiproton production rate of 20×10^{10} hr^{-1}.

A more realistic estimate of the antiproton flux must take into account the fact that antiprotons beam-beam collisions are not the only mechanism for antiproton loss. We define the antiproton utilization efficiency as the number of antiprotons lost through beam-beam collisions divided by the total number of antiprotons produced. During the latter part of Run Ib the antiproton utilization efficiency was about 7%.[i]

The second consideration in determining the antiproton flux required is that neither the luminosity nor the stacking rate is constant. For example, during the Run Ib period referred to above the Tevatron was producing beam-beam collisions for the experiments 51%[ii] of the time. The average initial luminosity of these stores was 1.25×10^{31} cm^{-2}-sec^{-1}, but the average rate of accumulating luminosity during a store (29 nb^{-1}/hr) corresponds to a luminosity 35%[iii] lower. Thus, the Run Ib experience is consistent with the "Snowmass Criterion": that the integrated luminosity obtained is equal to the peak luminosity times the length of the run divided by 3. The peak stacking rate during Run Ib was $7.2\text{x}10^{10}$ hr-1. During the same Run Ib running period the antiproton source was stacking 62% of the time at an average rate of $4.3\text{x}10^{10}$ hr-1 (60% of the peak value[iv]). Thus, the total number of antiprotons accumulated was 37% (also roughly 1/3) of the peak rate times the length of the run. It should be noted that the percentages of time given for both the Tevatron and the Antiproton Source have no corrections for effects such as scheduled and unscheduled maintenance; they represent actual operating experience during an extended run.

The antiproton utilization efficiency must increase dramatically for Run IIa when the luminosity is expected to increase to 2×10^{32} cm^{-2}sec^{-1} from the Run Ib value of 2×10^{31} cm^{-2}sec^{-1} while the stacking rate increases from 7×10^{10} hr^{-1} to 20×10^{10} hr^{-1}. If the duty factors and efficiencies experienced in Run Ib were to remain the same, then the antiproton utilization efficiency would have to increase to 42%. However, the use of the Recycler as post-Accumulator should side-step the problem of reduced stacking rate when the Accumulator stack size increases above about 50×10^{10}. Accounting for the increase in average stacking rate and assuming a negligible inefficiency in the process of transferring beam to the Recycler, an antiproton utilization of perhaps 25% would be sufficient to achieve the Run IIa goals. The increase in antiproton utilization efficiency is expected to arise from improved transmission through the Main Injector, from avoiding the inefficiency of coalescing the antiproton bunches, and from the recovery of unspent antiprotons by the Recycler at the conclusion of a Tevatron store.

For the purposes of the Run IIb design, we assume that the Run IIa goals will be met but that there will be no further increases in the antiproton utilization efficiency (see Table 2.1). Under these assumptions, the increase in luminosity is directly proportional to the increase in stacking rate, and we conclude that peak stacking rates of about $6\text{x}10^{11}$ antiprotons per hour are required to support two interaction regions at $4\text{x}10^{32}$ cm^{-2}-sec^{-1}. This rate is a 5-fold increase in stacking rate over the Tevatron I design, a 6-fold increase over the best stacking rate achieved, and a 3-fold increase over the projected Run II stacking rate. Clearly, dramatic increases in the antiproton production rate are an essential element of any plan to achieve a luminosity of $4\text{x}10^{32}$ cm^{-2}-sec^{-1} in the Tevatron proton-antiproton collider.

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[i] During the period October 1, 1994 to July 23, 1995 100.5 pb-1 of integrated luminosity was delivered to each of the two experiments and $1.91\text{x}10^{14}$ antiprotons were produced.
[ii] Reliability row in Table 2.1
[iii] Store Efficiency Factor row in Table 2.1
[iv] Pbar Production Efficiency row in Table 2.1.

Run	Ib	IIa (without Recycler)	IIa (with Recycler)	IIb	
Typical Luminosity	1.6	8.6	11.9	41.0	$x10^{31}cm^{-2}sec^{-1}$
Integrated Luminosity	3.1	17.1	23.4	80.9	pb^{-1}/wk
Interactions/crossing	2.5	2.2	1.1	3.7	
Pbar Bunches	6	36	103	103	
Store efficiency factor	0.65	0.65	0.65	0.65	
Form Factor	0.59	0.74	0.40	0.40	
Protons/bunch	23.0	27.0	27.0	27.0	$x10^{10}$
Pbars/bunch	5.6	3.1	2.7	9.4	$x10^{10}$
Pbars lost in collisions	8.4	34.1	46.8	161.7	$x10^{10}$
Total pbars	33.6	110.2	278.8	963.4	$x10^{10}$
Peak Pbar Prod. Rate	7.0	17.0	19.0	62.0	$x10^{10}$/hr
Avg. Pbar Prod.Rate	4.2	10.2	16.2	55.8	$x10^{10}$/hr
Pbar Prod. Eff.	60	60	85	90	%
Reliability	50	50	50	50	%
Pbar Transmission Eff.	50	90	90	90	%
Recycling efficiency	0	0	50	50	%
Pbar Utilization	12	28	24	24	%
β*	35	35	35	35	cm
Bunch Length (rms)	0.6	0.37	0.37	0.37	m
Energy	900	980	980	980	GeV
Bunch Spacing	3500	396	132	132	nS
Crossing 1/2 Angle	0	0	136	136	μrad per plane
Proton Emittance	23	20	20	20	π-mm-mrad
Pbar Emittance	13	15	15	15	π-mm-mrad
Luminosity lifetime	17	13	13	13	hr
Store Length	16	12	12	12	hr

Table 2.1 *Run II parameter table*.[i]

2.2 Run IIa Expectations

Table 2.1 is a working parameter table for Run IIa. It illustrates the changes required to achieve the Run IIa luminosity goals and also the benefits of antiproton recycling. Run IIa requires a modest improvement in proton intensity and about 8 times more antiprotons (spread over 6 times more bunches). The peak antiproton stacking rate is required to increase substantially (about a factor of 3) to produce the necessary antiprotons.

[i] The Run Ib column represents average of 32 stores over the period March 8-April 21, 1995

2.2.1 The Main Injector

The Main Injector project without the Recycler ring should provide initial luminosities up to 8.6×10^{31} $cm^{-2}sec^{-1}$. The Main Injector project goals are shown in Table 2.*2*. The major components of the Main Injector project are:

1. more protons on the antiproton production target (1.7x)
2. faster cycle time for antiproton production (1.6x)
3. increased antiproton transmission through the accelerator complex (1.8x)
4. shorter bunch lengths in the Tevatron because of improvements in RF coalescing efficiency (1.25x)
5. more protons per bunch in the Tevatron (1.17x)

Parameter	Goal	
Intensity per bunch	6×10^{10}	
Total Pbar production intensity	5×10^{12}	(84 bunches)
Proton beam transverse emittance	18π	mm-mrad
Proton beam longitudinal emittance	0.2	eV-sec
Main Injector transverse admittance (@8.9 GeV)	$40\ \pi$	mm-mrad
Main Injector longitudinal admittance (@8.9 GeV)	0.5	eV-sec
Coalesced bunch intensity	3×10^{11}	(per bunch)
Coalesced bunch transverse emittance	$18\ \pi$	mm-mrad
Coalesced bunch longitudinal emittance	2.0	eV-sec

Table 2.*2 Main Injector Project Goals*

2.2.2 The Recycler Ring

The Recycler ring will further increase the initial luminosity to a level of 2×10^{32} $cm^{-2}sec^{-1}$ by:

1. recovering antiprotons from the Tevatron (1.6x)
2. raising the average antiproton production rate. (1.4x)

The Recycler is described elsewhere.[4] The most important design goal is to recover, on average, 50% of the antiprotons that could potentially be recovered. This goal could be met, for example, if 75% of the antiprotons are recovered from 75% of the stores that end normally[i]. We assume that we will continue to achieve the 50% antiproton recovery efficiency for Run IIb despite the increased number of bunches, the higher intensities, and (possibly) somewhat larger emittances.

The average antiproton production rate will be increased by the Recycler ring because the antiproton stack in the Accumulator will be transferred to the Recycler before the stochastic cooling systems in the Accumulator saturate. Antiproton transfers from the Accumulator to the Recycler must be done relatively quickly, with good efficiency, and minimal phase space dilution. Since antiproton transfers from the Accumulator to the Recycler will be done much more frequently in Run IIb, this transfer process will be revisited in Run IIb.

[i] In Run Ib 71% of the stores were intentionally terminated. The others typically ended because of the failure of some critical component.

2.2.3 The Tevatron

Initial operation in Run IIa will be with 36 proton bunches and 36 antiproton bunches. As the luminosity approaches 2×10^{32} $cm^{-2}sec^{-1}$, the number of interactions per crossing will rise to a level that may be unacceptable to the detectors. At this point, the number of bunches will be increased by a factor of about three. The bunch spacing would shrink from 396 nS to 132 nS. At 132 nS bunch spacing, a crossing angle will have to be introduced at the detectors in the Tevatron to eliminate unwanted parasitic crossings. This crossing angle (136 μrad ½ angle per plane) will unfortunately reduce the luminosity by ~40% to 1.2×10^{32} $cm^{-2}sec^{-1}$.

In order to recycle the antiprotons, they must be separated from the protons. We plan to eliminate the protons at the end of a Tevatron store, before deceleration. This plan has the advantage of making the deceleration process much easier because of the absence of beam-beam interaction effects. In addition, this scheme allows the deceleration of the antiprotons on the central orbit which has better field quality and more aperture than the helical orbit used for acceleration. However, the plan does require removal of the protons from the Tevatron at high field, when the Tevatron magnets have the least margin against quenches induced by beam loss. While we have substantial experience with removing the protons with scrapers for special experiments (the proton and antiproton beams are spatially separated), it typically takes half an hour to complete the process. Improvements both in technique and speed would be highly desirable. At the moment, it is uncertain how this goal will be accomplished in Run II.

The Run IIb parameters require the removal of about 3 times the number of proton bunches. The techniques established for Run II may require modification. We assume that an adequate solution will be found based on Run II experience.

2.3 Run IIb Strategy

The key feature in the Run IIb parameter list is to increase the antiproton production rate by a factor of three over Run IIa. The major components of the plan are:

1. Increase the number of protons on the antiproton production target
2. Increase the antiproton collection efficiency by:
   a. Increasing the gradient of the antiproton collection lens
   b. Increasing the aperture of the antiproton collection transfer line and Debuncher ring
3. Increase the antiproton flux capability of the Accumulator Stacktail momentum stochastic cooling system
4. Implement electron cooling in the Recycler Ring
5. Streamline and improve antiproton transfers between the Accumulator and the Recycler.

In addition to increasing the number of antiprotons in the collider, we are pursuing an ambitious research program aimed at reducing beam-beam effects in the Tevatron collider with an electron lens.

The following sections will give a brief overview of each of the Run IIb projects.

2.3.1 Protons on the Antiproton Production Target

Studies[5] have shown that in order to achieve very high performance of the proton source (Linac and Booster) there are many issues that would need to be addressed. In turn this results in a rather expensive project to make big improvements in the intensity of protons out of the Main Injector. We therefore have concentrated on a project called slip-stacking that takes advantage of the large momentum acceptance of the Main Injector and the fast cycle rate of the Booster.

With slip-stacking, two successive Booster batches are injected into Main Injector and coalesced into a single batch via RF manipulations. This project has the potential of doubling the amount of protons on the antiproton production target for a single Main Injector acceleration cycle. However, the minimum size of the longitudinal phase space of the combined batch must be at least double the size of a single Booster batch. This larger longitudinal phase space would result in larger bunch lengths of the protons on target but because of inherent non-linearities in the antiproton debunching process, the larger proton bunch lengths do not translate into larger final momentum spread of the antiprotons after debunching. The length of time it takes to accelerate the second Booster batch plus the time it takes to coalesce both batches will add about 10% to the length of the Main Injector acceleration cycle. Assuming negligible loss during the coalescing and acceleration process, we are expecting an effective increase by a factor of 1.8 in the number of protons on target per unit time.

The advantage of this project is that it requires relatively simple electronics to be installed into the Main Injector low-level RF system, which can be done parasitically during Run IIa operations. The main disadvantage of this project is that it involves RF manipulations of intense beams at very low RF voltages resulting in a severe beam-loading situation. We plan on correcting the beam-loading with direct RF feedback around the RF cavities in the Main Injector. Simulations show that very large loop gains are needed to remove the beam loading to a sufficient level. The large loop gains are associated with a number of stability issues.

When the Main Injector starts providing beam for the NUMI project sometime in 2004-2005, the Main Injector acceleration cycle time will have to be increased by about 20% to accommodate the injection of five extra Booster batches destined for the NUMI target. The effective increase in the number of protons on target from Run IIa to Run IIb will then be reduced from a factor of 1.8 to a factor of 1.5.

2.3.2 Antiproton Collection

The phase space of the antiprotons produced from the production target is much larger than the collection aperture of the transfer line (AP2) connecting the target to the Debuncher ring and the Debuncher ring itself. The production efficiency of 15 antiprotons per 10^6 protons on target achieved in late Run Ib was a result of an effective 150 π-mm-mrad (normalized) collection aperture. By increasing the collection aperture to 300-400 π-mm-mrad, we can expect an increase in antiproton production efficiency to 29-35x10^{-6} antiprotons/proton. There are only a few physical apertures in the collection system that are smaller than 400π-mm-mrad. Most of the aperture limitations are a result of misalignment. A large fraction of this project will be to align the apertures of collection components using beam-based alignment techniques. The small number of components that do not have the 400 π-mm-mrad physical aperture will be upgraded or replaced.

A pulsed Lithium Lens is used to focus the antiprotons into the AP2 beamline. If the lens gradient can be increased from the present 750 T/m to 1000 T/m (the TEV I design goal), the antiproton production efficiency would increase to 32×10^{-6} for a 300 π-mm-mrad aperture and 40×10^{-6} for a 400 π-mm-mrad aperture. The Lithium lenses exhibit a finite lifetime, which is lower for higher gradients. Although the understanding of lens failure is not complete, the current design has certain identifiable weaknesses. Two approaches are being pursued. On the one hand, a new solid-Lithium lens design is well advanced. On the other, an R&D project, involving the use of liquid Lithium, is underway in collaboration with the Budker Institute, Novosibirsk. Since the handling of liquid Lithium is very difficult, the liquid lens is treated as more speculative than the solid lens work.

By increasing the lens gradient and the collection aperture, the combined increase in production efficiency could be a factor of 2.0 – 2.7 over Run Ib.

2.3.3 Antiproton Source Stochastic Cooling

The 4-8 GHz Debuncher stochastic cooling upgrade that was completed before the start of Run IIa was designed to accommodate the antiproton fluxes that were anticipated for Run IIb[6]. The Stacktail momentum stochastic cooling system in the Accumulator was designed to cool relatively large stacks for Run IIa. Large stacks in the Accumulator place severe constraints on how much antiproton flux the Stacktail system can accommodate because of the limited dynamic range of the system.

In Run IIb, the antiprotons will be transferred to the Recycler before the Accumulator stack size becomes too big. With the constraint of large stacks removed, the Stacktail system can be reconfigured so as to accommodate the large increase in antiproton flux. We feel that this reconfiguration can be done with the present 2-4 GHz bandwidth system so that very little (if any) new hardware would have to be built. The downside of this approach is that the stacktail system will do less cooling and place a larger burden of cooling on the Debuncher and Recycler momentum cooling systems. An alternative approach is to upgrade the Stacktail momentum system to 4-8 GHz as was suggested in the TEV33 draft Report.[2] However, building stochastic cooling electrodes that function at 8 GHz in the high dispersion sections of the Accumulator is thought to be exceeding difficult.

2.3.4 Recycler Electron Cooling

As mentioned in the preceding section, the brunt of momentum cooling large antiproton stacks will be placed on the Recycler ring. At present, stochastic cooling is installed in the Recycler Ring. Because the cooling rate of stochastic cooling systems is inversely proportional to the number of particles, the antiproton accumulation rate will deteriorate as the stack grows bigger.

Electron cooling can reduce the spread in all three components of beam momentum simultaneously. Its primary advantage over stochastic cooling is that the cooling effect is practically independent of antiproton beam intensity up to the Recycler stack sizes of about 2×10^{13} antiprotons. Its greatest disadvantage is that the effect is very weak until the antiproton emittances are already close to the values wanted in the collider. Thus, the two processes can be seen as complementary rather than competitive. Electron cooling will prove very powerful in the Recycler as an add-on to the stochastic pre-cooling in the Antiproton Source and Recycler.

For electron cooling to work, the particle velocity of the electron beam must match the velocity of the antiproton beam. Since we are going to use electron cooling to cool 8 GeV antiprotons, the energy of the electron beam must be 4.3 MV. To obtain sufficient cooling rates for Run IIb, the electron beam current will be about 300 mA resulting in electron beam power of 1.3 MW. Since present high voltage sources for cold electron beams can only provide power in the range of tens of kilowatts, extremely high re-circulation efficiency of the electron beam must be obtained.

A major R&D program has been underway for some years to develop an electron cooling capability at Fermilab. The practice and principles of electron cooling are well established for ions with kinetic energy of less than 500 MeV/nucleon. For antiprotons at 8 GeV, the fundamentals are the same, but hardware development is required and the technical problems differ. To date, electron cooling at relativistic energies remains an unproven technology, and thus constitutes a high-risk segment of the Run2b upgrades plan. Fermilab is currently the only laboratory pursuing the high-energy electron cooling R&D at full scale

2.3.5 Rapid Antiproton Transfers

One of the key improvements of the Main Injector project was improved antiproton transfer efficiency though the accelerator complex. For Run IIb, the same transfer efficiency is needed. Presently, at each 8 GeV antiproton transfer between the Accumulator to the Main Injector, we spend well over one hour preparing the transfer line. The long setup time is the result of many undesirable features of operating this line at low energies where hystersis effects and tight physical apertures have serious consequences.

During Run IIb, transfers between the Accumulator and Recycler will occur every fifteen minutes. Clearly, the setup time for the transfer line should be a small fraction of this interval. One approach would be to replace the 8 GeV operation of this line with the construction of a single dedicated 8 GeV transfer line. However, this option would be extremely expensive and installation would require significant interruption to integrating luminosity during Run IIa .

The approach that we have decided for Run IIb is a careful analysis and redesign of the optics at 8 GeV and to develop a rigorous set of protocols for handing hysterisis effects. In addition, operational aspects of the 8 GeV will be streamlined with more diagnostics and software. With a more forgiving optics design and frequent transfers, we expect the effects of pulse-to-pulse variations on the performance of the line should be greatly diminished.

2.3.6 Antiproton Tuneshift in the TEVATRON

In the Tevatron, the antiproton bunches suffer a tuneshift due to their interactions with the more intense proton bunches. In multibunch operation, the tuneshifts vary from antiproton bunch to antiproton bunch, leading to an effective spread in tune. An electron lens, consisting of a short, low energy, electron beam propagating along the axis of a solenoidal field, can induce a tuneshift on the antiproton bunches, which has the opposite sign to that, which they experience, from the protons. With appropriate choice of parameters two such lenses could provide effective beam-beam tuneshift compensation. An R&D program has resulted in the construction and, recently, the successful testing of a single such device. If results continue to be positive the use of such devices could lead to a longer luminosity lifetime in the Tevatron and hence to a large integrated luminosity. Because of the R&D nature of this project, we have not explicitly assigned any luminosity gains for Run IIb from this project. As mentioned earlier, operations with up to 6 bunches each of protons and antiprotons appear possible for antiproton tune shift parameters up to 0.02-0.025. Although there is no experience as yet with larger numbers of bunches, controlling the tune spread of the antiprotons whether bunch-to-bunch or within a bunch will be an important aspect. We therefore see the Tevatron electron lens as a potentially important new tool. As this project matures, we will evaluate its role in Run IIb.

3 Sub-Project Description

The goal of Run IIb accelerator upgrades is to triple the antiproton production rate over the anticipated Run IIa target. In this chapter, we describe the scope and current status of each of the sub-projects. Before these projects are described in detail, a brief overview of the Fermilab accelerator complex will be given.

The Fermilab Collider Accelerator Complex

The Fermilab accelerator complex is shown in Figure 3.1. Antiproton production at Fermilab begins with the production of H- ions that are accelerated to 750 keV in the Crockoft-Walton pre-accelerator. The ions are injected into the Linac were they are accelerated to a kinetic energy of 400 MeV. The H- ions are stripped of their electrons at injection into the Booster. The stripping of H- ions allows the production of high intensity proton beams by multi-turn injection. Typically ten to eleven turns are injected into the Booster. The Booster RF systems bunches the proton beam into 84 bunches. The train of 84 bunches is called a Booster "batch". The Booster accelerates the protons to 8 GeV. The Booster can support an acceleration cycle rate of 15 Hz. At 8 GeV, the batch of protons is extracted from the Booster into the MI-8 transfer line and injected into the Main Injector. The Main Injector accelerates the beam to 120 GeV. The beam at 120 GeV is kicked out of the Main Injector into the P1 transfer line.

The P1 transfer line extends from the Main Injector to the Tevatron. At the end of the P1 line the beam flows into the P2 line. The P2 line is actually a remnant of the old Main Ring Accelerator. The P2 line connects to the AP1 transfer line. At the end of the AP1 transfer line is the antiproton target station. The 120 GeV protons hit a nickel target and the resulting secondary beam is transferred into the AP2 transfer line. The first magnetic element of the AP2 line is the lithium lens. The AP2 line accepts only 8 GeV secondaries (with a 5% momentum spread) and funnels the beam into the Debuncher ring. The Debuncher ring has a slightly larger circumference than the Booster Ring. The primary purpose of the Debuncher ring is to reduce the large momentum spread of the antiproton beam by bunch rotation. The debunching process lasts about 60 mS. Since the Main Injector requires a minimum acceleration period of 1.5 S, the antiproton beam is stochasticly pre-cooled in the Debuncher for the remaining time.

Just prior to the extraction of another 120 GeV proton batch from the Main Injector to the target station, the pre-cooled antiproton beam is transferred from the Debuncher to the injection orbit of the Accumulator storage ring. The longitudinal phase space density of the antiproton beam is compressed by a factor of 10,000 by the Accumulator Stacktail momentum stochastic cooling system. After enough antiprotons have been accumulated in the core orbit of the Accumulator, the antiproton production process is halted. The beam is bunched with the Accumulator RF systems and extracted out of the Accumulator into the AP3 transfer line. The AP3 line connects back up to the AP1 line. For antiproton transfers, the energy of the AP1, P2, P1 and Main Injector is set to 8 GeV. The antiprotons follow the reverse route to Main Injector and during the latter part of Run IIa will be injected into the 8 GeV Recycler Ring were the beam will be cooled with previously injected stacks from the Accumulator.

When the Tevatron is ready for another collider store, the proton beam will be preferentially scraped away at 980 GeV. The remaining antiprotons will be decelerated to 150 GeV in the Tevatron and transferred back to the Main Injector via the P1 line. The antiprotons are decelerated to 8 GeV in the Main Injector and transferred to the Recycler for assimilation into the stored core of antiprotons.

With the Tevatron energy set at 150 GeV, a batch of protons is accelerated to 8 GeV in the Booster. However, only seven of the 84 bunches are extracted out of the Booster and transferred into the Main Injector. The seven bunches are accelerated to 150 GeV in the Main Injector. At 150 GeV the seven bunches are coalesced into a single bunch by a series of longitudinal bunch rotations using RF systems of several different harmonics. The single proton bunch is injected into the Tevatron. This process is repeated for the desired number of bunches in the Tevatron (36 in Run IIa. The switch to 132 nS operation will require multi-bunch coalescing.) Once the Tevatron is filled with protons, antiprotons are extracted out of the Recycler and coalesced into high intensity bunches in a similar process. The antiprotons are transferred from the Main Injector to the Tevatron via the A1 line. Once the Tevatron is filled with protons and antiprotons, the Tevatron is ramped to an energy of 980 GeV and the proton and antiproton beams are brought into collision.

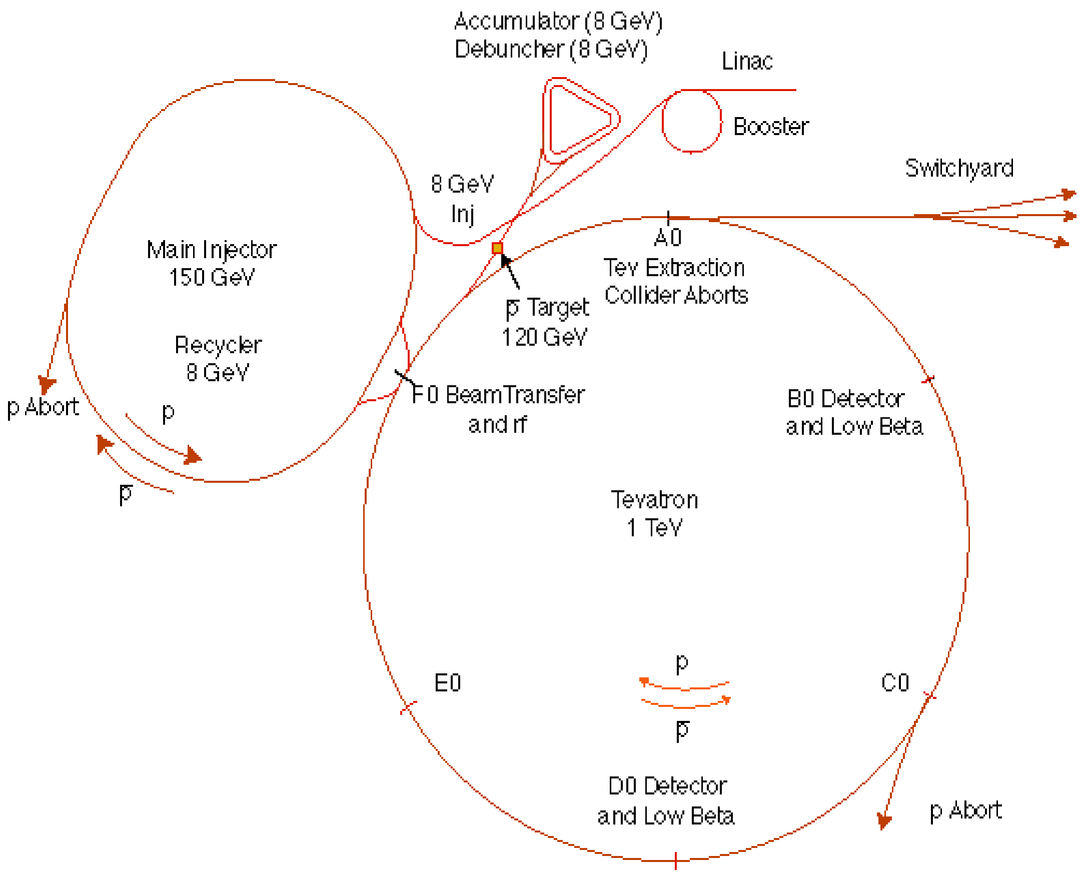

Figure 3.1 *The Fermilab Accelerator complex.*