1. INTRODUCTION AND SUMMARY*

The Tevatron proton-antiproton Collider is the highest-energy particle collider currently operational anywhere in the world. To exploit this unique tool fully, and to meet the goals of the Fermilab high energy physics research program through the 1990's and into the twenty-first century, a phased upgrade of the Fermilab accelerator complex is underway. The initial Run II goal is to achieve a luminosity of 5×10^{31} cm^{-2}sec^{-1} and an integrated luminosity of 2 fb^{-1}. It is thought that the ultimate potential of the initial Run II upgrades is to achieve luminosities up to 2×10^{32} cm^{-2}sec^{-1}. Some of this potential will be need to achieve the Run II goal for integrated luminosity in a reasonable length of time–say 2 years–after the initial luminosity goal is reached. The Run II luminosity goals are about a factor of 100 increase over the original 1.0×10^{30} cm^{-2}sec^{-1} design goal of the Tevatron Collider, accompanied by creation of simultaneous high intensity fixed target capability at 120 GeV.

The first phase of the upgrade program, an increase in the Linac energy from 200 MeV to 400 MeV, was completed in 1993 and has supported Tevatron collider operations at luminosities in the range of 1.5-2.5×10^{31} cm^{-2}sec^{-1} during Run Ib. The second phase of the upgrade involves the replacement of the existing Main Ring with a new accelerator, the Fermilab Main Injector, and the construction of a new antiproton storage ring, the Recycler, within a common tunnel. The Main Injector and Recycler together are expected to support a luminosity in excess of 1×10^{32} cm^{-2}sec^{-1} in the Tevatron collider. Improved performance is based on enhanced antiproton production, storage, and recovery capabilities following initiation of Main Injector and Recycler operations. In addition the Main Injector is designed to provide a slow (or fast) resonantly extracted 120 GeV beam containing 3×10^{13} protons with a 2.9 (or 1.9) second cycle time.

The Fermilab Main Injector is a large aperture, rapid cycling, proton synchrotron designed specifically to address the fundamental limitations inherent in the present Main Ring. With the advent of the Tevatron at Fermilab the role of the Main Ring changed significantly from its original mission of delivering 400 GeV protons for fixed-target operations. The conversion of the Main Ring to a supporting role in the early 1980s introduced a completely new set of operational requirements that were never envisaged in the original Main Ring design. Accommodating the needs of antiproton production, bipolar injection into the Tevatron, and physical avoidance of the colliding detector experiments has inevitably resulted in reduced Main Ring performance characteristics. Possible enhancements to the physics program, such as test beams for detector development and high intensity/low energy proton beams for high energy physics research, are all precluded by the present operational and physical constraints in the Main Ring. The replacement of the Fermilab Main Ring by the Main Injector addresses all of these issues in an elegant and efficient manner.

The Recycler Ring, which will be installed in the Main Injector enclosure, will provide a factor of ~2 in luminosity beyond that projected with the Main Injector alone, as well as providing a platform from which an additional increases in luminosity could be achieved. The initial (Run II) performance goals established for the Recycler ring are a stacking rate of 2×10^{11} antiprotons/hour, a total storage capability of 3×10^{12} antiprotons, and a capability for re-cooling relatively large emittance antiprotons recovered from the Tevatron via the Main Injector.

This report presents the design and operating parameters of the Fermilab Main Injector, the Recycler, and the remainder of the Tevatron complex during the initial operating cycle of the Main

* Last revised on July 17, 1998.

Injector era--a cycle referred to as Collider Run II. It should be noted that while many of the improvements described in this report are expected to form a basis for even greater luminosities, up to 1×10^{33} cm^{-2}sec^{-1} in the long term. Some of these concepts and improvements are discussed in subsequent chapters, but a complete description of the nature and feasibility of these improvements is beyond the scope of the Run II Handbook.

Table 1.1 summarizes the operational performance of the last collider run, Run Ib, accompanied by operational goals for the complex in Run II. Normalized emittances containing 95% of the beam are quoted. The horizontal and vertical emittance goals are equal as are the proton and antiproton bunch length goals. The antiproton intensity shown in the center column of the table is more than sufficient to achieve the initial Run II goal of 5×10^{31} cm^{-2}sec^{-1}, but is not expected to be the maximum that could be obtained with 36×36 operation. In particular, the Recycler was designed to stochastically cool enough antiprotons to obtain a luminosity of 2×10^{32} cm^{-2}sec^{-1}. However, as the luminosity increases the number of interactions increases and adversely affects the particle detector trigger rates and the ability of the experimenters to interpret the data.

One way to reduce the number of interactions per crossing is to increase the number of bunches. The rightmost column illustrates operation with 121 bunches at 132 nsec spacing. The number of bunches is tentative (see the discussion in Chapter 6) but the 132 nsec spacing is set by the trigger hardware at the experiments. The bunch parameters in the rightmost column are identical to those for 36×36 operation, but more than 3 times the number of antiprotons (121/36 to be exact) are required. The luminosity is increased by less than a factor of 2 because of the luminosity penalty incurred by the introduction of the 136 μrad crossing angle. This mode of operation is attractive when the antiproton production rate and recycling efficiency are high and the number of interactions per crossing are a concern. A more detailed discussion of the considerations of luminosity, store length, store lifetime, and the number of interactions per crossing are shown in Chapter 6.

Table 1.1. Operational performance in Run I and goals for Run II. The leftmost column shows parameters typical of the last collider run, Run Ib. The middle column shows parameters exceeding the initial Run II with 36×36 operation, and the rightmost column illustrated the performance obtained with the same bunch parameters but filling 121 antiproton bunches at a 132 nsec bunch spacing instead of the 36 that will be used initially. Normalized emittances containing 95% of the beam are quoted. The horizontal and vertical emittances are assumed equal and proton and antiproton bunch lengths are assumed to be equal.

RUN	Ib (1993-95) (6x6)	Run II (36x36)	Run II (140x121)	
Protons/bunch	$2.3x10^{11}$	$2.7x10^{11}$	$2.7x10^{11}$	
Antiprotons/bunch*	$5.5x10^{10}$	$3.0x10^{10}$	$3.0x10^{10}$	
Total Antiprotons	$3.3x10^{11}$	$1.1x10^{12}$	$3.6x10^{12}$	
Pbar Production Rate	$6.0x10^{10}$	$2.0x10^{11}$	$2.0x10^{11}$	hr^{-1}
Proton emittance	23π	20π	20π	mm-mrad
Antiproton emittance	13π	15π	15π	mm-mrad
β*	35	35	35	cm
Energy	900	1000	1000	GeV
Antiproton Bunches	6	36	121	
Bunch length (rms)	0.60	0.37	0.37	m
Crossing Angle	0	0	136	μrad
Typical Luminosity	$0.16x10^{31}$	$0.86x10^{32}$	$1.61x10^{32}$	$cm^{-2}sec^{-1}$
Integrated Luminosity†	3.2	17.3	32.5	pb^{-1}/week
Bunch Spacing	~3500	396	132	nsec
Interactions/crossing	2.5	2.3	1.3	

*The antiproton intensities given are merely examples. Higher antiproton intensities yield proportionally higher luminosities. The initial Run II upgrades are expected to have the ultimate potential to achieve luminosities of $2x10^{32}$ with 36 antiproton bunch operation.

†The typical luminosity at the beginning of a store has traditionally translated to integrated luminosity with a 33% duty factor. Operation with antiproton recycling may be somewhat different.

1.1 Tevatron Performance in Run Ib

The Tevatron Collider operated in Run Ib with a typical luminosity at the beginning of a store of $\sim 1.6\times 10^{31}$ $cm^{-2}sec^{-1}$. In the absence of a crossing angle or position offset, the luminosity in the Tevatron is given by the expression:

$$L = \frac{fBN_p N_{\bar{p}}}{2\pi(\sigma_p^2 + \sigma_{\bar{p}}^2)} F(\sigma_l / \beta^*) \qquad [1.1]$$

where f is the revolution frequency, B is the number of bunches in each beam, N_p ($N_{\bar{p}}$) is the number of protons (antiprotons) in a bunch, σ_p ($\sigma_{\bar{p}}$) is the rms proton (antiproton) beam size at the interaction point, and F is a form factor that depends on the ratio of the bunch length, σ_l, to the beta function at the interaction point, β*. The luminosity can be rewritten in a form that more directly displays its dependences on the limiting factors within the Tevatron complex:

$$L \propto \frac{3\gamma f \xi (BN_{\bar{p}})}{\beta^* N_{IR}(1+\frac{\varepsilon_{N\bar{p}}}{\varepsilon_{Np}})} F(\sigma_l / \beta^*) \quad . \qquad [1.2]$$

Here ε_N represents the normalized transverse emittance containing 95% of the beam, N_{IR} is the number of interaction regions, and ξ is the total head-on beam-beam tune shift seen by the antiprotons:

$$\xi = \frac{r_o}{4\pi}\frac{N_p}{\varepsilon_{N_p}} N_{IR} = .000733 \frac{N_p}{\varepsilon_{N_p}} N_{IR} \qquad [1.3]$$

where r_o is the classical radius of the proton. The numerical expression on the right of (1.3) is evaluated with N_p in units of 10^9 and ε_{Np} in units of π mm-mrad.

Fundamental limitations are related to the quantities ξ and ($BN_{\bar{p}}$). The beam-beam tune shift that can be tolerated by the antiprotons is believed to be limited by the tune space available between resonances up to about tenth order; tune shifts as high as 0.024 have been found to be tolerable. The second quantity, ($BN_{\bar{p}}$), represents the total number of antiprotons in the collider. Note that for a given total number of antiprotons, the luminosity does not depend explicitly on the number of bunches.

The performance of the Tevatron Collider during Run Ib represents a significant improvement relative to the previous collider run and is attributable to completion of the Linac upgrade and other improvements within the complex. The Linac upgrade has led directly to increased proton bunch intensities delivered from the Booster and through the Main Ring. The direct results have been more intense proton bunches in collision (2.3×10^{11} vs. 1.2×10^{11}) and a significant increase in the number of protons targeted for antiproton production (3.3×10^{12} vs. 2.0×10^{12} every 2.4 seconds). The increase in targeted protons has supported an increase in the antiproton production rate (from about 4×10^{10}/hour to about 6×10^{10}/hour) and an increase in the intensity of antiproton bunches in collision (5.5×10^{10} vs. 3.1×10^{10}).

When operating with six bunches, as in Run Ib, there are twelve potential proton-antiproton collision points in the Tevatron. Ten of these are now avoided through the utilization of electrostatic separators. In Run Ib the antiproton tune shift at the maximum proton intensity was about 0.015, limited by the proton beam brightness. An antiproton tune shift of 0.024 was achieved prior to the utilization of separators when all the beam crossings contributed nearly equally to the beam-beam tune shift. We expect that increases of 50% or so in N_p/ε_N are possible before beam-beam limitations set in. Long range beam-beam effects were relatively small during Run Ib but will become increasing significant in Run II. One of the design goals for the Tevatron is to keep the effect of these long range interactions to be sufficiently small such that the collisions at the interaction points produce the bulk of the beam-beam tune shift.

Antiproton availability was the most important factor limiting luminosity in the past and will continue to be so in Run II. As demonstrated in Equation 1.2 and displayed explicitly in Figure 1.1, the luminosity in the Tevatron is proportional to the total antiproton intensity. The total number of antiprotons in the collider is determined by the product of the antiproton production rate, the typical store duration, and the transmission efficiency from the Antiproton Accumulator to storage in the Tevatron. A typical store length of 10 hours, an average stacking rate of 6×10^{10}/hour, and an antiproton transmission of 70% account for the observed average number of antiprotons in the Tevatron in Run Ib. However, it should be noted that the antiproton intensity and therefore the luminosity varied widely over the course of Run Ib.

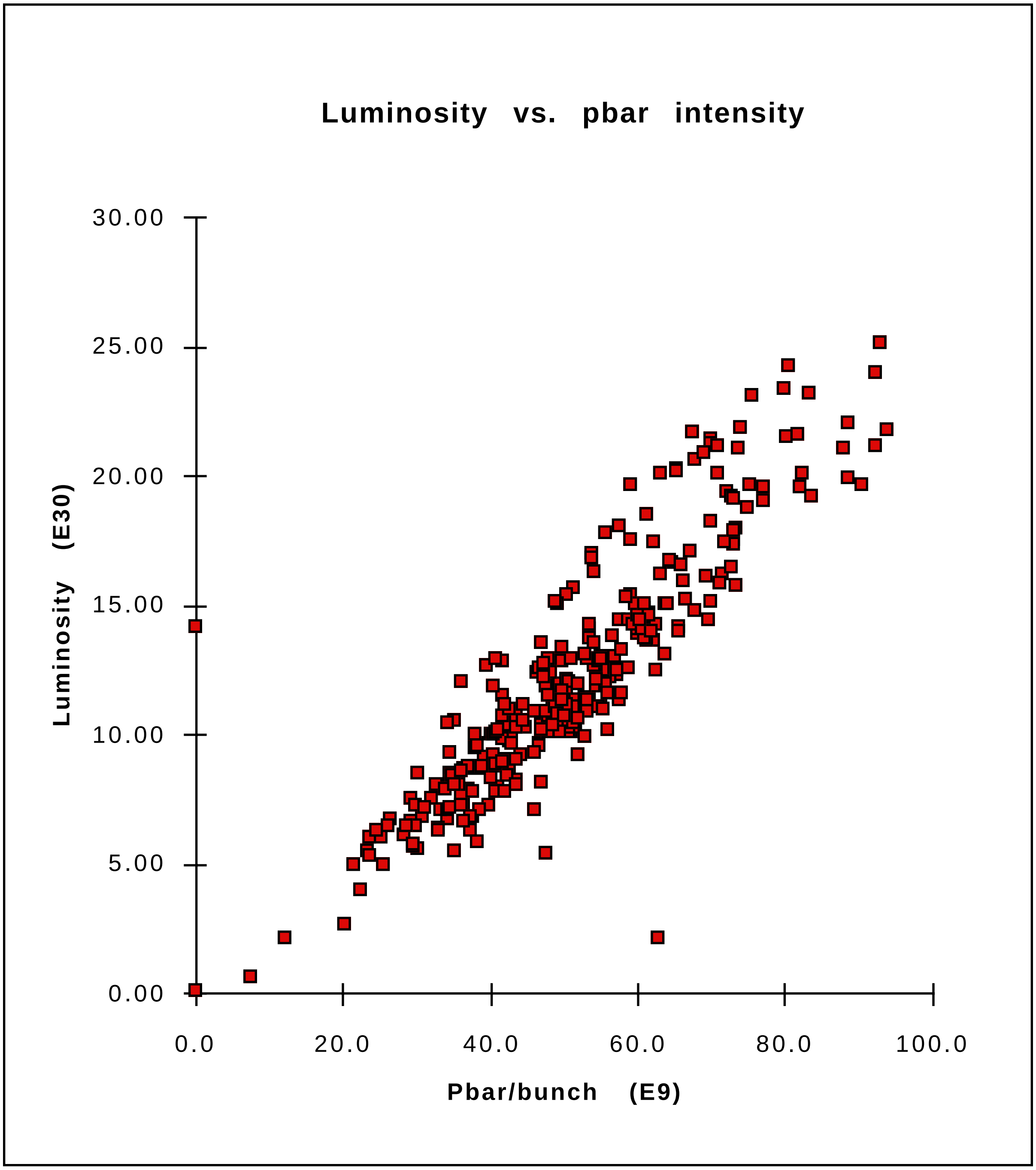

Figure 1.1. Luminosity observed in Run Ib vs. antiproton bunch intensity for all stores over the period July 23, 1994-July 9, 1995.

1.2 Run II Performance Goals

Performance goals for Collider Run II are presented in Table I.1. A luminosity goal of 5×10^{31} $cm^{-2}sec^{-1}$ has been established for this run, supported by the Main Injector and the Recycler rings. Two basic strategies are followed to attain the luminosity goal: using a proton beam brightness that produces an antiproton beam-beam tune shift close to the anticipated limit; and accumulating and delivering to the Tevatron as many antiprotons as possible through direct production and through recovery at the end of collider stores. It is expected that the number of antiprotons available will gradually increase as Run II progresses because improvements in accumulating, transferring, and recycling antiprotons. The beta function at the interaction point, β^*, is assumed to remain at the present value of 35 cm. The bunch length shown in the table is based on the achievement of longitudinal emittances of 2 eV-sec in both the proton and antiproton beams. This emittance represents a significant improvement over the currently achieved 5 eV-sec. While the longitudinal emittance goal is aggressive, we expect improvements in the Main Injector for coalescing fewer proton bunches and from bypassing the coalescing of antiproton bunches. The antiproton bunch intensities listed in Table I.1 assume a recycling efficiency, defined as the fraction of antiprotons leaving the Recycler that are returned following completion of a store, of 50%.

1.2.1 Protons

The Proton Source at Fermilab is composed of the 400 MeV Linac (with accompanying H^- ion source and Cockcroft-Walton accelerator) and the 8 GeV Booster. The Linac/Booster is currently capable of delivering an intensity of 5×10^{10} protons per bunch with a transverse normalized emittance of less than 15π mm-mrad, and a longitudinal emittance of less than 0.1 eV-sec/bunch. Protons are delivered from the Booster in 84 bunches spaced by 18.9 nsec. A total intensity of 6×10^{10} protons per bunch has been specified for the Main Injector era--a 20% improvement over current performance. In this mode of operation the Booster will be delivering 5.0×10^{12} protons per batch to the Main Injector for acceleration to 120 GeV and delivery to the antiproton production target every 1.5 seconds. As described in Section 5.1, alternative scenarios are used during Main Injector fixed target operations.

The requirements on the Linac/Booster for proton loading of the Tevatron collider are similar. A pulse train of 5 to 7 bunches, containing $5\text{-}6\times10^{10}$ protons each, will be delivered from the Booster to the Main Injector. Transverse and longitudinal emittances of about 15π mm-mrad and 0.1 eV-sec/bunch are required. These bunches will be coalesced at 150 GeV in the Main Injector into a proton bunch containing 2.7×10^{11} protons with a longitudinal emittance of 2.0 eV-sec, the exact value depending on the number of bunches that are coalesced. It is expected that the number of bunches coalesced into a single proton bunch and the number of proton bunches that are formed simultaneously in the Main Injector will be determined operationally. The may be some advantage in transverse emittance from coalescing lower intensity bunches, but there will be a penalty in longitudinal emittance. With the new short batch kicker, Main Injector to Tevatron transfer will be able to coalesce from 1 to 4 batches. After coalescing, protons will be transferred to the Tevatron.

In principle the Proton Source and Main Injector will be able to produce proton beams bright enough to produce the maximum tolerable antiproton head-on beam-beam tune shift of 0.024 (cf. Equation 1.3). As can be seen from Equation 1.2, for fixed antiproton beam parameters and assuming operation in an antiproton beam-beam limited regime, luminosity increases as the proton emittance increases. However, diminishing returns set in once the proton emittance becomes much larger than the antiproton emittance. Figure 1.2 displays the proton emittance required to limit the antiproton head-on tune shift to 0.022 as a function of proton bunch intensity, assuming two head-on collisions per revolution. As can be seen from Equation 1.3, the required emittance increases linearly with proton intensity. The figure also shows the corresponding luminosity as the proton parameters are varied in this fashion with the antiproton parameters held fixed. The proton intensity and emittances chosen in Table 1.1 are a compromise between the desire to keep the emittance somewhat below the currently achieved level and to maximize luminosity. However, increases in proton emittance are severely limited by the injection aperture and the long range beam-beam tune shift. It is not clear that emittances much beyond the nominal 20π mm-mrad are feasible. The final optimization of proton parameters will most likely follow empirical studies after commencement of operations.

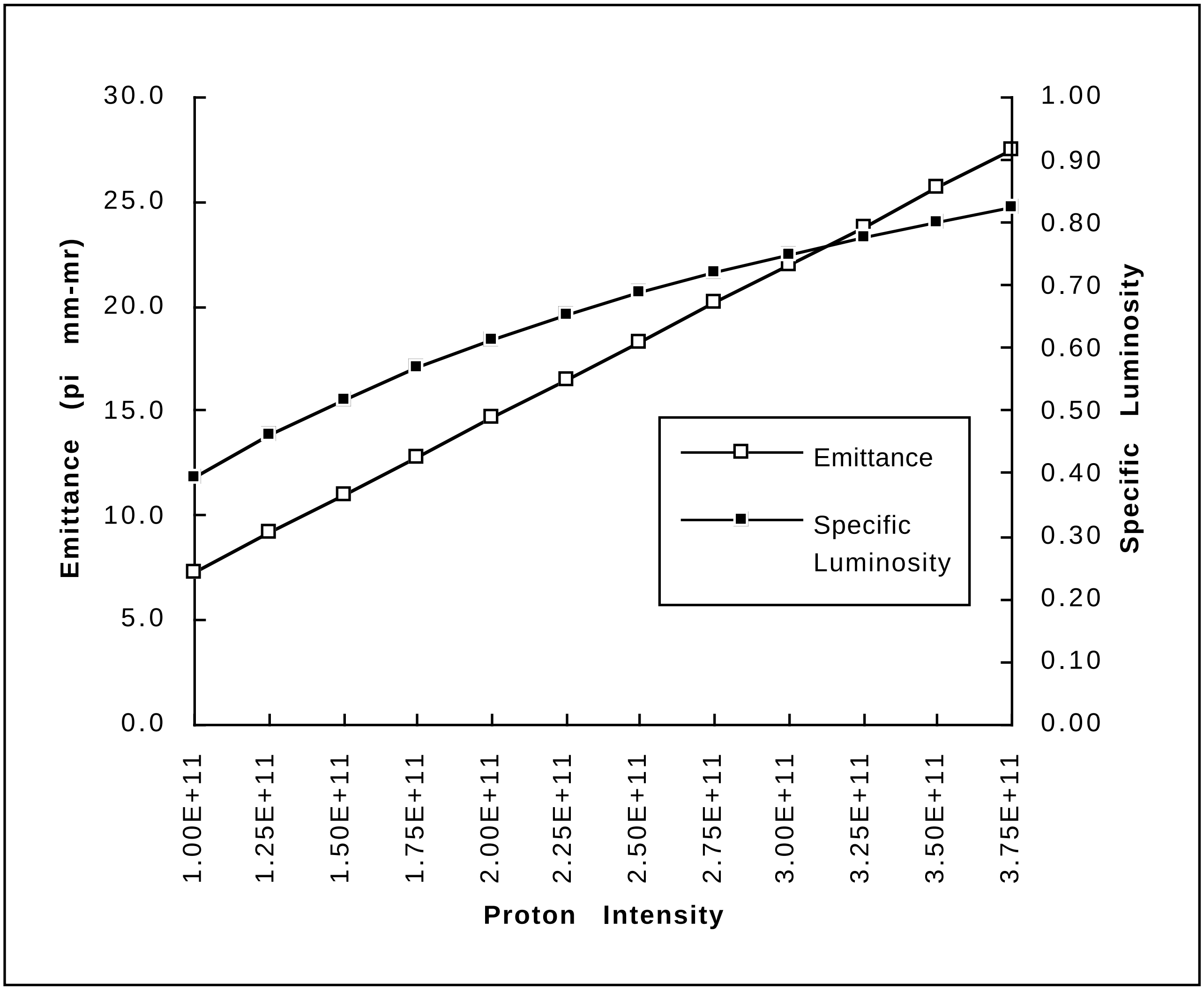

Figure 1.2. Proton emittance (mm-mrad) and luminosity per antiproton (arbitrary units) for the beam-beam limited situation. The head-on beam-beam tune shift seen by the antiprotons is .022 and the antiproton beam emittance 15π mm-mrad in this case. Long range beam-beam interactions are ignored.

1.2.2 Antiprotons

Luminosity in the Tevatron collider is proportional to the total antiproton intensity under current operating conditions. As described in Section I.1, antiproton availability represents the primary impediment to increased luminosity, both now and for the foreseeable future. The Antiproton Source is currently capable of supporting an accumulation rate of up to 7×10^{10}/hour at modest (less than 1×10^{12}) stack size, decreasing to 5×10^{10}/hour for stacks in excess of 1.5×10^{12}. The stacking rate is limited by apertures, cooling systems, and the number of protons on target. The Main Injector is designed to provide a 50% increase in the number of protons per pulse, from 3.3×10^{12} to 5.0×10^{12}, along with a 60% faster repetition rate, yielding a stacking rate in excess of 15×10^{10}/hour at large stacks. Planned improvements to the Debuncher and Accumulator stochastic cooling systems will support a stacking rate of 20×10^{10}/hour; a corresponding production rate may be possible if the Main Injector exceeds its design intensity or if modest improvements to the Debuncher acceptance are implemented. These planned improvements are sufficient to support the antiproton parameters listed in the middle column of Table I.1.

The Recycler can increase the number of antiprotons available at the beginning of each store by a factor of two. The Recycler accomplishes this by being able to store and cool as many as 3×10^{12} antiprotons, thus relieving the Accumulator stack-tail system of the responsibility of coping with antiproton stacks above 10^{12}, by recovering unspent antiprotons at the end of Tevatron Collider stores, and by improving reliability in the long term storage of antiprotons during stores while stacking.

In order to accumulate antiprotons in the Recycler ring stochastic cooling will be utilized. As described in Section IV stacks of up to about 3×10^{12} antiprotons can be created with the planned stochastic cooling systems. This performance is adequate to support the antiproton needs of Run II. A high stacking rate can be maintained by performing frequent transfers of antiprotons from the Accumulator to the Recycler. The frequency of such transfers will be determined operationally, but is nominally about once every 2.7 hours.

An important feature of the Recycler ring is the capability to re-cool antiprotons left over from the previous store. It is expected that about 75% of the initial complement of antiprotons will be available at the end of a typical Run II collider store. If two thirds of these can be decelerated and re-cooled, the number of antiprotons in collision in the Tevatron at the beginning of a store will be twice the number produced during the intervening store. This translates directly into a factor of two in weekly integrated luminosity.

The Main Injector, Antiproton Source, and Recycler are expected to provide the antiproton beam parameters specified in the right-most column of Table 1.1. Typically the Antiproton Source will produce and deliver to the Recycler 1.3×10^{12} antiprotons during a 8 hour collider store. These will be combined with an additional 1.5×10^{12} antiprotons recovered from the prior store, cooled, bunched and delivered to the Main Injector for acceleration and transfer to the Tevatron. The required transverse and longitudinal emittances of 10π mm-mr and 1.5 eV-sec in each of 36 bunches should be achievable.

1.2.3 Luminosity Lifetime and Stacking Rate

The store luminosity will continually decrease from its initial value as protons and antiprotons are consumed through interactions and as the bunch emittances increase. For the beam parameters expected for Run II, the initial luminosity lifetime is dominated by emittance growth due to intrabeam scattering, while after several hours the effect of antiproton loss due to luminosity becomes relatively more important. Figure 1.3 shows the time evolution of collider luminosity expected for the initial parameters of the 36×36 store listed in Table 1.1. This calculation is based upon a model that includes the effects of beam loss due to luminosity, intrabeam scattering, and noise induced transverse and longitudinal emittance growth. When compared with the observed evolution of high luminosity stores ($\sim2\times10^{31}$ cm^{-2}sec^{-1}) during Collider Run Ib the model agrees well.

The initial luminosity lifetime is 6.6 hours, but grows rapidly as the store progresses. The luminosity drops to half its initial value after 7 hours and to 1/e of its original value after about 12 hours. At the end of an 8-hour store 76% of the original antiproton beam remains in the Tevatron, but the transverse emittance is increased to 18π mm-mrad and the longitudinal emittance is increased to 2.66 eV-sec. Without the Recycler ring the remaining antiprotons would be disposed of, but with the Recycler they can be recovered for use in a later store.

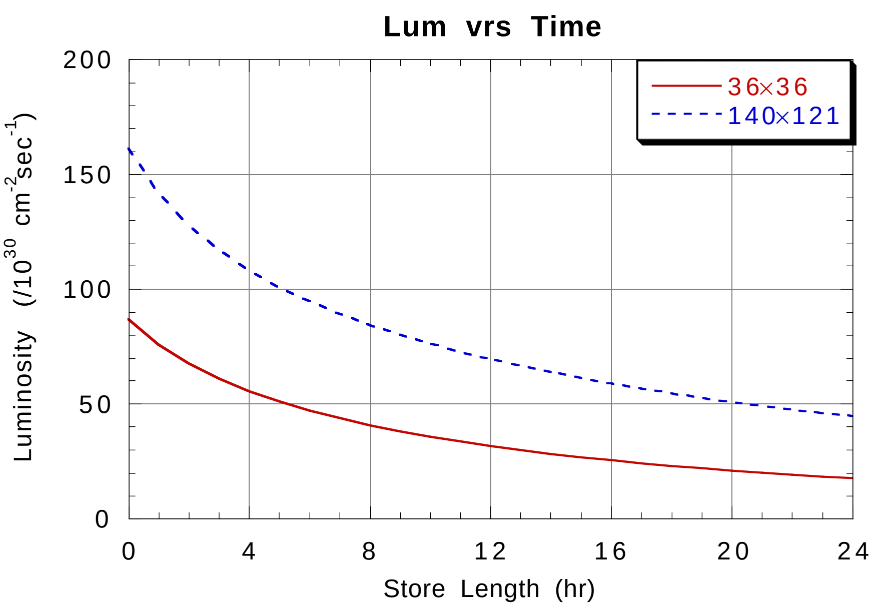

Figure 1.3. Predicted time evolution of luminosity for the two sets of store parameters listed in Table 1.1.

The Run Ib performance and Run II goals for antiproton production, transfer, and recycling are shown in Table 1.2. The Recycler stack size goals are taken from the Recycler Technical Design Report and correspond to the number of antiprotons required to achieve a luminosity of 2×10^{32} $cm^{-2}sec^{-1}$ with a 7 hour store time and a 1 hour shot set-up time. The initial antiproton intensity depends on the store length, the stacking rate, and the antiproton recovery efficiency. It is anticipated that the optimum initial antiproton intensity and store length will ultimately be established on the basis of operational experience. The improvements required to decrease the shot setup time to 1 hour are discussed in Chapter 7. The efficiencies given are for the nominal design emittances given in section 1.3. Degradation in efficiency is to be expected for larger than design emittances.

Table 1.2. Operational antiproton stacking requirements for the current collider conditions and for Run II.

Parameter	Run IB	Run II (Main Injector + Recycler)
Stacking Rate (E10/hr)	5	20
Antiproton at end of Store	73%	~75%
Deceleration Efficiency	---	80%
Acceleration Efficiency	75%	90%
Store Duration (hr)	12	7

Injection Time (hr)	2.5	≤1
Required Usable Stack (E10)	44	278
Antiprotons Recycled (E10)	0	148

1.3 Subsystem Performance Requirements

Performance requirements for the various accelerators within the complex are based upon the considerations discussed in Section 1.2 and are summarized below. Detailed descriptions of performance projections and required upgrades are contained in the remainder of this document.

1.3.1 Linac/Booster

- *Antiproton Production*
  - -5×10^{12} protons per pulse
  - $\leq 20\pi$ mm-mrad transverse emittance
  - Longitudinal emittance ≤0.2 eV-sec
  - 1.5 second repetition rate
- *Proton Coalescing in Main Injector*
  - 6×10^{10} protons/bunch in 5-7 bunches, repeated 36 times with a 4 second period.
  - $\leq 15\pi$ mm-mrad transverse emittance
  - Longitudinal emittance in range ≤0.15 eV-sec
- *Main Injector Fixed Target*
  - 5×10^{12} protons per pulse
  - 20π mm-mr transverse emittance
  - Longitudinal emittance in range 0.2 eV-sec
  - 15 Hz operation with a duty cycle up to 6/28
- *Tevatron Fixed Target*
  - 5×10^{12} protons per pulse
  - 20π mm-mrad transverse emittance
  - Longitudinal emittance in range 0.2 eV-sec
  - 15 Hz operation with 6 consecutive Booster batches delivered to the Main Injector; two such ensembles, separated by 2.4 seconds, repeating about once per minute

1.3.2 Antiproton Source

- *Antiproton Production*
  - 2×10^{11}/hour stacking rate for stacks up to 10^{12} antiprotons
- *Antiproton Extraction*
  - Delivery of $1\text{-}6\times10^{11}$ antiprotons, in a bunch train 1.6 μsec long to the antiproton Recycler ring.
  - Transverse emittance $\leq 10\pi$ mm-mrad
  - $\Delta p/p \leq 10^{-3}$ (full width)

1.3.3 Recycler

- *Antiproton Accumulation*
  - Accumulate/cool $1\text{-}6\times10^{11}$, 8.9 GeV antiprotons, every 0.5 to 3 hr, up to a total stack of 3×10^{12} antiprotons.

- Equilibrium transverse emittance of ≤10π mm-mrad
- Equilibrium longitudinal emittance of ≤60 eV-sec

♦ *Antiproton Recovery*
- Cool dilute antiprotons at 8.9 GeV with cooling time <2 hours.
- Initial transverse emittance ≤30π mm-mrad
- Initial longitudinal emittance ≤144 eV-sec for 36 bunches

♦ *Antiproton Extraction (36x36 operation)*
- Deliver to the Main Injector four bunches containing 7×10^{10} antiprotons each, capable of being captured in 2.5 MHz buckets. Nine cycles are required.
- Transverse emittance ≤10π mm-mrad
- Longitudinal emittance ≤1.5 eV-sec/bunch

1.3.4 Main Injector

♦ *Antiproton Production*
- 5×10^{12}, 120 GeV protons on target every 1.5 sec
- 20π mm-mrad transverse emittance
- Longitudinal emittance <0.3 eV-sec

♦ *Collider Protons*
- Coalesce and recapture into 53 MHz buckets, 5-11 bunches of 0.15 eV-sec each containing $3\text{-}6\times10^{10}$ protons/bunch delivered from the Booster. Accelerate to 150 GeV and deliver to the Tevatron. A total of 36 coalesced bunches is required. The number of cycles required depends on the number of Booster batches simultaneously coalesced.
- Transverse emittance ≤15π mm-mrad
- Longitudinal emittance ≤2 eV-sec per coalesced bunch

♦ *Collider Antiprotons*
- Bunch rotate and capture into 53 MHz buckets, four bunches of 1.5 eV-sec each containing 7×10^{10} antiprotons provided from Recycler at 8.9 GeV. Accelerate to 150 GeV and deliver to the Tevatron. Nine cycles are required.
- Transverse emittance ≤10π mm-mrad
- Longitudinal emittance ≤1.5 eV-sec per coalesced bunch

♦ *Antiproton Deceleration*
- Accept 4 antiproton bunches at 150 GeV from the Tevatron with transverse emittance of 35π mm-mrad and longitudinal emittance of 3.5 eV-sec/bunch, decelerate to 8.9 GeV, and transfer to the Recycler. Repeat nine times.

♦ *Main Injector Fixed Target*
- Resonantly extract 3×10^{13} protons per pulse, at 120 GeV, with a 1.9 second repetition rate and a several millisecond extraction time.
- Resonantly extract 3×10^{13} protons per pulse, at 120 GeV, with a 2.9 second repetition rate and a one second extraction time.
- Resonantly extract 2.5×10^{13} protons per pulse, at 120 GeV, with a 1.9-2.9 second repetition rate, after delivering 5×10^{12} protons onto the antiproton production target in the same cycle.
- ≤30π mm-mrad transverse emittance

♦ *Tevatron Fixed Target*

- 1.5×10^{13} protons per Main Injector cycle at 150 GeV
- $\leq 30\pi$ mm-mrad transverse emittance
- Longitudinal emittance in range 0.1-0.5 eV-sec

1.3.5 Tevatron/Switchyard

♦ *Proton-Antiproton Collider Mode*
- Accelerate and bring into collision 36 proton and 36 antiproton bunches, at 1 TeV per beam, with the above listed beam parameters.
- Reliably produce a luminosity of 2×10^{32} $cm^{-2}sec^{-1}$.

♦ *Antiproton Deceleration*
- Remove protons at end of store, decelerate antiprotons to 150 GeV, and transfer 4 bunches at a time into the Main Injector. Repeat nine times.
- $\leq 25\pi$ mm-mrad transverse emittance
- Longitudinal emittance in range ≤ 3.5 eV-sec/bunch at 150 GeV

♦ *Proton Fixed Target Mode*
- Accelerate and slow spill 3×10^{13} protons to the experimental areas at 800 GeV.
- Tevatron beam delivered to Meson, Neutrino, and Proton Areas

1.4 Accelerator Improvement Plan

Upgrades to the existing accelerator complex required to meet the performance goals listed above have been and will be funded mostly as Accelerator Improvement Projects (AIPs). A summary of projects required is given in Table I.4-1. Further details may be found in subsequent chapters of this report.

Table 1.3. Accelerator Improvement Projects required to meet Run II performance goals.

AIP	Why	R&D	Start Project	Install/ Commission
Antiproton Injection Kicker	Injection with 396 nsec spacing	Complete	1992	Summer 1995
Coalescing Cavity Upgrade	Improved coalescing efficiency	Complete	1994	Spring 1995
Antiproton BPM Upgrade	Reliability, simplification, dynamic range	Complete	1995	Summer 1998
MR/Tev TBT Upgrade	Turn-by-turn capability at all BPMs	Complete	1995	Summer 1995
Booster Extraction Upgrade	Improved aperture	Complete	1995	Fall 1997
Debuncher Cooling Upgrade	20E10/hour stacking rate	Underway	1996	Winter 1998
Accumulator Lattice Upgrade	Accommodate 2-4 GHz Stack-tail upgrade	Complete	1997	Summer 1998
Accumulator Stack-tail Upgrade	20E10/hour stacking rate	Underway	1998	Winter 1998
Antiproton Target Sweeping*	5E12 protons on target	Underway	1998	Fall 1999
Tevatron Dampers*	3E11/bunch 3E13 total beam	Complete	1995	1998-1999

*These projects will probably be funded as R&D projects.