TEVATRON LUMINOSITY UPGRADE PROJECT *

John P. Marriner, Fermilab, Batavia, IL, USA

Abstract

Fermilab has embarked on a luminosity upgrade for the Tevatron. The major components of this upgrade are the Main Injector project (including the Main Injector and Recycler Rings), improved stochastic cooling in the Antiproton Source, and increasing the number of bunches in the Tevatron from 6 to 36. The goal of the next running period is to accumulate 2 fb^{-1} of data for each of the two experiments.

1 HISTORICAL PERSPECTIVE AND GOALS OF RUN II

The Tevatron proton-antiproton collider luminosity has grown dramatically over the last 10 years as illustrated in Figure 1. The initial design goal of 1×10^{30} $cm^{-2}sec^{-1}$ was achieved in the 1988-89 run. In this run, the 6 proton and 6 antiproton bunches collided at 10 points around the ring in addition to the desired interaction points at B0 and D0. Electrostatic separators were subsequently installed, and the beam-beam effect was thereby eliminated from the 10 unwanted collision points. As a result, in the run starting in 1992 (and known as Run I), it was possible to operate with higher intensity and lower emittance proton beams. The separators, and improvements made in the antiproton stacking rate, resulted in an increase in the Tevatron luminosity by an order of magnitude. This paper concerns the preparations for Run II, whose goal is to increase the luminosity by yet another order of magnitude.

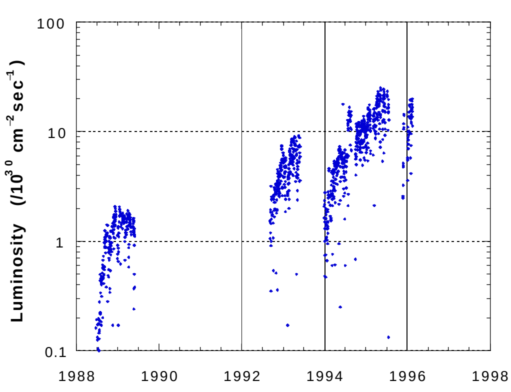

Figure 1. Initial luminosity of each Tevatron collider store since 1988.

2 LUMINOSITY CONSIDERATIONS

The luminosity of the Tevatron is given by

$$L = \frac{3\gamma f_0}{\beta^*}\left(BN_{\bar p}\right)\left(\frac{N_p}{\varepsilon_p}\right)\frac{F\left(\beta^*,\theta_{x,y},\varepsilon_{p,\bar p},\sigma^L_{p,\bar p}\right)}{1+\varepsilon_{\bar p}/\varepsilon_p}$$

where $\gamma=E/mc^2$, f_0 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, ε_p ($\varepsilon_{\bar p}$) is the proton (antiproton) emittance (95% of the beam area), β^* is the beta function at the interaction point, and F is a form factor with a complicated dependence on beta functions, crossing angles, emittances, and bunch lengths. The numerical factor 3 arises from the use of 95% emittances and the normalization to $F\leq1$. The quantity ($BN_{\bar p}$) is the total number of antiprotons colliding in the Tevatron. The scarcity of antiprotons is the chief limitation to the luminosity of the Tevatron proton-antiproton collider. In order to obtain the maximum number of antiprotons, the Main Ring was devoted (as will be the Main Injector) to antiproton production, producing about 2 antiprotons for every 10^5 120-GeV-proton targeted. The second factor (N_p/ε_p) is proportional to the beam-beam tune shift if the crossing angle at the interactions regions is zero and if long range interactions can be ignored. The beam-beam tune shift, in this case, is given by

$$\xi = \frac{r_o}{4\pi}\frac{N_p}{\varepsilon_p}N_{IR} = .000733\frac{N_p}{\varepsilon_p}N_{IR},$$

where r_0 is the classical radius of the proton and N_{IR} is the number of interaction regions (currently 2 for the Tevatron). Based on previous experience, the maximum tolerable beam-beam tune shift is thought to be about .02—the distance between the 5th and 7th order resonances near the Tevatron working point of 20.61. In the more general case with a crossing angle, the expression for the beam-beam tune shift can be very complicated, but there is still a limit on the proton intensity and emittance.

The Run II goals are summarized by the parameters listed in Table 1. 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 needed to achieve the Run II goal for integrated luminosity in a reasonable length of time–say 2

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years–after the initial luminosity goal is reached. Two sets of parameters are shown for Run II: one for the 21 rf bucket spacing (396 nsec) and one for the 7 rf bucket spacing (132 nsec). With the parameters chosen, the luminosity is higher for the 132 nsec case simply because the total number of antiprotons is assumed to be greater (the same intensity per bunch) despite a luminosity penalty arising from the introduction of a crossing angle for the 132 nsec case (see discussion below). The shorter bunch spacing is not required to achieve the higher luminosity. However, if the luminosity reaches 2×10^{32} $cm^{-2}sec^{-1}$ it is desirable to spread the antiprotons amongst more bunches so that the number of interactions per crossing is reduced.

Table 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 luminosity goal with 36×36 operation, and the rightmost column illustrates 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	**Run Ib (1993-95) (6x6)**	**Run II (36x36)**	**Run II (140x121)**	
Protons/bunch	2.3×10^{11}	2.7×10^{11}	2.7×10^{11}	
Antiprotons/bunch*	5.5×10^{10}	3.0×10^{10}	3.0×10^{10}	
Total Antiprotons	3.3×10^{11}	1.1×10^{12}	3.6×10^{12}	
Pbar Production Rate	6.0×10^{10}	2.0×10^{11}	2.0×10^{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	0.16×10^{31}	0.86×10^{32}	1.61×10^{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 2×10^{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.

Inspection of Table 1 reveals that most of the gain in luminosity in Run II comes from the increase in the number of antiprotons: the intensity per bunch is somewhat higher than in Run I and the number of bunches increases from 6 to 36. A small increase in the proton intensity and a decrease in longitudinal emittance are expected from the higher proton intensities that will be available from the Main Injector. The higher antiproton intensity results from the higher intensity beam in the Main Injector (5×10^{12} per batch compared to 3.5×10^{12} in the Main Ring) and the higher repetition rate (1.5 sec instead of 2.4 sec). These improvements, plus a modest improvement in the antiproton acceptance, will result in a 3-fold increase in the antiproton flux. The larger transverse and longitudinal acceptance of the Main Injector should largely eliminate the antiproton losses that were routinely encountered in the Main Ring. Finally, the ability of the Recycler to accept decelerated antiprotons accounts for a factor of 2 to 3 of the increase in luminosity.

3 DESCRIPTION OF THE ACCELERATORS

The Fermilab Accelerator complex is shown in Figure 2. The 400 GeV linac feeds the Booster, which accelerates protons to 8 GeV. The beam is transferred to the Main Injector via the 8 GeV line and is accelerated to 120 GeV for antiproton production or to 150 GeV for transfer to the Tevatron. The 120 GeV beam is targeted, and antiprotons produced at the target are collected and stochastically cooled in the Antiproton Source, which consists of the Debuncher and Accumulator Rings. The stored antiproton beam is transferred to the Recycler every 1-4 hours. At the beginning of each Tevatron collider store, antiprotons are transferred from the Recycler, accelerated in the Main Injector, and transferred to the Tevatron. At the end of each store, antiprotons are decelerated in the Tevatron and Main Injector, and recaptured in the Recycler.

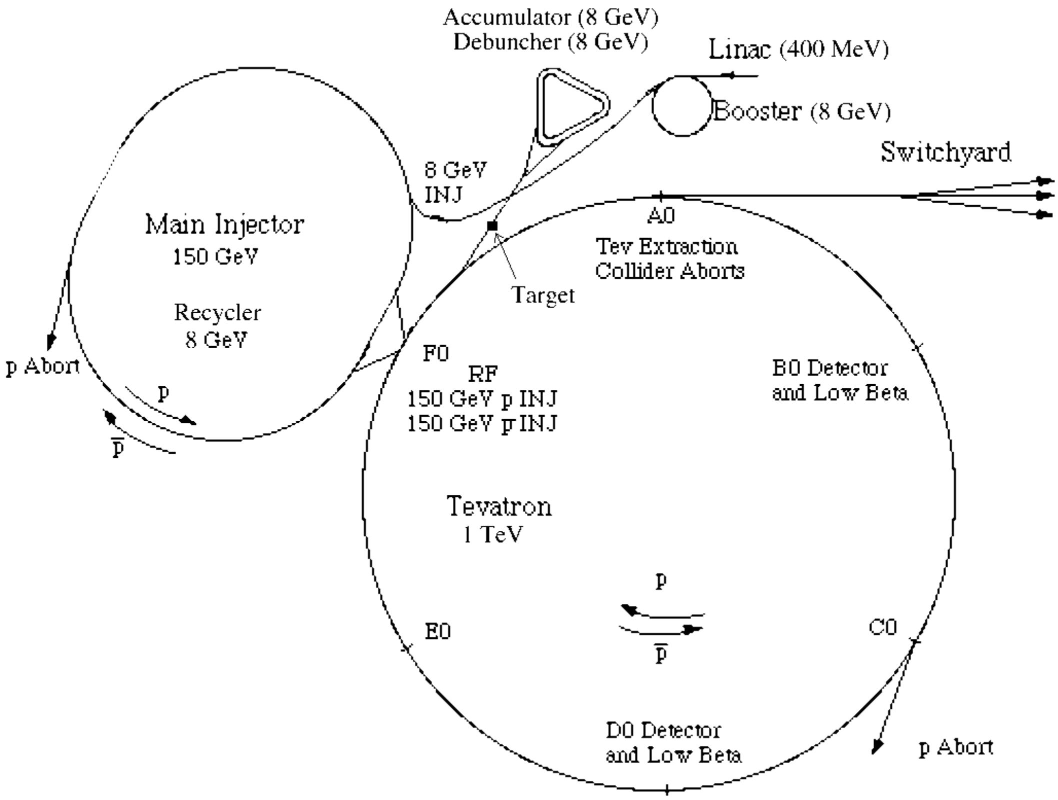

Figure 2. The layout of the Fermilab accelerator complex is shown.

3.1 Proton Source

The linac was upgraded from 200 MeV to 400 MeV in 1992. No further changes are planned for Run II, expect modifications to improve diagnostics and reliability.

The Booster has a number of modifications being made. The most extensive modification involves the addition of steel shielding over the extraction region but beneath an existing service building. The increase in shielding became necessary when the extraction area was relocated for Main Injector operation and also because we intend to use more of the 15 Hz Booster cycles to deliver beam in the future to other users, such as neutrino experiments. An upgrade to the orbit correction magnets in the extraction region has removed the need to compromise the injection orbit in order to cleanly extract the 8 GeV beam. Improvements to decrease the extraction kicker rise time will also reduce the losses at extraction. We intend to operate the Booster with a missing bunch in the future to further reduce the extraction losses. This modification will require changes to the Booster rf synchronization, as does the fact that the Main Injector rf harmonic number is different from that of the Main Ring. Other modifications will improve the reliability of the nearly 25 year old machine.

3.2 Main Injector

The Main Injector provides the engine that powers the luminosity upgrade. The Main Injector will allow the production of higher intensity proton beams. This ability is most useful to the collider for antiproton production, leading to a projected 3-fold increase in the stacking rate. The higher intensity is possible because the Booster can provide higher intensity beams if an increase in emittance can be tolerated. The Main Ring effective aperture (about 15π mm-mrad normalized to 8 GeV) was too small to take advantage of this capability, but the Main Injector aperture of 40π mm-mrad should handle the increased emittance easily. The larger momentum aperture offers the possibility of stacking multiple Booster pulses into the Main Injector and targeting them for antiproton production. This capability could result in antiproton intensities beyond those planned for Run II.

3.3 Recycler

The Recycler is intended to perform two functions. First, it will store the high intensity antiproton beam prior to transfer to the Tevatron. In previous runs, the stacking rate in the Accumulator decreased after several hours of antiproton stacking. Beam transfers to the Recycler every 1 to 4 hours will eliminate the decrease in stacking rate in the Accumulator. Second, the Recycler will collect the unspent antiprotons after they have been decelerated in the Tevatron and the Main Injector.

The Recycler uses permanent magnet technology for reduced fabrication, installation, and operational costs and for increased reliability[1]. The Recycler will use a fixed frequency, variable waveform, rf system to create barrier buckets to bunch the beam for injection and extraction.

The Recycler will initially use stochastic cooling, but an upgrade to electron cooling is planned. The electron cooling is especially challenging because it requires a 4 MeV electron beam[2].

3.4 Antiproton Source

Most of the modifications to the Antiproton Source involve improvements to the stochastic cooling systems that are required to cool the higher antiproton flux. The existing 2-4 GHz Debuncher cooling systems will be replaced with a 4-8 GHz band cooling system. The 4-8 GHz system will use novel pickup and kicker designs based on coupling a wave-guide to the beam chamber through a series of small holes. A sensitive pickup (or kicker) can be fabricated when the phase velocity in the wave-guide is equal to the beam velocity. The 4-8 GHz cooling band will be sub-divided into 4 small bands over which this synchronization condition remains valid. We chose to use the more difficult 4-8 GHz technology because of its potential to cool antiproton beams with intensities higher than those specified for Run II.

The Accumulator stack tail (longitudinal) cooling system is being scaled in a straightforward way to the 2-4 GHz band from its current 1-2 GHz. However, in order to accomplish the scaling, the transition energy of the Accumulator must be changed to keep the stochastic cooling "mixing factor" the same in the new cooling band as it was in the old.

High speed, pulsed magnets will be used to sweep the proton beam in a circle on the antiproton production target. The beam sweeping is required in order to avoid excessive peak energy deposition in the production target. Provided that a matched set of magnets is used upstream and downstream of the target the beam can be swept over the target without a loss in acceptance. The design of this sweeping system is challenging because of the short duration of the proton beam pulse (1.6 μsec).

3.5 Tevatron

A project to build a new, fast rise-time proton injection kicker has been initiated. Initially, we planned to inject protons in 3 groups of 12. The 2-μsec interval between the groups of 12 did not require a fast rise time kicker. However, in beam tests performed in 1996 we were unable to obtain much more than 1/4 of the desired proton intensity. The creation of the intense proton bunches needed for the Tevatron makes use of bunch coalescing: the combination of about 10 bunches in longitudinal phase space to form a higher intensity, higher emittance bunch. Severe beam loading in the rf cavities prevented us from achieving the Run II intensity when we attempted to coalesce more than 1 bunch at a time. While it may very well be possible to solve this problem with better beam loading compensation, we have chosen to build a "short batch" kicker with a rise time of 396 nsec. The rise time is adequate to allow the injection of 1 to 4 coalesced proton bunches per cycle. This kicker will allow us to finesse the beam loading problem and operate in the regime where we have already been able to achieve the required proton intensities. An upgrade to this kicker to improve the rise-time to 132 nsec is planned, so that we can apply a similar strategy at the reduced the bunch spacing.

Our beam studies in 1996 also indicated that we needed to improve errors in our kicker waveform—particularly during antiproton injection. Figure 3 shows the measured emittance of the proton beam after repeated firing of the antiproton injection kicker. The gross differences in the emittance are attributed to ripple in the antiproton kicker waveform. While it is likely that some improvements will be made by optimizing the kicker timing, we intend to build and install a novel, agile trim kicker magnet power supply that will be able to trim the kicker pulse by 2% on a bunch-by-bunch basis. The trim kicker could be programmed by an arbitrary waveform or operated in a feedback system to damp injection oscillations.

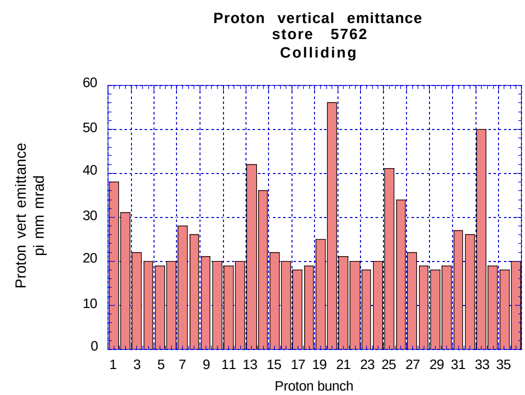

Figure 3. Emittance of 36 Tevatron proton bunches after repeated firing of the antiproton kicker.

We plan to upgrade the Tevatron energy so that it will run at 1 TeV (compared to the current 900 GeV). The basic strategy is to use cold compressors to reduce the two-phase helium to sub-atmospheric pressures (8 to 10 psi). The nominal operating temperature is thus reduced from a nominal 4.6 °K to 3.6 °K. A proton beam has been accelerated to 975 GeV during a period when the cold compressors were tested. However, the performance of the Tevatron appears to limited by a few weak magnets that appear on the tail of a distribution of quench currents that is about 800 A (200 GeV) wide. Because of irregularities in the cryogenic systems, some Tevatron magnet locations are slightly colder than others. We intend to take advantage of this situation by "shuffling" the weak magnets into the colder locations.

One of the major sources of heat leaks in the Tevatron is at the leads, the places where the high current copper conductors (carrying typically 5000 A) join the superconducting material. A new approach to the design of the leads is possible with high temperature superconducting technology, and it promises to virtually eliminate the heat load the leads present to the helium refrigeration system. An R&D program to replace leads with high temperature superconductor has been initiated and has produced a successful prototype.

An interesting possibility for the future involves compensating the beam-beam tune shift seen by the antiprotons with a low energy (20 keV) electron beam. The electron beam would collide with the antiproton beam at a location in the ring removed from the interaction region but would provide a tune shift that would be equal and opposite to the proton beam. The electron beam would be placed in a solenoidal magnetic field to maintain stability. An R&D program is underway to test this concept.

4 SCHEDULE

We expect the Main Injector to be ready for beam in July 1998. We expect to have beam in the Main Injector in September, after the civil construction has progressed to the point where the Booster can be operated. We hope to have the Recycler ready for beam and the reinstallation of F0 finished in October 1998. We plan a Tevatron fixed target run in 1999 followed by colliding beams operation early in 2000.

5 132-NSEC BUNCH SPACING

After the luminosity reaches 5×10^{31} $cm^{-2}sec^{-1}$, we plan to study operation with 132-nsec bunch spacing. The major motivation for decreasing the bunch spacing is to reduce the number of antiprotons per bunch (keeping the total number fixed) so that the number of interactions per crossing remains modest. At a luminosity of 2×10^{32} $cm^{-2}sec^{-1}$, the number of interactions per crossing would reach 5.8 if the number of bunches remains at 36. Operation at a spacing of 132 nsec requires some modifications to the kickers and rf systems, but these modifications seem to be straightforward. However, it also appears necessary to introduce a crossing angle at the interaction region in order to avoid excessive beam-beam tune shift from the collision points nearest the interaction region. The crossing angle will result in a reduction of the luminosity (compared to a crossing angle of 0) and also dramatically changes the nature of the beam-beam interaction. We anticipate that significant experimental work will be required to characterize operation at 132 nsec.

6 LUMINOSITY UPGRADES BEYOND RUN II

Additional luminosity upgrades, beyond those planned for Run II, are possible We expect that there will be another run (Run III) of the Tevatron before the LHC becomes operational. However, it is clear that the modifications will have to be made on a substantially smaller scale than was done for Run II. The upgrades will almost certainly be directed towards increasing the antiproton stacking rate. In Run Ib, 7% of the antiprotons produced were consumed in collisions at the interaction points. We project that the improved transmission efficiency in the Main Injector and the antiproton recovery capability of the Recycler will increase this fraction to 32-42% in Run II. This fraction approaches the fundamental limit on the average luminosity: the antiproton collision rate can not be higher than the rate of antiproton production. While there is room for improvement in this ratio, it seems likely that the major increases in luminosity will have to come from improvements in the stacking rate.

If the combination of two Booster batches in the Main Injector proves feasible, it will be possible to nearly double the Main Injector intensity thereby doubling the stacking rate. An additional factor of 2 can be obtained by removing the aperture restrictions in the Antiproton Source that limit the beam acceptance. Together, these could result in a factor of 4 increase in flux. This increase in flux would require improvements in the cooling systems in the Antiproton Source and the Recycler. It appears that a modest upgrade of the 4-8 GHz cooling systems in the Debuncher, a major upgrade of the Accumulator system to 4-8 GHz, and the implementation of electron cooling in the Recycler would meet the cooling requirements.

7 CONCLUSION

We expect to achieve colliding beams in early 2000. The initial Run II luminosity goal is 5×10^{31} $cm^{-2}sec^{-1}$, while the ultimate potential luminosity of the Run II upgrades is thought to be 2×10^{32} $cm^{-2}sec^{-1}$. Run III luminosities can be expected to be 2 to 5 times those obtained in Run II.

REFERENCES

[1] G.W. Foster, “Permanent Magnets for Accelerators: Experience with Beam,” this conference.

[2] A.C. Crawford, et al., “Successful MeV-Range Electron Beam Recirculation,” this conference.