RECORD LUMINOSITIES AT THE TEVATRON & FUTURE POTENTIALITY*

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Abstract

Fermilab Collider Run II has been in progress for nearly six years. During this tine the D0 and CDF experiments have each acquired total integrated luminosities of nearly 2.2 fb^{-1}. Also during this time the peak instantaneous luminosities increased by more than a factor of 25 – from 10 to as high as 270×10^{30} cm^{-2} s^{-1}. An aggressive collider upgrade program continues to make significant progress along side luminosity production operations. This paper will give the status of Tevatron operations and expectations for the remainder of Run II.

PRESENT OPERATIONS

At the present time the Fermilab accelerator complex is providing beam for several high energy physics experiments. In addition to two collider experiments (CDF and D0), proton beam is made available for 120 GeV fixed target experiments and two neutrino experiments (NuMI and MiniBooNE).
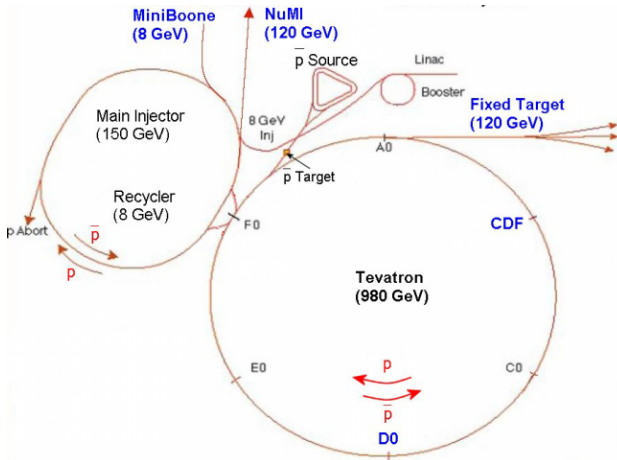

Figure 1: The Fermilab accelerator complex. Four high energy physics programs are supported: collider experiments CDF and D0, NuMI, MiniBooNE, and 120 GeV fixed target experiments.

The layout of the Fermilab accelerator complex and experiments is shown in Figure 1. Protons are accelerated and directed toward their final destination as follows:

- Protons from the Linac are accelerated to 8 GeV in the Booster synchrotron at 15 Hz.
- 4.2×10^{12} protons at 8 GeV are directed to MiniBooNE at a rate of approximately 2.5 Hz [1].
- 8.2×10^{12} protons at 8 GeV are accelerated to 120 GeV in the Main Injector every 2.4 sec for antiproton production.

- 11.5×10^{12} protons at 8 GeV are accelerated to 120 GeV in the Main Injector every 2.4 sec for neutrino production for the NuMI experiment.
- Varying amounts of 8 GeV protons are accelerated to 120 GeV and slow extracted every 61 sec for switchyard fixed target experiments

The contention for protons amongst the various experimental programs places some constraints on the operation of the Tevatron for the collider experiments.

During routine operation the injector chain operates to accumulate antiprotons while a collider store spins in the Tevatron. The average length of a collider store is about 20 hours. After a collider store is terminated a new store is inserted using the newly accumulated antiprotons.

Present and anticipated parameters of the Tevatron collider are given in Table I.

Table 1: Collider Parameters

Parameter	Present†	Upgrade	Units
Peak Luminosity	185	300	10^{30} cm^{-2} s^{-1}
Luminosity Lifetime	8.5	‡	hr
Store hours per week	97	105	hr/wk
Integrated Luminosity	5.1	‡	pb^{-1}/store
Total Run II ∫ Ldt	2.2	7	fb^{-1}
Protons per bunch	250	270	10^9
$\bar{p}$ per bunch	58	127	10^9
Number of bunches	36×36	36×36	
β* at IPs	28	28	cm
$\bar{p}$ stacking rate to Accumulator	17.5	30	10^{10}/hr
$\bar{p}$ stacking rate to Recycler	12.0	‡	10^{10}/hr

† Average values for FY2007
‡ No upgrade goal specified

Antiproton Stacking

Antiproton stacking consists of accelerating 120 GeV protons onto a nickel target disk through a process called slip stacking [2][3]. 8 GeV secondaries are collected off of the target using a high gradient lithium lens. This beam is injected into the Debuncher ring where the 19 nsec bunch structure from the targeted protons is rotated in longitudinal phase space to produce a narrow energy spread. The beam is stochastically cooled for 2.4 sec and transferred to an orbit on the high energy side of the Accumulator ring. The newly injected pulse of antiprotons is moved with RF to an orbit near the central

momentum and then stochastically stacked into the core of the stored $\bar{p}$ distribution (see Figure 2).
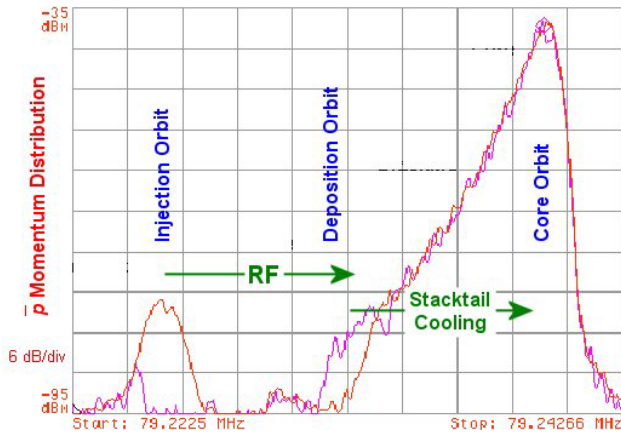

Figure 2: Longitudinal $\bar{p}$ distribution during stacking. The high energy side of the Accumulator is on the left side of the plot, low energy is on the right.

Antiprotons are stacked into the Accumulator in this manner until $60 - 70 \times 10^{10}$ have been accumulated. The antiproton stack is then transferred to the Recycler Ring. The time between Accumulator to Recycler transfers is approximately 3 to 4 hours.

Loading the Collider

About 20 hours after a collider store has been inserted into the Tevatron the luminosity will have fallen sufficiently low to require a new store. Reloading the Tevatron with a new store is a process that typically takes about two hours.

Reloading the collider consists of the following basic steps:

- Set the Tevatron energy to 150 GeV
- Accelerate 36 proton bunches through the Linac → Booster → Main Injector chain to 150 GeV and inject into the Tevatron.
- Ramp the Tevatron separators to place the proton bunches on helical orbits.
- Accelerate 9 sets of 4 $\bar{p}$ bunches from the Recycler Ring to 150 GeV and inject into the Tevatron.
- Ramp the Tevatron to 980 GeV.
- Ramp the low-β inserts to establish β^*.
- RF cog the proton and antiproton bunches into collisions.

Depending on operational exigencies, about 6 to 7 stores are loaded into the Tevatron in this manner each week.

Run II Luminosity History

The performance of the Tevatron collider has improved dramatically since commissioning began in early 2001 (see Figure 3). At the present time the initial luminosity of a collider store is typically $200 - 250$ cm^{-2} s^{-1}. The best initial luminosity achieved to date is 277 cm^{-2} s^{-1} on January 18, 2007. This is a factor of 25 better than what

was achievable at the beginning of the run. Under good conditions, the collider is presently capable of integrating 40 pb^{-1} per week. A total of 2.2 fb^{-1} has been integrated since the beginning of Run II.

This remarkable improvement has been achieved by a program of sequenced upgrades that were installed during three brief shutdowns and commissioned during collider production running. The progress shown has also occurred despite several significant setbacks as indicated by the several dips in peak luminosity in Figure 3.
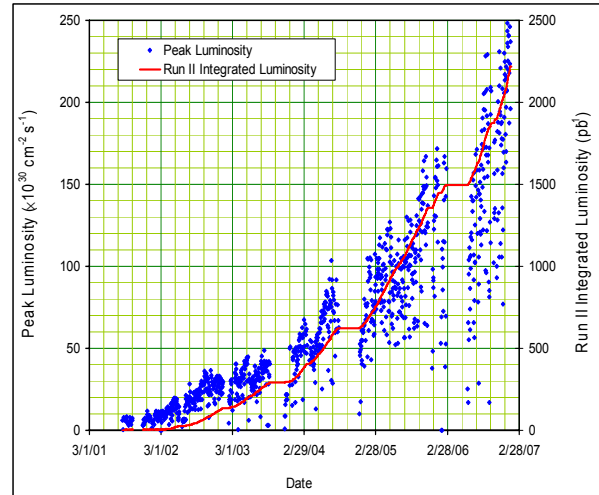

Figure 3: Peak and integrated luminosity versus time since the beginning of Run II.

RECENT PROGRESS

While the focus of this paper is on the recent progress of the upgrade program, the significant milestones of the Run II upgrades project are given in Table 2.

Table 2: Run II Upgrades Milestones

Milestone	Date
Start of Run II commissioning	March 2001
Collider operational	July 2003
Recycler electron cooling operational	July 2005
Slip stacking operational	August 2005
Lower β^* from 35 cm to 28 cm	September 2005
Recycler only operations*	October 2005
Tevatron separator upgrade	Spring 2006

* $\bar{p}$ from Recycler only used to load collider

The details of these projects and many earlier accomplishments are documented in references [4][5][6].

Antiproton Production Issues

The antiproton accumulation rate ("stacking" rate) has increased almost two-fold since the beginning of FY 2006. This is due to several factors including:

- Increased beam on target due to slip-stacking
- Completion of the high gradient lithium lens upgrade

- Completion of much of the planned AP2 injection line and Debuncher aperture improvements.

For the first half of Run II the $\bar{p}$ stacking rate remained at an average of about 7×10^{10}/hr. During a shutdown in late 2004 several antiproton source upgrades were installed that increased the apertures of the Debuncher and its injection line. During this same shutdown there were several improvements made to the transfer line between the Accumulator and the Debuncher.

After the recovery from the 2004 shutdown the stacking rate again stagnated at around 10×10^{10}/hr. In late November of 2005 the Tevatron experienced the first if its three magnet failures. The Tevatron down time made the rest of the accelerator complex available for machine studies. The antiproton source took advantage of this time to properly commission the upgrades that were installed during the previous shutdown. The result, as can be seen in Figure 4, was a significant step upward in the $\bar{p}$ stacking rate.
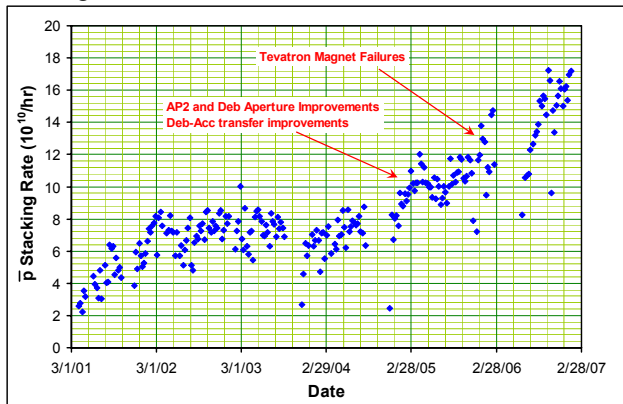

Figure 4: Average weekly stacking rate since the beginning of Run II.

Much of the increase in stacking rate in late 2005 can be attributed to increased proton intensity on the $\bar{p}$ production target due to the commissioning of slip stacking [2][3]. Slip stacking is a method of cogging two proton batches from the Booster into one batch in the Main Injector. The proton intensity on target increased by about 33% by the time slip stacking commissioning was complete.

The increased beam power on the $\bar{p}$ target comes with the complication that the target material is consumed at an increased rate. The target consists of three nickel disks. Approximately 6×10^{18} protons can be targeted on each disk. Thus it takes about 5 weeks to use up one target disk.

A further boost to the antiproton yield was accomplished by the completion of a project to increase the gradient of the lithium collection lens. To date the lens gradient has been raised by about 30%. In conjunction with the gradient increase the study time afforded by the Tevatron failures facilitated a 32% increase in the admittance from the lens through the Debuncher. Figure 5 illustrates the impact of lens gradient on $\bar{p}$ yield. There has been an overall increase in antiproton yield into the

Debuncher ring of about 40% due to the combination of aperture and lens gradient improvements.
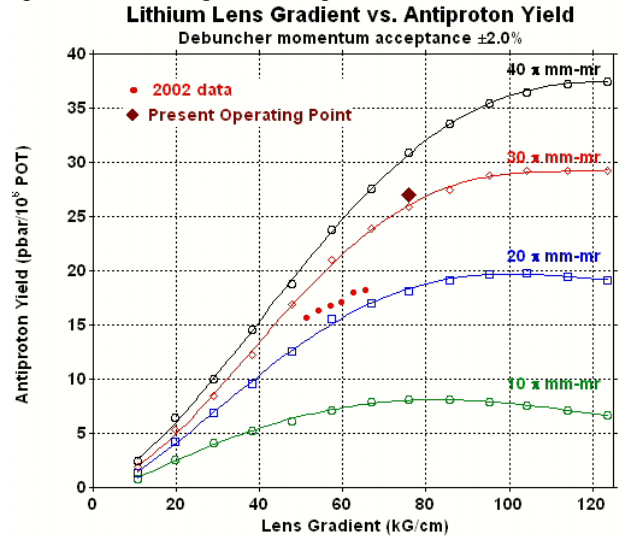

Figure 5: $\bar{p}$ yield versus Li lens gradient for various acceptances. The solid curves are a model, the symbols represent measurements. The 2002 measurement data was taken in the vicinity of the operating point at that time.

The bottleneck for stacking presently resides with the stacktail cooling system in the Accumulator ring. The stacktail cooling must accomplish two tasks in a timely manner for $\bar{p}$ stacking to function properly: (1) it must move beam off of the deposition orbit (see Figure 1) prior to the arrival of the next pulse from the Debuncher, and (2) it must transmit the flux arriving from the deposition orbit to the core at a rate that is sufficient to sustain a high stacking rate. The stacktail cooling system is currently at the limit of its capability in both of these tasks.

The longitudinal $\bar{p}$ distribution in the vicinity of the deposition orbit is highly time dependant – the pulse of deposited beam must transform from its initial shape into nothing in the space of the 2.4 sec stacking cycle time. Any beam left on the deposition orbit is RF phase displaced toward the injection orbit when the next pulse arrives. The rate at which this transformation can occur is proportional to the gain and bandwidth of the stacktail cooling system at the location of the deposition orbit. The gain is limited by system stability. Also, core heating effects and non-linear intermodulation distortion in the traveling wave tubes that drive the stacktail kickers intensify with increasing gain. A modification to the stacktail cooling system that will increase the bandwidth by 20% is presently under development. In addition, the core heating effects have been extensively studied. A scheme to optimize stacktail kicker locations will be implemented soon and is expected to mitigate the core heating somewhat. With these changes we expect the system to be able to clear the deposition orbit sufficiently fast to sustain a stacking rate of 30×10^{10}/hr.

The longitudinal $\bar{p}$ distribution in the stacktail region (the region between the deposition orbit and the core) is a static distribution that increases exponentially as the $\bar{p}$

energy decreases to the energy of the core with a characteristic energy, E_d. The maximum flux, Φ_{max}, through the stacktail is given by:

$$\Phi_{max} = \frac{W^2 \eta E_d}{f_{rev} p \ln\left(\dfrac{F_{min}}{F_{max}}\right)}$$

where W is the system bandwidth, η is the Accumulator slip factor, f_{rev} is the beam revolution frequency, p is the beam momentum, and F_{min} and F_{max} are the band edges of the stacktail cooling system. Φ_{max} can be increased by increasing the bandwidth, η, and E_d. With the 20% bandwidth improvement mentioned above, Φ_{max} is expected to be very near 30×10^{10}/hr.

Table 1 shows that there is a large difference between the rate at which antiprotons are stacked in the Accumulator and the rate into the Recycler. This is primarily caused by the time required to transfer beam from the Accumulator to the Recycler. This is a process that presently takes about 20 minutes. Hardware, software, and procedural changes are being developed to permit Accumulator to Recycler transfers to take place on event – reducing the time required from 20 minutes to about 30 seconds. We expect these changes to be implemented over the course of the next year.

Tevatron Issues

The early part of fiscal year (FY) 2006 saw three separate major Tevatron magnet failures. Each of these failures was initiated by a "mild" quench. A mild quench is a quench in which the affected magnets warm up by only 10-15 °K. The Tevatron has experienced an average of 8 quenches per month since the start of collider production running in the summer of 2003. Ordinarily the recovery time from a mild quench is less than one hour. In these three cases however, the down time ranged from one week to three weeks. The total time lost to the program was about 6 weeks. The damage caused by two of these quenches was determined to be the result of stuck Kautzky pressure relief valves. The particular valve component that caused these two valves to fail was replaced in all (~1200) Tevatron Kautzky valves during the spring 2006 shutdown.

Despite the difficulties, there has been significant improvement in the performance of the Tevatron in recent months. FY 2006 saw the installation of electrostatic separator upgrades, a vastly improved Tevatron beam position monitoring (BPM) system, and a lattice upgrade that facilitated a 25% decrease in the interaction point (IP) β^*.

The separator upgrade project consists of the installation of the addition of additional high voltage (HV) electrostatic separator modules, the installation of polarity reversing switches, and increased HV capacity. The separator improvements that have been installed to date have allowed increased separation of the $\bar{p}$ and p beams at the first parasitic collision points. This significantly mitigates beam-beam effects and resulted in

an estimated 20% improvement in integrated luminosity. This improvement is illustrated in Figures 6 and 7.

The Tevatron BPM system underwent a major overhaul. With this upgrade the proton position measurement resolution improved by an order of magnitude (new resolution $\approx$ 10-25 μm). The new system also allows measurement of the $\bar{p}$ orbits – a capability the previous system did not have. The improved BPM performance has greatly improved the ability to measure and correct the Tevatron lattice [7].
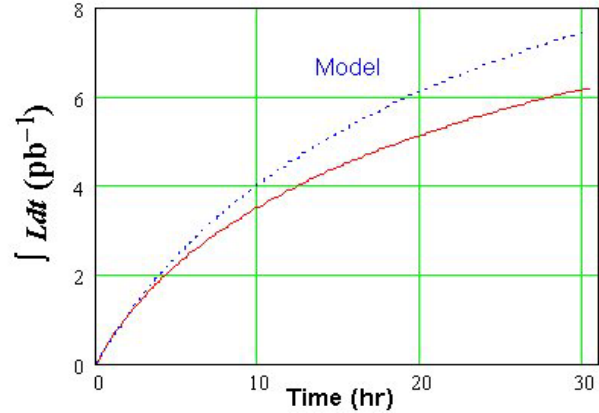
Figure 6: Comparison of a Tevatron luminosity model with data from a collider store *before* the separator upgrade installation. The model does not include beam-beam effects – hence the disparity between the model and the data.
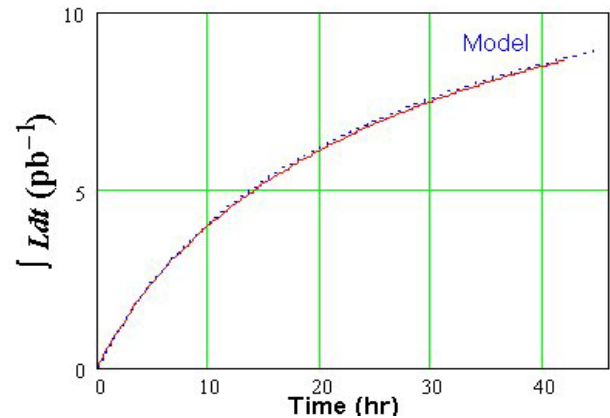
Figure 7: Comparison of the luminosity model with data from a collider store *after* the separator upgrade installation. The model (sans beam-beam) agrees well with the data.

As a consequence of the improved optics measurement capability allowed by the BPM upgrade, new Tevatron optics were developed that permitted a decrease in β^* at the IPs from 35 cm to 28 cm.

The $\bar{p}$ intensity in the Tevatron has reached the level where the proton beam is being driven by the antiproton beam. This problem will become more severe as $\bar{p}$ intensity increases. The solution that is contemplated is a change in the Tevatron working point from the vicinity of 4/7 to the vicinity of 1/2 (see Figure 8). With this change

the Tevatron will accommodate nearly 40% more tune spread; however it will also increase the chromatic lattice functions. This working point change will be implemented after a reconfiguration of the Tevatron's sextupole correction circuits to permit compensation of the anticipated chromatic effects.
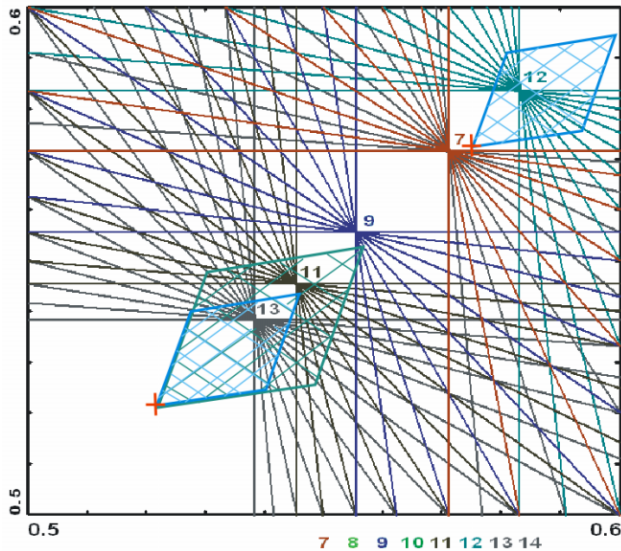

Figure 8: Tevatron tune diagram. The present operating range between 4/7 and 3/5 straddles 12th order resonance lines. The new working point will be near the ½ resonance where there is 40% more operating room.

SUMMARY

Enormous progress has been made in the last two years of Run II operation. The peak luminosity for collider stores has increased by nearly a factor of 2.5. The collider now integrates $30 - 40$ pb^{-1} per week. This progress is due to more antiprotons available to the collider as a consequence of the increased $\bar{p}$ stacking rate as well as

Tevatron improvements that allow more luminosity to be gained per $\bar{p}$ (β^* reduction) and better store lifetime (separator improvements).

The Run II upgrades project is nearing completion. Over the next year improvements to the stacktail cooling system, further Debuncher cooling and aperture improvements, and further increases in Li lens gradient should permit $\bar{p}$ stacking at a rate of 30×10^{10}/hr. Implementing Accumulator to Recycler transfers on event will increase the overall rate of $\bar{p}$ accumulation in the Recycler. The Tevatron working point change will allow the collider to accommodate the increased $\bar{p}$ brightness.

Run II is projected to end in late 2009. With the present rate of progress, Fermilab is on track to reach a total integrated luminosity of 7 fb^{-1} by that time.

REFERENCES

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