FERMILAB TEVATRON OPERATIONAL STATUS*

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Abstract

The Fermilab Tevatron Proton-Antiproton Collider is currently the world's highest energy hadron collider. The luminosity of the Fermilab collider has been significantly increased with the Main Injector operating at its design goals. Further increases in luminosity have been the result of combining antiprotons from the Recycler and Accumulator storage rings. Recent commissioning of proton slip-stacking in the Main Injector has noticeably increased the antiproton accumulation rate. The increased stacking rate permits the sustained operation of using antiprotons from both the Accumulator and Recycler. Further increases in peak luminosity are expected from electron cooling in the Recycler and increased antiproton flux from the Antiproton Source.

INTRODUCTION

The Fermilab Collider is a Antiproton-Proton Collider operating at 980 GeV. A layout of the complex is shown in Figure 1.

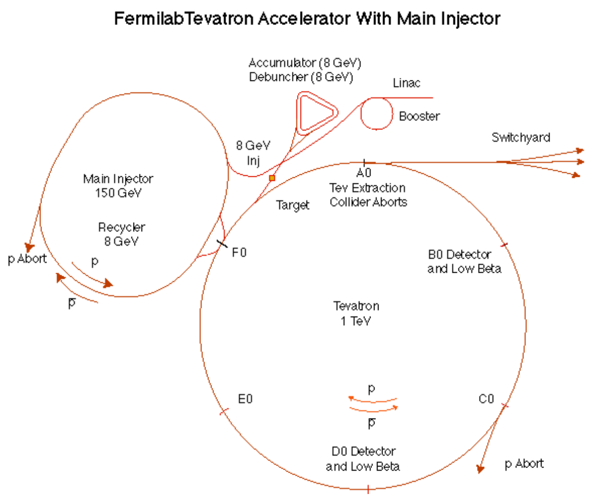

Figure 1. Layout of the Fermilab collider complex

Protons are accelerated though the following process:

- H- ions are accelerated to 750 keV in the Crockoft-Walton
- H- ions are accelerated to 400 MeV in the Linac
- H- ions are stripped and multi-turn injected onto the Booster
- Protons are accelerated from 400 MeV to 8 GeV in 33 mS in the Booster
- In the Main Injector,Protons are accelerated from 8 GeV to 120 GeV for pbar production in 1.5-2.4 seconds and to 150 GeV for TEVATRON filling in 3.0 seconds
- Protons are accelerated from 150 GeV to 980 GeV in the TEV

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Antiprotons are accelerated through the following process:

- 1×10^8 8 GeV antiprotons are made every 2-4 seconds by smashing 7×10^{12} 120 GeV protons on a Nickel target
- 8 GeV Pbars are focused with a lithium lens operating at a gradient of 760 Tesla/meter
- ~30,000 pulses of 8 GeV antiprotons are collected, stored and stochastically cooled in the Debuncher and Accumulator and Recycler Rings
- The stochastic stacking and cooling increases the 6-D phase space density by a factor of 600×10^6
- 8 GeV antiprotons are accelerated to 150 GeV in the Main Injector and to 980 GeV in the TEVATRON

PERFORMANCE SUMMARY

As shown in Figures 2-4, the Tevatron has seen a 3-fold increase in peak luminosity, integrated luminosity per week, and total integrated luminosity since the last Particle Accelerator Conference in 2003.

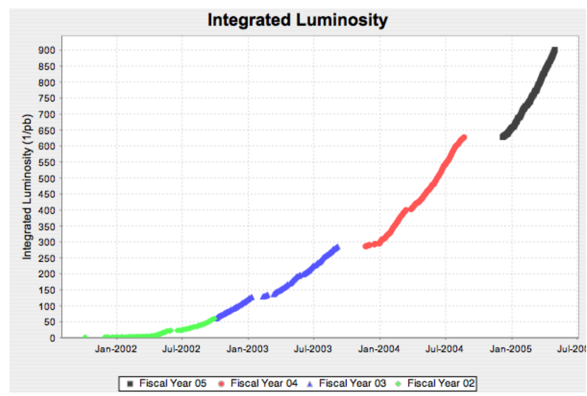

Figure 2. Integrated luminosity of Run II

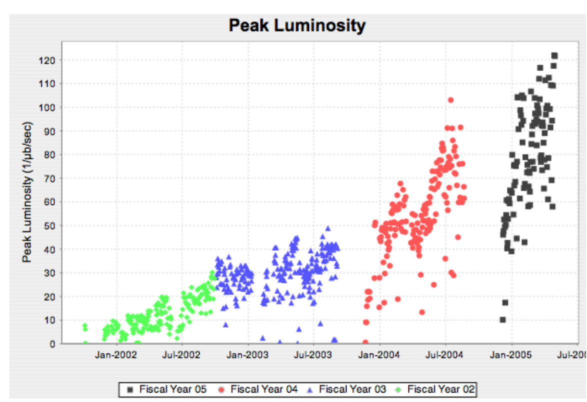

Figure 3. Peak Luminosity history in Run II.

The luminosity increase is mostly due to:

- Better performance of the injector chain
- Introduction of the Recycler into operations
- Alignment of the Tevatron

- Decision to "run" the Collider which required a rigorous approach to attacking operational problems at the expense of de-emphasizing long periods of dedicated machine studies.

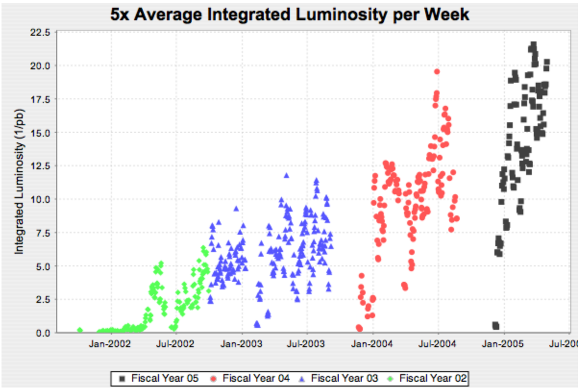

Figure 4. Integrated luminosity per week during Run II.

INJECTOR PERFORMANCE

The instantaneous luminosity for a proton-antiproton collider is given as:

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

The major luminosity limitations are the number of antiprotons (BN_{pbar}), the proton beam brightness (N_p/ε_p), and the antiproton emittance (ε_{pbar}). As shown in Figure 5, the strategy to increasing luminosity in the Tevatron is to increase the number of antiprotons available to the collider.

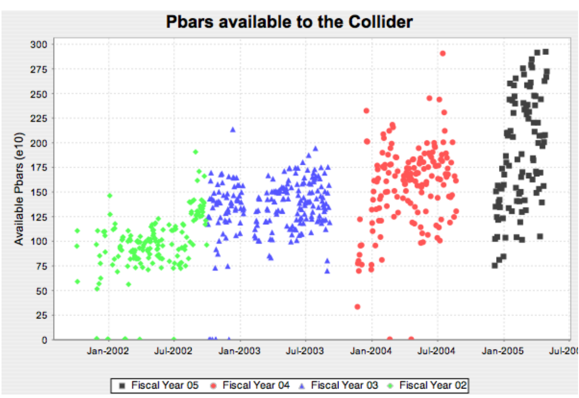

Figure 5. Amount of antiprotons available to the Tevatron collider during Run II.

Increasing the amount of antiprotons is done by increasing the transfer efficiency of antiprotons to low beta in the Tevatron., increasing the antiproton production rate via the Run 2 Upgrades, and providing a third stage of antiproton cooling with the Recycler.

The Recycler

The Recycler is designed to a be a third stage antiproton accumulator ring which initially uses stochastic cooling and will eventually will use electron cooling[1]. The Recycler ring shares the same tunnel as the Main Injector. The major magnetic elements are made from permanent magnets.

At the end of August 2003, the Recycler performance was far below expectations. The beam lifetime was less than 60 hours and the transverse emittance growth was 12π-mm-mrad/hour (95% normalized). To fix the Recycler, Fermilab took drastic measures by

- lengthening the Fall 2003 shutdown to bake the entire Recycler
- instituting the Pbar Tax (Investment) to guarantee the Recycler adequate study time and access to the tunnel
- re-organizing the Accelerator Physics Dept. to give the Recycler and Tevatron more accelerator physicists

The Recycler bake-out was extremely successful. The transverse emittance growth reduced by a factor of 10-20 and the lifetime increased to over 600 hours. Since then, Recycler commissioning has progressed rapidly. A stand alone Recycler shot to the Tevatron occurred in January of 2004 and stacks greater than $150x10^{10}$ antiprotons have been achieved. The Recycler is now operational in the "Combined Shot" mode[2].

Combined Shots

The Accumulator antiproton stack size is operationally limited to less than $200x10^{10}$ antiprotons because of the small stacking rate at large stacks and the growth of the transverse emittance as a function of stack size.

Combined Shots is a mode of operation in which antiprotons from both the Accumulator and the Recycler are extracted for the same collider store. For example out of the 36 antiproton bunches in the Tevatron, twelve bunches might be from the Recycler and twenty four bunches might be from the Accumulator. The bunch ratio between the Recycler and Accumulator is governed by Recycler phase space density (stochastic cooling) and the Accumulator-Recycler transfer time.

Combined Shot operations were first proposed in February 2004 by Brian Chase. Dual energy ramps in the Main Injector were completed and tested by May 2004[3]. The first attempt at a combined shot was in June of 2004. A record luminosity of $103x10^{30}cm^{-2}sec^{-1}$ was recorded on 7/16/04. Combined Shots were introduced to routine operations in December 2004 and the peak luminosity has steadily increased since then resulting in a peak luminosity of $127\ x10^{30}cm^{-2}sec^{-1}$ recorded in May 2005

Combined Shot operations gives enormous flexibility in the Run II Upgrade schedule by providing a natural merging of commissioning of electron cooling into operations when electron cooling is ready[1]. Also Combined Shot operations push Recycler commissioning progress by plunging it into operations. Combined Shot operation is also a luminosity enhancement by providing a larger amount of antiprotons for smaller transverse emittance.

The major obstacles to Combined Shot operation is stacking rate, injector complex 8 GeV energy alignment[3], longitudinal emittance growth in both the

Accumulator and Recycler and the transfer time between Accumulator to Recycler.

Antiproton Production – Slip Stacking

Slip stacking is the process of combining two Booster batches at injection into in the Main Injector to effectively double the amount of protons on the antiproton production target. Slip stacking was successfully commissioned in the summer of 2004 and is now used operationally in 2005 [4][5]. As shown in Figures 8-9, slip stacking has provided a significant boost to the antiproton production rate.

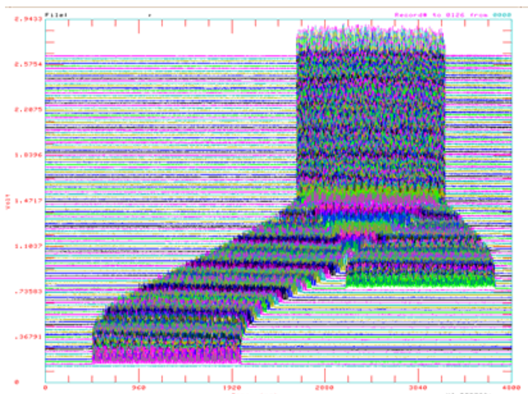

Figure 6. Slip stacking of two Booster batches in the Main Injector

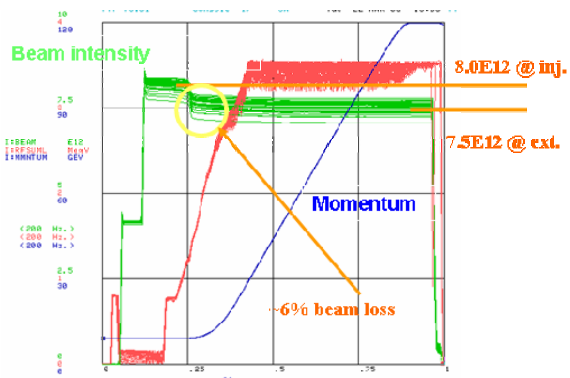

Figure 7. Main Injector intensity profile of slip stacking.

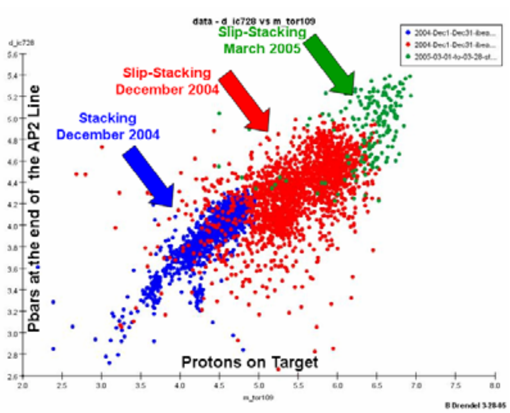

Figure 8. The amount of antiprotons produced as a function of proton beam on the antiproton production target.

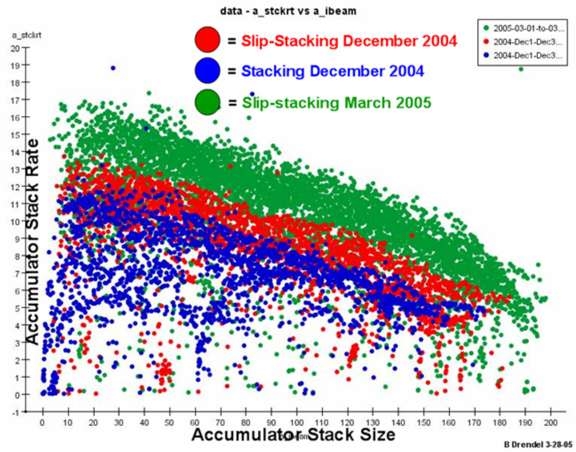

Figure 9. Antiproton production rate vs. antiproton stack size.

TEVATRON ACCOMPLISHMENTS

A major accomplishments in the Tevatron over the past two years is the alignment of the Tevatron[6]. The alignment task was broken into a number of sub-projects:

- Tev-Net
- Smart bolt retro-fit [7]-[10]
- Dipole Un-Rolls
- P1 Line roll
- IP low-beta regions
- Tight aperture areas [11]

The alignment of the Tevatron resulted in

- Better injection efficiency
- Smaller emittance at collisions
- Better ramp efficiency
- Better store-store reproducibility

In addition to the alignment of the Tevatron, the collision optics at both interaction regions were measured and corrected. As shown in Figure 10, the resulting corrections increased the luminosity in the collider on the order of 20%. Also, a large effort has been expended in trying to understand beam-beam effects in the Tevatron[12]-[14].

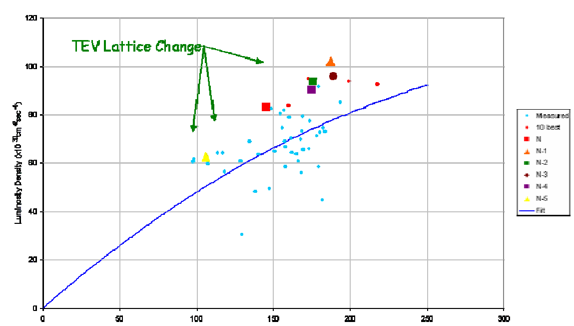

Figure 10. Luminosity per proton as a function of antiproton stack size before and after correcting the collision optics.

In concert with understanding the collision optics and beam-beam effects, and as part of the Run II Upgrades, the Tevatron helix has undergone modifications [15]. These modifications include the installation of more separators and polarity switches to aid in beam studies and providing the flexibility for different helix configurations. Figure 11 shows the results of changes in luminosity lifetime as a function of the helix separation.

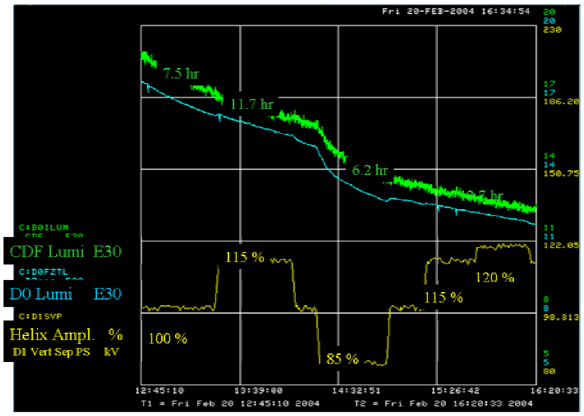

Figure 11. Luminosity lifetime as a function of the helix separation.

Instrumentation for the Tevatron has undergone significant upgrades[16]-[21]. The major instrumentation project has been a new BPM system that can see both protons and antiprotons[22]-[25] as shown in Figure 12.

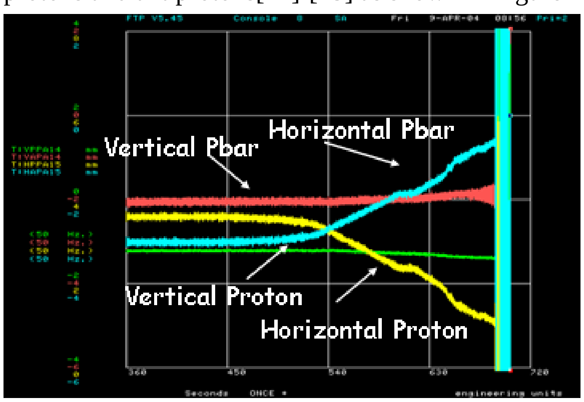

Figure 12. Tevatron BPM signals as the Tevatron helix is opened.

One of the major concerns with operating the Tevatron in Run II has been the danger of accelerator and detector damage due fast beam loss. The luminosity is proportional to the number of protons **per bunch** (N_p) but the proton beam current is proportional to the number of bunches x N_p. An example of a fast beam loss incident that was initiated by misbehavior of a roman pot detector is shown in Figure 13. Because of the potential for serious damage, every serious beam incident is fully diagnosed and implications are digested by the experimental collaborations. Any corrective action usually involves work on the accelerator. A major lesson learned is that the experiments must be protected by collimators as much as possible. Also the beam loss monitor system is undergoing an upgrade [26] so that it can trigger a beam abort quickly and reliably in the case of a beam accident.

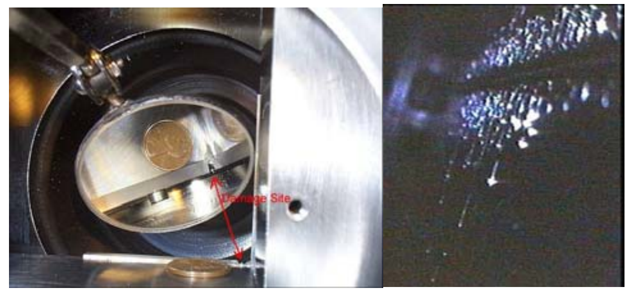

Figure 13. Damage to collimator due to a rapid beam loss incident.

FUTURE LUMINOSITY

Our plan is to deliver the design projection, but, develop an understanding of fallback scenarios. Combined-source operation and the phased Stacktail upgrade allow a more natural introduction of key upgrades (electron cooling and Stacktail upgrades) and provide a more robust fall-back position. We have three luminosity scenarios

- Design Projection: Electron cooling and Stacktail upgrade.
- Fall-back Projection: no Electron cooling, Combined-source operation beyond 2005 (20% gain), and Debuncher to Accumulator transfer issues solved.
- Base Projection: no electron cooling, Debuncher to Accumulator transfer issues solved, minor improvements, and no gain from Combined–source operation.

The luminosity per week and the integrated luminosity projections are shown in Figures 14-15.

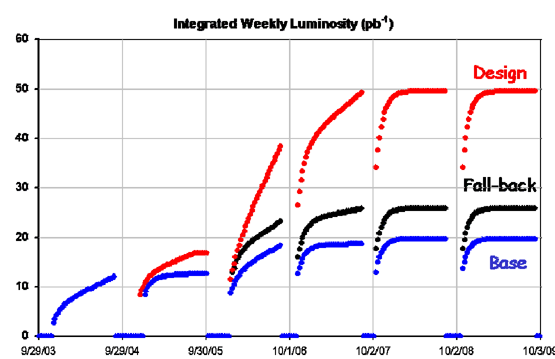

Figure 14. Integrated luminosity per week projection.

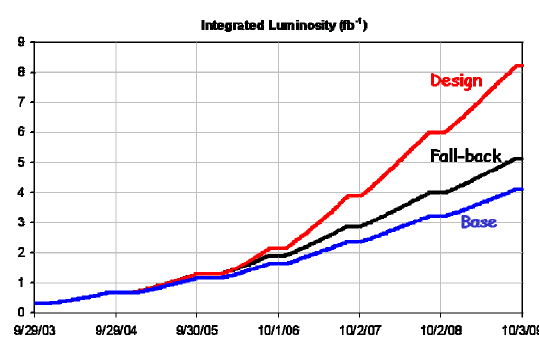

Figure 15. Total integrated luminosity projection.

SUMMARY

Since the last Particle Accelerator Conference in 2003, the Tevatron has seen a 3-fold increase in peak luminosity, integrated luminosity per week, and total integrated luminosity. The luminosity increase is mostly due to better performance of the injector chain, introduction of the Recycler into operations, alignment of the Tevatron, and a decision to “run” the Collider. This new focus emphasizes a rigorous approach to attacking operational problems while de-emphasizing long periods of dedicated machine studies.

The Run II Upgrades are on track to provide over $8fb^{-1}$ by 2009. The Recycler is operational, electron cooling is progressing well, and slip stacking is operational. The major challenge left in Run II is the increasing the antiproton production rate via the AP2- Debuncher aperture upgrade, improving Debuncher to Accumulator transfers, the Stacktail Momentum cooling upgrade, and implementing rapid transfers between the Accumulator and Recycler.

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