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IMPROVEMENTS TO ANTIPROTON ACCUMULATOR TO RECYCLER TRANSFERS AT THE FERMILAB TEVATRON COLLIDER*

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Abstract

Since 2005, the Recycler has become the sole storage ring for antiprotons used in the Tevatron Collider. The operational role of the Antiproton Source has shifted to exclusively producing antiprotons for periodic transfers to the Recycler. The process of transferring the antiprotons from the Accumulator to the Recycler has been greatly improved, leading to a dramatic reduction in the transfer time. The reduction in time has been accomplished with both an improvement in transfer efficiency and an increase in average stacking rate. This paper will describe the improvements that have streamlined the transfer process and other changes that contributed to a significant increase in the number of antiprotons available to the Collider.

INTRODUCTION

The Fermilab accelerator complex is used to concurrently provide particle beams for neutrino, fixed-target and colliding beams experiments. For more than 20 years, the Tevatron accelerator has been used as the collider storage ring, colliding 980 GeV protons with 980 GeV antiprotons (also called pbars). Experiments at Tevatron straight sections B0 (CDF) and D0 (Dzero) have detectors located at the collision points of the counter-rotating particles. Historically, the integrated luminosity that can be delivered to the experiments has been mostly limited by the rate at which antiprotons can be produced by the Antiproton Source. Figures 1 and 2 illustrate the relationship between the number of antiprotons produced each month and the monthly integrated luminosity during the latter part of Collider Run II.

The Antiproton Source is comprised of two storage rings, the Debuncher and Accumulator, as well as beam lines and a target station. The Main Injector provides a 120 GeV proton beam of 8E12 to the target station every 2.2 seconds. Antiprotons in the secondary beam are transported to the Debuncher ring, where the beam's transverse and longitudinal phase-spaces are greatly reduced. The antiprotons are then transferred to the Accumulator ring. In the Accumulator, successive groups of antiprotons are momentum-cooled into a region known as the core. This process is known as pbar stacking.

Prior to Collider Run II, which began in 2001, the Accumulator core was the final destination for pbars before transfer to the Tevatron via the Main Ring. When the Main Injector ring was designed as a replacement for the Main Ring, another antiproton storage ring known as the Recycler was proposed [1]. A separate storage ring dedicated to cooling the antiprotons prior to transfer to the Tevatron could allow the Antiproton Source to increase the pbar accumulation rate. The Recycler ring installation was not completed until after the beginning of Run II. A lengthy period of commissioning and upgrades followed, which included the installation of electron cooling. In 2005, the Recycler ring and electron cooling entered operation.

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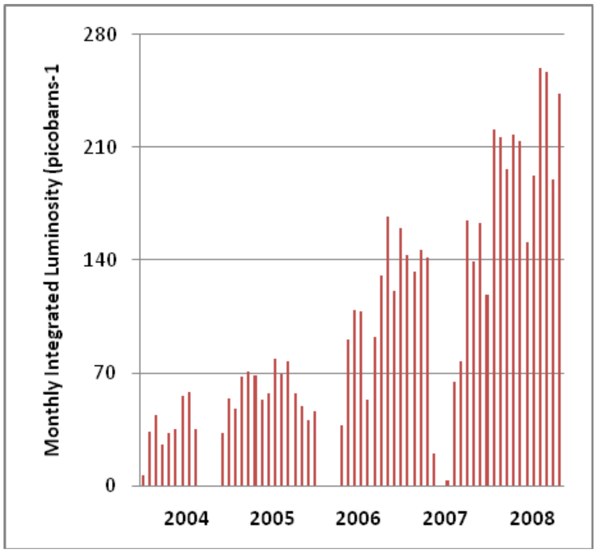

Figure 1: Integrated Luminosity

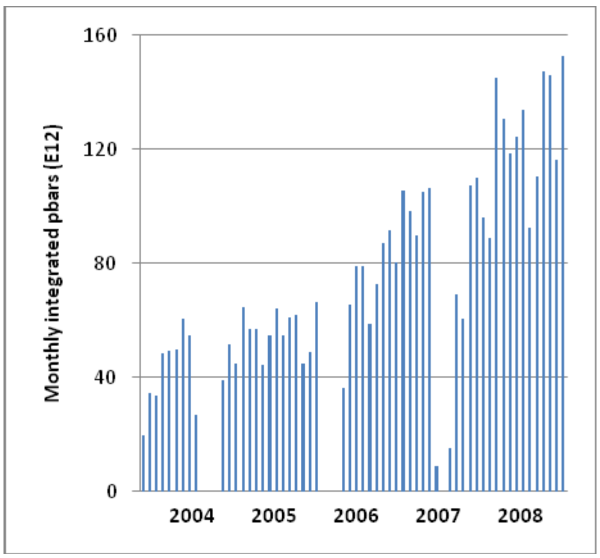

Figure 2: Antiprotons transferred to the Recycler

TRANSFERS TO THE RECYCLER

Antiprotons transferred between the Accumulator and Recycler travel through a series of beam lines and the Main Injector. A small deceleration takes place in the Main Injector so the antiprotons have the appropriate energy for the Recycler. Antiprotons injected into the Recycler are merged into the region of stored antiprotons, which is called the stash.

Changes to reduce time spent on transfers

The procedure formerly used for transferring antiprotons to the Tevatron was the starting point for transfers to the Recycler. Since the original procedure was synchronized to the other accelerators during collider "shot set-up", there were many embedded delays and other inefficiencies. Because the Antiproton Source set-up could be done in parallel with the Tevatron set-up for a Collider store, there was no compelling reason to speed up the process. When the procedures and software for Collider set-up were adapted for use on Recycler transfers, the first efforts at streamlining involved removing steps associated with transfers to the Tevatron.

During 2005, the Recycler shifted from commissioning to operational use. By that time, the interruption to stacking for transfers had been reduced from more than an hour to about 45 minutes. For much of 2005, the Recycler and Accumulator simultaneously provided antiprotons for the Tevatron in a mode called "combination shots". Prior to the commissioning of electron cooling for the Recycler, the Recycler's stochastic cooling was inadequate to provide the necessary phase space to support sole operation. By the end of 2005, electron cooling was operational and the Recycler was used as the sole storage ring for antiprotons destined for the Tevatron [2]. Through the first half of 2006, little additional progress was made in reducing the stacking interruption required to transfer antiprotons to the Recycler.

The updated scheme for transfers to the Recycler [3], known as "frequent, rapid transfers", was part of the Run II upgrade plan written in 2001. Although some of the specified improvements had been commissioned by 2006, critical tasks remained to be completed. The new scheme called for the following major changes in order to accomplish periodic transfers of one minute duration:

- Time would not be spent cooling the beam into the core. Transfers would seamlessly occur during antiproton stacking, with appropriate RF and cooling systems briefly gated off during the transfer process.
- The AP-1 line power supplies, originally operated in distinct stacking and transfer modes, would be ramped to save time spent switching modes.
- As many preparation steps as possible were to be accomplished while stacking so that they could be moved out of the time used for transfers.
- Upgraded beam position electronics were built as part of the Run II upgrade plan. New software was required to efficiently use the position data from antiproton transfers.
- Beam line tune-ups needed to be much less frequent, on a time scale of once every day or two.
- Specialized "Time Lines" needed to be constructed to eliminate the need for dedicated tune-up and transfer events running for long periods of time.
- ARF-4, the RF system used to accelerate antiprotons to the extraction orbit, needed to have waveforms built that would speed up the extraction process.

Changes to improve efficiency

Typical transfer efficiencies during the first half of 2006 varied between 75-95%, with a median efficiency of about 89%. The goal for the Run II rapid transfer scheme was a median efficiency of 95%. This was a challenge because many of the steps taken to speed up the transfer process, as well as improvements to pbar stacking, caused larger antiprotons transverse emittances. The beam line acceptance was not large enough to maintain the transfer efficiency as the transfer time was shortened. Indeed, early efforts at speeding up transfers did not result in an overall improvement in performance because of the reduction in efficiency.

In order to reach a transfer efficiency of 95% in conjunction with speeding up the antiproton transfers, the following steps were taken:

Date Peak rate	**Nov. 2005** 15.0E10/Hr	**Jan. 2008** 25.5E10/Hr	**April 2009** 29.0E10/Hr
Percentage Stacking time	87.0	94.0	98.5
Transfer efficiency	89.0	95.0	96.0
Percentage of peak rate	90.0	92.0	94.0
Percentage Of ideal rate (Effective rate)	69.7 (10.5E10/Hr)	82.2 (21.0E10/Hr)	88.9 (25.8E10/Hr)

- The beam line optics was modified to improve the dynamic aperture and the reference trajectory was defined based on scans of the physical aperture.
- A Pbar injection damper was built for the Main Injector to reduce emittance dilution from steering errors.
- Pbar orbit data from the upgraded beam position system was used to monitor the trajectory.
- Antiproton bunches were shortened in the Accumulator with RF to reduce steering errors caused by current "ringing" on the leading and trailing edges of the extraction kicker pulse.

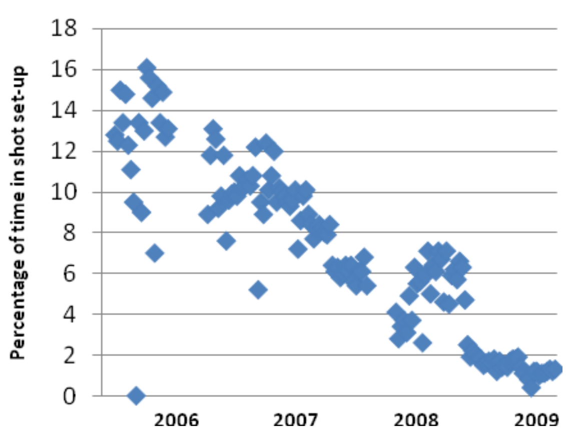

Figure 3: Percentage of time in shot set-up

RAPID TRANSFER IMPLEMENTATION

In the summer of 2006, following a two month maintenance period, the final implementation of rapid transfers began. The software that was used to orchestrate the transfer process was heavily modified to minimize the interruption to pbar stacking. New software tools were integrated into the rapid transfer process, greatly reducing the time spent setting devices. Software changes were made incrementally after thorough testing to minimize the impact to operations. Software changes were prioritized, so that those with the greatest benefits were implemented first. This approach yielded immediate benefits, with continued progress in the years that followed. Figure 3 shows the percent reduction in running time spent in transfer set-up since 2006, from about 14.0% in 2006 to 1.3% at the present time.

In parallel with the software improvements, efforts were made to improve the beam transport process. Because the time spent cooling the beam prior to transfers had been eliminated as a time-saving measure, beam line apertures and beam trajectory became critically important. Beam line optics had already been improved prior to 2006, but further optics and aperture improvements were implemented to improve efficiency. The pbar BPM upgrade for the beam lines was crucial in better controlling the beam line trajectory during transfers.

Table 1: Effective Stacking Rate

As the size of the Accumulator core grows, the stacktail momentum system is adversely affected and the pbar stacking rate is reduced. Because of this feature, it is desirable to keep the size of the core as small as possible. However, until the transfer set-up time became acceptably short, it was not optimal to run with frequent transfers from small stacks. The combination of an increased average stacking rate and smaller interruption to stacking from the transfer set-up process led to a significant increase in the number of antiprotons transferred to the Recycler. Table 1 provides the relative contributions from the improvements to the rapid transfer process as well as simultaneous improvements in the peak stacking rate. The "Effective Stacking Rate" is the net combination of the effects, expressed as an hourly antiproton production rate.

The average number of pbar stacking hours per week has increased substantially since 2005. Figure 4 shows the overall distribution of weekly hours for 2005 and 2009. The increase in stacking time from 110 to 135 hours (23%) comes primarily from two sources. About 16 hours of the 25 hour increase has come from the reduction in Accumulator to Recycler transfer set-up time, just described. Most of the remaining nine hours has come from optimizing stacking time during collider set-up for antiproton transfers from the Recycler to the Tevatron. After the Accumulator was no longer used for antiproton transfers to the Tevatron in late 2005, pbar stacking could continue during collider set-up. The set-up was later optimized to provide the greatest possible number of pbar stacking cycles during the tune-up process.

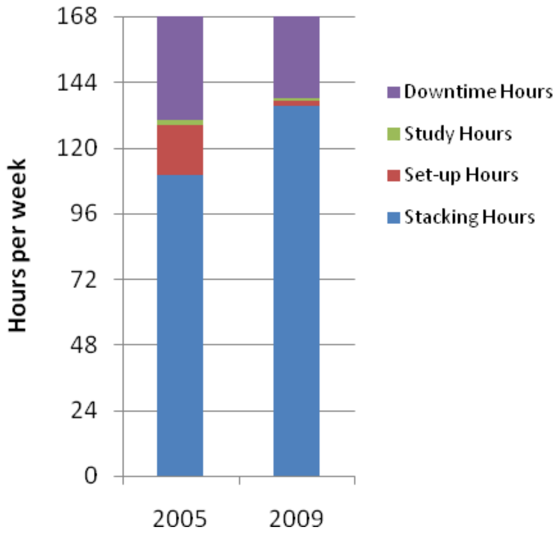

Figure 4: Antiproton Source running time

CONCLUSION

The implementation of the Rapid Transfer upgrade has been very successful, contributing to an increase in average stacking rate and the number of stacking hours per week. The operational time spent setting up for antiproton transfers to the Recycler has been reduced to less than one minute for each pair of transfers. The time reduction has been achieved primarily through reorganizing the set-up process and software improvements. Transfer efficiency has been improved through beam line optics and orbit improvements and a reduction in emittance dilution during transfers. The combination of an increase in stacking time and average stacking rate have led to a factor of 2.5 increase in the number of antiprotons available to the collider program since 2005. This, in turn, has contributed significantly to the factor of four increase in integrated luminosity for the collider experiments over the same time period.

REFERENCES

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