PROGRESS IN ANTIPROTON PRODUCTION AT THE FERMILAB TEVATRON COLLIDER*

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Abstract

Fermilab Collider Run II has been ongoing since 2001. During this time peak luminosities in the Tevatron have increased from approximately 10 × 10^{30} $cm^{-2}sec^{-1}$ to 300×10^{30} $cm^{-2}sec^{-1}$. A major contributing factor in this remarkable performance is a greatly improved antiproton production capability. Since the beginning of Run II, the average antiproton accumulation rate has increased from 2 × $10^{10}\bar{p}$/hr to about 24 × $10^{10}\bar{p}$/hr. Peak antiproton stacking rates presently exceed 28 × $10^{10}\bar{p}$/hr. The antiproton stacking rate has nearly doubled since 2005. It is this recent progress that is the focus of this paper. The process of transferring antiprotons to the Recycler Ring for subsequent transfer to the collider has been significantly restructured and streamlined, yielding additional cycle time for antiproton production. Improvements to the target station have greatly increased the antiproton yield from the production target. The performance of the Antiproton Source stochastic cooling systems has been enhanced by upgrades to the cooling electronics, accelerator lattice optimization, and improved operating procedures. In this paper, we will briefly report on each of these modifications.

INTRODUCTION

Operation of the Fermilab Antiproton Source is approaching 25 years. The Antiproton Source consists of the target station, beam transport lines, Debuncher and Accumulator rings. Over the last three years, an intensive effort to improve antiproton production and stacking rates has taken place. All enhancements mentioned in this paper occurred while the collider was in operation, rendering each change an incremental improvement that was not always easy to quantify. Observation of the stacking rate and weekly production totals (Figures 1, 2, and 3) testify to the documented advancements in stacking. The increases in stacking described in the paper have taken place since beam on target was doubled with the advent of successful slip stacking of protons in the Main Injector [1].

ANTIPROTON PRODUCTION

The fundamental method for accumulating antiprotons has not changed since the Fermilab Antiproton Source first entered operation in 1985 [2]. Antiproton production

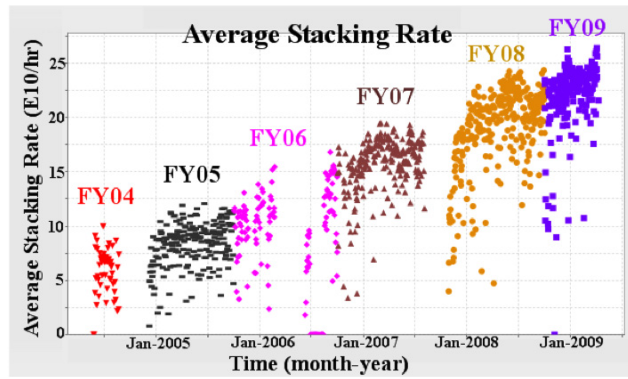

Figure 1: Average Antiproton stacking rate.

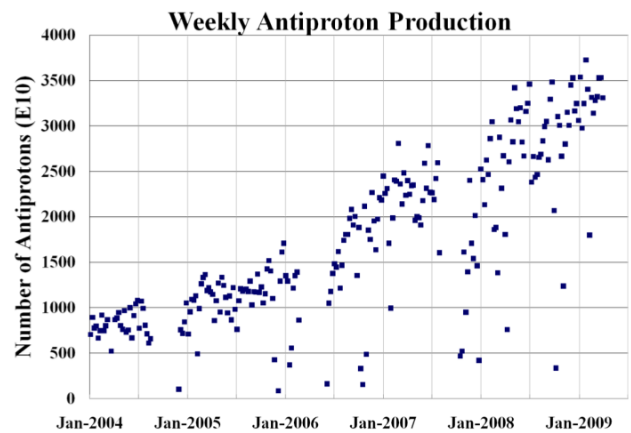

Figure 2: Weekly antiproton production.

consists of the rapid compression (by 5 to 6 orders of magnitude) of the phase space volume of antiprotons collected from the target for accumulation in a storage ring. While the basic procedure has not altered, the capability of every step in the process has been greatly upgraded.

Slip stacking, introduced in 2005, has doubled the number of protons on the Antiproton production target. Improvements in the Main Injector and in the Antiproton Source stochastic cooling systems have allowed a reduction in the duration of the $\bar{p}$ production cycle yielding an increased $\bar{p}$ flux from the target. Lithium lens improvements implemented in 2006 allow higher gradients for better matching into the $\bar{p}$ collection beam line while increasing the operational lifetime of each lens [3]. A variety of machine operation cycles (including study cycles) cause erratic beam position on the antiproton target. A new automatic orbit correction process keeps the beam centered on the target-lens system

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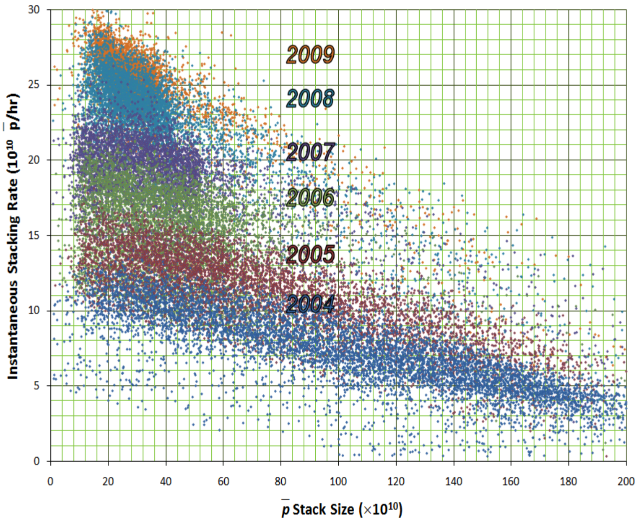

Figure 3: Instantaneous antiproton stacking rate as a function of Accumulator stack size since 2004.

and steers the secondaries beam to the center of the beam line aperture into the Debuncher ring. These same orbit deviations can cause intensity fluctuations of the beam arriving into the Debuncher. Aperture upgrades in the beam line downstream of the target station and in the Debuncher ring (completed in 2006) collect antiprotons into a 95% larger phase space volume. Stochastic cooling improvements provide smaller beams for more efficient transfer between the various beam lines and rings of the Antiproton Source complex. The stacktail cooling system, which merges each new $\bar{p}$ pulse with the stored beam, has been upgraded to handle the increased $\bar{p}$ flux.

Prior to October of 2005, antiprotons were accumulated in the Accumulator ring for later transfer to the collider. As the beam intensity in the Accumulator increases toward levels that are useful to the collider experiments, the $\bar{p}$ stacking rate decreases significantly. This stacking degradation with increasing stack size is due to the combined effects of Accumulator core heating by the stacktail cooling system and trapped ion effects that begin to be manifested at high intensities. Beginning in late 2005 the Recycler Ring was commissioned and put into operation as the final storage ring for antiprotons. This has eliminated most of the intensity dependant degradation in stacking rate by transferring the accumulated stack to the Recycler Ring before the stacking rate decline becomes too severe (see Figure 3).

Associated with the hardware upgrades was a significant overhaul of software and procedures for Antiproton Source operation [4]. These changes provide for almost uninterrupted use of the Antiproton Source for antiproton stacking at maximal rates.

TARGET STATION

In recent years as beam power has increased, radiation hardness and consequently the reliability and service life of target station components became a top priority. Most notably in 2005, improvements include a water-cooled collimator added upstream of the single-turn pulsed magnet and addition of ceramic insulators to the single turn pulsed magnet. The lifetime of these components has increased from 4 months to 24 months. Target reliability improved with a new target design consisting of larger cooling disks and an increased target rotation velocity in May 2006. A new collection lens design was implemented in October 2006. This lens design has operated reliably at a 30% higher gradient with a 20% increase in secondary yield. A newly designed radiation-hardened, internally cooled transformer design installed in June 2007 is expected to exceed the typical lifetime of the original transformer measured at 4 x 10^{19} protons on target. Targets installed prior to February 2009 experienced a lifetime of 3 to 4 months due to severe oxidation by beam heating and exhibited a greater than 10% pulse to pulse yield fluctuation. The most recent target design was installed in February 2009, has provided consistent pulse to pulse yield for nearly two months, and is expected to have a service life of at least one year.

LATTICE MODIFICATIONS

Lattice optimization in the Debuncher, Accumulator, and AP3-P1 transfer lines was undertaken from 2006-2007. A new method of fitting the optics model to the measured data was employed in the rings using the OptiM and LOCO software recently adapted at Fermilab. The Debuncher acceptance was limited by the upper two stochastic cooling bands pickups and kickers operating from 6-8 GHz. At one point, modification of these tanks by increasing aperture was contemplated, but proved to be too costly and would reduce their sensitivity. Optics modifications improved the beta functions in these tanks and the betatron phase advance between pickups and kickers is now closer to the optimal odd multiple of $\pi/2$. The resulting aperture increase eliminated the need to modify cooling tanks [5].

Accumulator optics favored the increase of the slip factor by 15% with the intention of improving stochastic cooling performance, reduced beam heating, and maximizing acceptance. Special attention was given to reducing the residual dispersion in the zero dispersion straight sections. Additional quadrupole shunts were installed in both rings to facilitate the desired changes to the lattice optics [6].

BPMs in the 8 GeV transfer line and Debuncher rings were upgraded. Orbit measurements are now used to improve matching and transfer efficiency of antiprotons into the Debuncher [7].

STOCHASTIC COOLING

Each of the 21 stochastic cooling systems in the Antiproton Source was investigated and improved. Some of the more significant changes are documented here.

The installation of a gain and phase equalizer into stacktail system in the spring of 2007 resulted in improved system bandwidth, although not as much as expected. The major limitation being the introduction of strong transverse and longitudinal heating of the beam by the stacktail system. In an attempt to mitigate the longitudinal heating, an equalizer was also added to the core momentum system and stacktail notch filter 3 reverted to a superconducting filter [8] with improved notch depth and bandwidth, resulting in approximately a 35% increase in the effective bandwidth of longitudinal core cooling.

The eight kicker tanks in the Stacktail system are located in a low dispersion section of the Accumulator Ring. Unfortunately in addition to longitudinal kicks, these kickers also generate transverse quadrupole kicks. The amplitude of the kick grows proportionally to the particle displacement from the kicker's electrical center. Beam based measurements showed the electrical center position is shifted with frequency up to ~2 mm and this dependence is slowly changing with time for reasons not completely understood. In early years of stacking, these displacements were corrected by transverse correction kickers, which were part of the Stacktail system. Routine retuning of these kickers was required to reduce transverse heating. Careful electrical centering of the Stacktail kicker tanks proved to be a more effective method of reducing transverse core heating. To further reduce the core heating, the stacktail kickers located at the ends of kicker straight section (placed at largest beta-functions) were swapped with the core momentum kickers located in the center of kicker straight section.

Longitudinal Debuncher cooling is power limited during a significant portion of the cooling cycle. Increasing system bandwidth would not result in a significant cooling improvement. All four Debuncher longitudinal cooling systems utilize the same optical notch filter. A two-turn delay notch filter was added to the single turn filter to increase system gain slope mid cycle. Switching by means of fast optical fiber switches from single to two-turn delay at one second into the cooling cycle, results in doubling of cooling force derivative for the same system gain. This also reduces momentum cooling range from ±0.46% to ±0.28%, but after 1 s into the cycle, the majority of antiprotons are inside this reduced cooling range, minimizing adverse effects. The resulting 10% reduction of the final energy spread in Debuncher improved the stacking rate.

ANTIPROTON TRANSFERS

With the Recycler operational, the time required to transfer antiprotons became a significant source of inefficiency in the antiproton accumulation process. The pursuit of rapid transfers began in 2006 and has been incrementally implemented since then. This enhancement has contributed to an increase in the number of antiproton stacking hours per week and increased average stacking rate with smaller core sizes of 3 x 10^{11} antiprotons nominal. The success has been achieved primarily through reorganizing the transfer set-up process and improvements to transfer software. Transfer efficiency has been increased mostly through beam line optics adjustments and orbit modifications [9].

CONCLUSION

Antiproton production is now exceeding the original design values of 10 x 10^{10} per hour by a factor of close to three. During the 24 years of operations, many accelerator systems have been upgraded or replaced to achieve the current configuration. Fermilab currently plans to continue antiproton production and the collider program through 2010 and possibly 2011.

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