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# Production and accumulation of the antiprotons in the Tevatron Run II

01.04.20 - Physics of charged particle beams and accelerator technology

ABSTRACT

of the dissertation to obtain the academic degree of Doctor of Sciences Physical and Mathematical Sciences

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The dissertation was performed in the Laboratory of High Energy Physics of Joint Institute for Nuclear Research. Materials and experiments were carried out at Fermi National Laboratory, USA.

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**Scientific Novelty and Practical Value**

The development of the theory of stochastic cooling created a way to understand in detail the operation of stochastic cooling systems when the Schottky bands are close to be overlapped or overlapped. An optimization of the operation of all Antiproton Source systems made it possible to achieve the theoretical maximum of the accumulation rate and the phase density of the antiproton beam needed for the collider. This work required a detailed analysis of the operation of all systems of the Antiproton Source; including: focusing the proton beam on the target, choosing the optimal design parameters for the lithium lens, correcting the optics of the storage rings of the Antiproton Source and increasing their acceptance, correction of the gain for all stochastic cooling systems, construction and optimization of the high energy electron cooling.

**Author's personal contribution**

The contribution of the author to the presented results is undoubtedly decisive. In 2006-2009 the author supervised the work on the Tevatron complex upgrades. He both determined the direction of the work of the involved departments, and did considerable part of purely scientific work aimed at an increase of the Tevatron luminosity. This work included carrying out numerical and analytical calculations, conducting experimental studies, analyzing the results and preparing publications. His participation in the Tevatron Run II made a decisive contribution into its success. In 2012 the author was elected to be a fellow of the American Physical Society (APS) with citation "For significant contributions to the accelerator physics underlying the outstanding performance of the Tevatron Collider complex, and the successful commissioning of the CEBAF at Jefferson Lab". The work carried out in the Tevatron Run-II is presented in the form of scientific publications, as well as in the form of the book "Accelerator Physics at Tevatron Collider" (Springer, 2014, edited by V. Lebedev and V. Shiltsev). An important part of scientific achievements is the mentorship of many successful students and young researchers, peer review of scientific publications in a number of scientific journals. He was awarded to be an Outstanding Referee for Physical

Review Journals in 2015, presently serves one-year term as a chair of the APS DPB Publication Committee.

An upgrade of the Antiproton Source, discussed in the dissertation, was essential part of the overall effort on Tevatron luminosity upgrade.

**The following Items are Submitted for Defense**

1. Optimization of the Fermilab Antiproton Source operation. Including:
   – Optimization of the proton beam focusing on the target.
   – Choice of the direction for the upgrade of the lithium lens and an optimization of its performance.
   – Optics correction for all storage rings and transfer lines of the Antiproton Source. That included an increase in their acceptance and, where applicable, optics optimization for the stochastic cooling, both for the transverse and the stacktail.
2. Improvement and optimization of all stochastic cooling systems of the accelerator complex. Including:
   – Development of the stochastic cooling theory;
   – Proving that the signal suppression makes relatively small effect on the cooling rate of well corrected and phased system;
   – Measurement and correction of the gain of stochastic cooling systems;
   – Development and optimization of equalizers that correct the amplitude and phase of the stochastic cooling system gain. These were the first equalizers in the world, the use of which resulted in faster stochastic cooling; in contrast to a removal unwanted signals/features at the band boundaries which was a typical application of equalizers before this work;
   – The agreement between the calculated and measured cooling rates is within the measurement accuracy, ~ 15%. Prior to this work, typical calculations gave cooling rates twice as fast as those measured.
3. Measurement and correction of optics in an electron cooling system operating at the beam energy of 4.2 MeV
4. The joint work of stochastic and electron cooling systems made it possible to achieve:

– the phase density of the antiproton beam required for the collider;
– a good lifetime, ~600 hours, required for the accumulation of a large antiproton current;
– an optimal operation of the Antiproton Accumulator which maximized the stacking rate.

Most of the work was done at Fermilab in 2001-2009. Out of the work, which was carried out by the author for the Tevatron Run II, only the work directly related to the subject of the dissertation is listed below:

2001 - 2002 - calculations and optimization of the target and the lithium lens;

2002 - 2005 - selection of the optimal strategy for increasing the collider luminosity and, in particular, optimization of collider operation scenario;

2006 - 2009 - optimization of stochastic cooling systems, and optimization of common operation of stochastic and electron cooling in Recycler.

The results of the work were reported at seminars in the Fermilab and international conferences.

**Structure and Volume of the Dissertation**

The dissertation consists of an introduction, historical outline, four chapters and a conclusion. The dissertation text contains 172 pages, 75 figures, 9 tables. The list of literature tours consists of 123 works.

**Reliability of results**

The reliability of the obtained results is confirmed by the record rate of antiproton accumulation, as well as good agreement between the calculated and measured parameters of the measured beam dynamics in the storage rings of the Antiproton Source. Main results were reported on the following international conferences PAC, EPAC, IPAC, NAPAC and ECOOL. In particular, the author delivered plenary talks at EPAC 2006 titled “Tevatron Operational Status and Possible Lessons for the LHC” and at PAC09 titled “Status of Tevatron Run II”. The talks summarized main results of the Tevatron Run II commissioning and supporting developments of the beam physics and technology.

**Publications**

Main results are published in a book, 12 papers in peer-reviewed scientific journals, and 7 conference reports.

## CONSCIZE CONTENT OF THE WORK

**The introduction** briefly substantiates the relevance of the issues considered in the dissertation, formulates the main objectives of the work, and also briefly outlines the content of individual chapters.

**Historical outline** shortly describes the history of Tevatron and an overview of the Fermilab Accelerator Complex of the Run II time.

**Chapter 1** presents the fundamentals of the antiproton production, focusing of the antiprotons coming out the target and beam optics correction for the rings and transfer lines.

At the very beginning of the Tevatron Run II we needed to chose the direction for the upgrade of target station. Detailed analysis, which final results are presented in Figure 1, showed that we need only a modest increase in the lithium lens gradient and the most promising avenue is related to an increase of the Debuncher acceptance to its theoretical maximum of ~40 mm mrad.

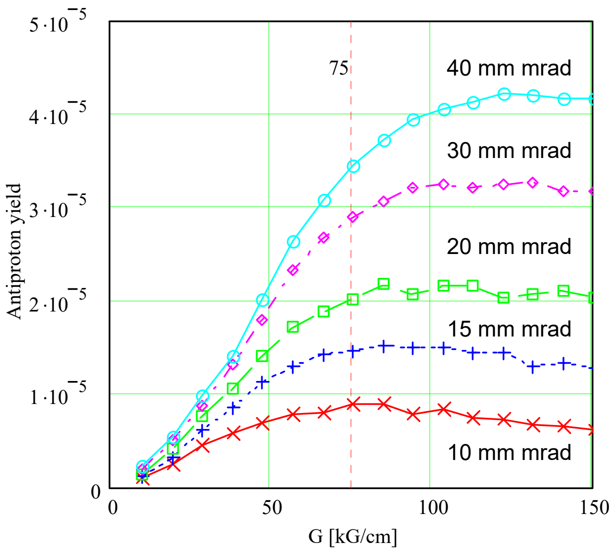


*Figure 1: Simulated dependence of antiproton yield on the lithium lens gradient; rms proton beam size at the target is 130 μm, target length is 8 cm.*

The lithium lens upgrade yielded its gradient increase by about 20% from ~60 to 75 kG/cm. Steering and optics correction resulted in its acceptance increase from ~20 to 35 mm mrad.

**Chapter II** considers the stochastic cooling theory and its application to practical problems.

On the theoretical side, two major questions needed to be clarified:

- How the band overlap affects the beam dielectric function appearing due to beam interaction through the cooling system?
- What is a practical way to characterize the effective bandwidth of the cooling system?

The updated theory stated that if the bands are close to be overlapped then a standard expression for the dielectric function of longitudinal cooling which describes the beam response near *n*-th harmonic,

$$\varepsilon_n(y) \approx 1 + \frac{1}{2\pi i\eta n} \int_{\delta\to 0_+} \frac{df_0(x)}{dx} \frac{G(n\omega_0)}{x - y - i\delta\,\mathrm{sign}(n)} dx ,$$

needs to be replaced by

$$\varepsilon(\omega) = 1 + \int_{\delta\to 0_+} \frac{df_0(x)}{dx} \frac{G(x,\omega)\, e^{i\omega(T_2(x)-T_{20})}}{e^{i\omega T(x)} - (1-\delta)} dx .$$

Here $\omega = n\omega_0(1-\eta y)$ is the circular frequency, $\eta$ is the slip-factor, $x \equiv \Delta p/p$, $G(x,\omega)$ is the cooling system gain, $f_0$ is unperturbed longitudinal distribution, and $(T_2(x) - T_{20})$ is the time difference between arrival to the kicker of a particle with momentum deviation $x$ and the reference particle. Similar expression was derived for the transfer cooling.

It was proved that the effective bandwidth of the system is characterized by the following equation

$$W = \frac{1}{2\pi} \sqrt{ \left( \int_0^\infty \mathrm{Re}(G(\omega))\, d\omega \right)^2 \Big/ \left( \int_0^\infty |G(\omega)|^2 \frac{d\omega}{\omega} \right) } \qquad (1)$$

This equation has been important for optimization of band equalizers which corrected the total gain of cooling system. The bands of all stochastic cooling systems were corrected to maximize their performance.

The detailed analysis of operation of different cooling system was carried out. It included transverse cooling and the following types of longitudinal cooling: Palmer cooling, filter cooling and transit-time cooling. In particular, it was considered how the efficiency of Palmer cooling depends on the band overlap, which is shown in Figure 2.

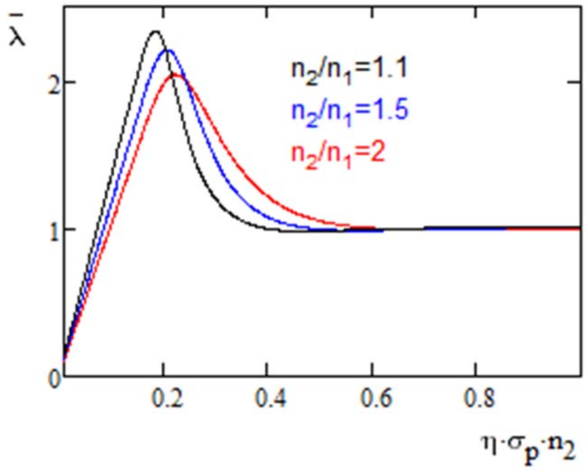


*Figure 2: Dimensionless cooling rate,* $\bar{\lambda} = 3NT_0\lambda / (2W)$*, for Palmer cooling at the optimal gain as a function of the band overlap at the upper band end for different bandwidths of the system.*

Further Chapter II describes technology used in the Fermilab stochastic systems: amplifiers and preamplifiers, kickers and pickups, notch filters, signal transmission, and equalizers.

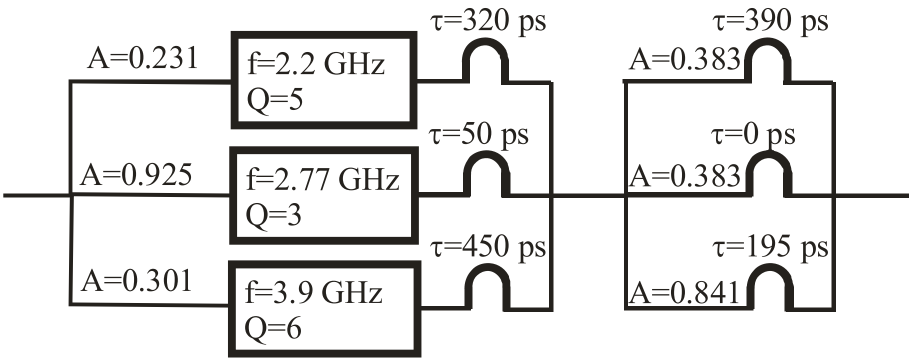


*Figure 3: Schematic of the stacktail prototype equalizer*

Among all stochastic cooling the upgrade of the stacktail was the most complicated. It required detailed beam-based measurements and sophisticated model describing the stacking process. The stacktail equalizer, as well as all other, was designed based on an increase of the effective band described by Eq. (1). Figure 3 presents a principle schematic of the stacktail equalizer which has 3 branches. The final equalizer had 5 branches. Both equalizers were built using microwave printed board technology. Figure 4 shows effect of the stacktail equalizer on the stacking rate.

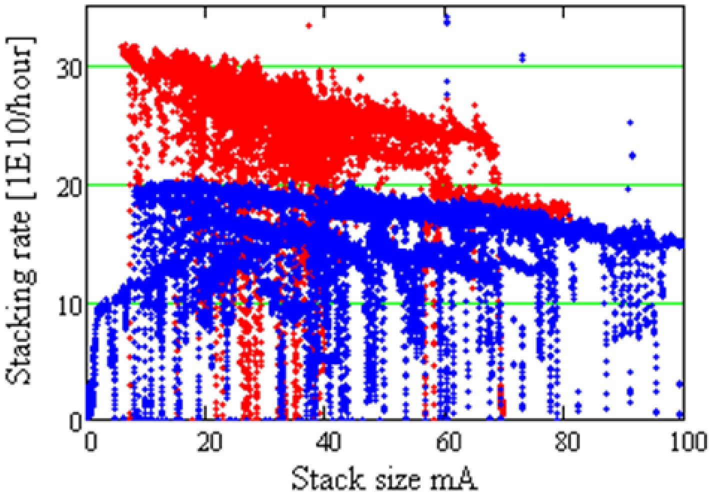


*Figure 4: Dependences of the stacking rate on the stack size before (blue dots) and after (red dots) stacktail upgrades*

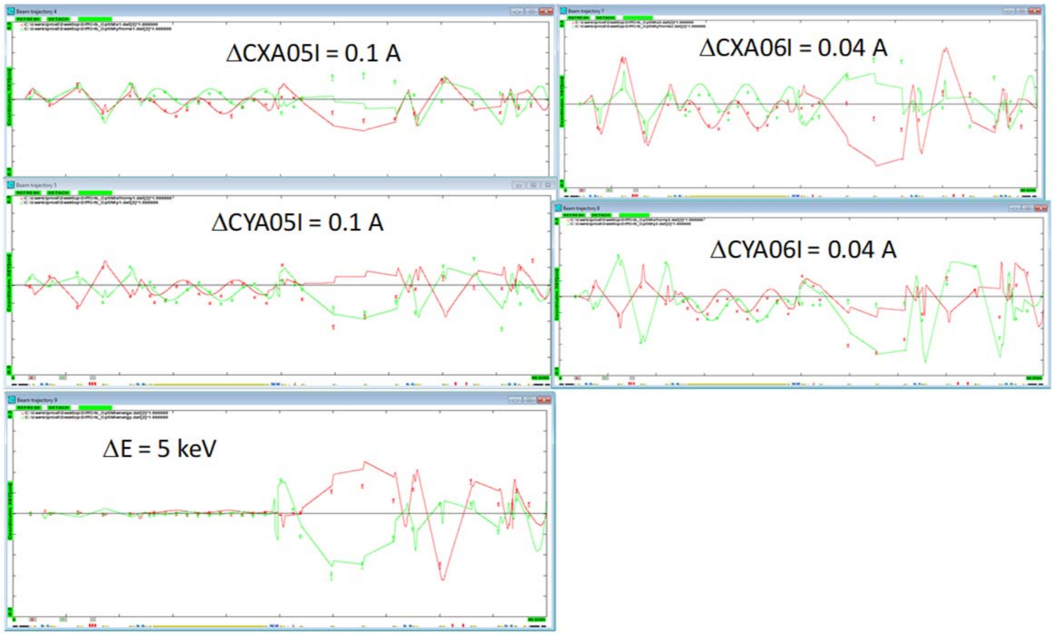


*Figure 5: Example of a standard optics measurement. Points are the measured differential trajectories, and the solid lines are fits by OptiM with fudge factors determined in the previous measurements. Upper four plots show responses to kicks by two pairs of each plane (x and y) correctors (last pairs in the Pelletron and first pair outside, before the first 90-degree bend), and the lower plot is the result of an energy increase. All trajectories are differential, i.e., shown after subtraction of the unperturbed trajectory. Red and green curves represent x and y projections, correspondingly. The error bars for the data points are the statistical errors of measurements.*

**Chapter III** describes the electron cooling and optimization of its use for the Tevatron collider.

First it explains that the magnetized cooling is not helpful for cooling of highly relativistic antiprotons, since the magnetized cooling overcools the very core of the distribution but is not more effective for cooling high amplitude particles. Then the detailed calculations of the cooling force and cooling rates for a Gaussian beam.

A special section is devoted to the optics measurements of the sophisticated beam transport which was greatly helpful for the optimization of the cooling. Figure 5 presents an example of such optics measurements which enabled to obtain detailed focusing properties of the focusing elements and optimize the beam transport.

Considerable part of the chapter describes experimental measurements carried out to optimize cooling and in particular measurements of cooling force.

**Chapter IV** describes optimization of cooling and accumulation in Recycler which is closely related to the stacking in Accumulator.

At time when the Recycler was proposed its construction had three goals: (1) recycle antiprotons left in the Tevatron at the end of each store, (2) accumulate antiprotons coming from the Antiproton source and merge them with "Tevatron" antiprotons, and (3) prepare the bunches which will be extracted from the Recycler and sent to the Main Injector and then to the Tevatron. Detailed analysis carried out for finding optimal scenario for the Tevatron operation showed that in the optimized scenario only small fraction of antiprotons left in the Tevatron at a store end can be delivered to the Recycler. The problem was that at the store end all beam emittances were exceeding the corresponding Recycler acceptances so that only about ~15-30% can be accepted into Recycler. Shortening the stores would allow to decelerate more antiprotons but that would not increase the integrated luminosity. For stores with normal duration the decelerated antiprotons would not increase the overall stacking rate significantly because time required for the deceleration and cooling of antiprotons would basically compensate an additional number of antiprotons coming from the Tevatron. Commissioning of antiproton deceleration required considerable beam time which basically would nullify any possible gain. This work was carried out in 2002-2003. Thus, when the Recycler came to the operation (2005-2006) only two goals were left: accumulate antiprotons and prepare bunches for the Tevatron. An addition of the Recycler to the antiproton complex was extremely helpful. It enabled to avoid large stacks in the Accumulator which, in its turn, enabled to keep the maximum staking rate in the Accumulator. In the first part of Recycler commissioning the Recycler was used as an additional storage ring for antiprotons and filling the Tevatron used antiprotons stored in both the Recycler and Accumulator. With commissioning the electron cooling the cooling in Recycler was greatly improved and Tevatron was filled from the Recycler only. Thus, an addition of electron cooling was absolutely essential for the maximizing antiproton production.

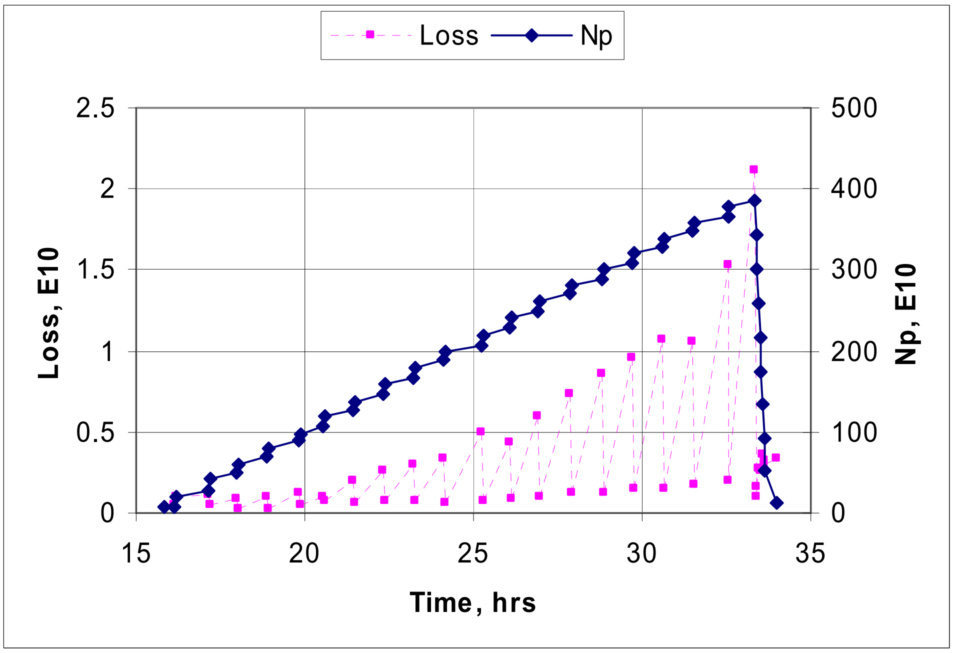


*Figure 6: Antiproton beam intensity and losses over a stashing cycle. In blue diamonds are the numbers of antiprotons in the Recycler before and after injections/extractions. The pink squares represent beam losses during injections/extractions (lower value data points) and between injections (higher value data points).*

The chapter considers in detail different emittance growth mechanisms and, in particular, the intrabeam scattering which is much more powerful than other ones. It is proved that in the Recycler lattice the beam comes to a quasi-equilibrium state when all temperatures in the beam are approximately equal.

The chapter describes in detail operational optimization of electron and stochastic cooling in the process of beam accumulation and bunch formation for the Tevatron shots. Figure 6 presents an example of beam accumulation in the Recycler.

**In conclusion**, the main results of the dissertation work are formulated. At the same time, they are statements submitted for the defense.

The dissertation text contains 172 pages, 75 figures, 9 tables. The list of literature tours consists of 123 works.

**Main results are published in a book:**

Editors: Lebedev V., Shiltsev V. Accelerator Physics at the Tevatron collider. New York: Springer New York, 2014.

**12 papers published in peer-reviewed scientific journals referenced by international databases recommended by the Higher Attestation Commission (ВАК):**

1. V.A. Lebedev, J.S. Hangst, and J.S. Nielsen, "Schottky noise in a laser-cooled ion beam", Phys. Rev. E., **52**, 4345 (1995)
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**and the following conference reports:**

1. V.A. Lebedev, "Single and Multiple Intrabeam Scattering in Hadron Colliders", Proceedings of 33rd ICFA Advanced Beam Dynamics Workshop on High Brightness Hadron Beams, October 2004, Bensheim, Germany.
2. V. Lebedev, V. Sajaev, V. Nagaslaev, A. Valishev, "Fully Coupled Analysis of Orbit Response Matrices at the FNAL Tevatron"; Proceedings of PAC 2005; Knoxville, May 2005.
3. V. A. Lebedev, "Stochastic Cooling with Schottky Band overlap", Workshop on Beam Cooling and Related Topics - COOL05. AIP Conference Proceedings, Volume 821, pp. 231-236 (2006).
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