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TEVATRON OPERATIONAL STATUS AND POSSIBLE LESSONS FOR THE LHC*

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Abstract

This paper provides an overview of the Tevatron Run II luminosity progress and plans, including SC magnet measurements and modeling of field errors in view of the LHC operation. It also discusses antiproton production, stacking and cooling.

STATUS OF THE COLLIDER

Commissioning of Tevatron Run II began in the spring of 2001 [1,2,3] and was formally finished in the summer of 2003 when we declared that the collider is operational. That changed an operational attitude to the studies requiring them to be better focused and organized. Although the study time was reduced, both peak and integrated luminosities demonstrated the same steady growth as before culminating in the peak luminosity of $172\cdot10^{30}$ cm^{-2}s^{-1} achieved in January 2006 and the best weekly integrated luminosity of 24.4 pb^{-1} in December 2005 (see Figures 1 and 2). This progress was a result of many improvements. The major contributors of the last two years are the commissioning of Recycler ring [4] into collider operations with consecutive commissioning of electron cooling, and a growth of antiproton production rate due to slip stacking, aperture improvements in Debuncher and Accumulator, and improvements of stochastic cooling. That resulted in the antiproton peak production rate of $2.01\cdot10^{11}$ hour^{-1} and the maximum stack size in Recycler of $4.36\cdot10^{12}$.

Three month shutdown in 2006 started one week earlier than scheduled (March 1) due to a failed Tevatron magnet. Recovery from the shutdown began in the end of May with first luminosity seen on June 13. Complete recovery took about 4 weeks.

TEVATRON

The worst problems preventing stable Tevatron operations were addressed in the first three years of Run II. The last two years resulted in further operational and engineering improvements aimed at achieving Run II luminosity goal of $3\cdot10^{32}$ cm^{-2}s^{-1}. In 2003 we found out that all Tevatron dipoles have coherent skew-quadrupole component [5]. It has been slowly growing since the magnet installation in 1982 due to compression of thermo-insolating spacers in the support of cold bodies of SC dipoles. It took 3 years and 3 major shutdowns to finish shimming for all 772 Tevatron SC dipoles this year. Another persistent problem is that the Tevatron tunnel is slowly sagging. It forces us to measure and, if necessary, correct positions and rolls for large number of magnets at every major shutdown. During 2006 shutdown about 50 quadrupoles we unrolled. Two additional electrostatic separators and second electron lens were also installed in this shutdown aiming further improvements in the machine operation.

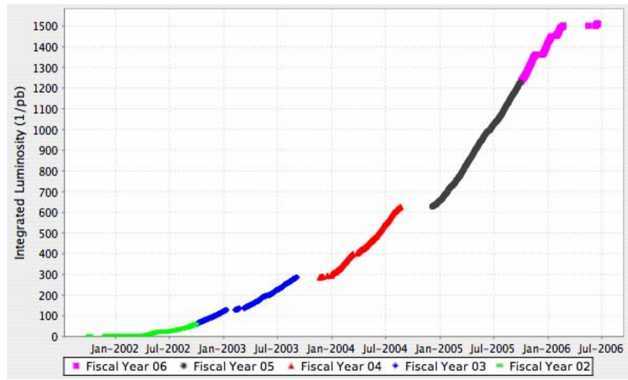

Figure 1: Run II luminosity integral (average of both CDF and D0 detectors).

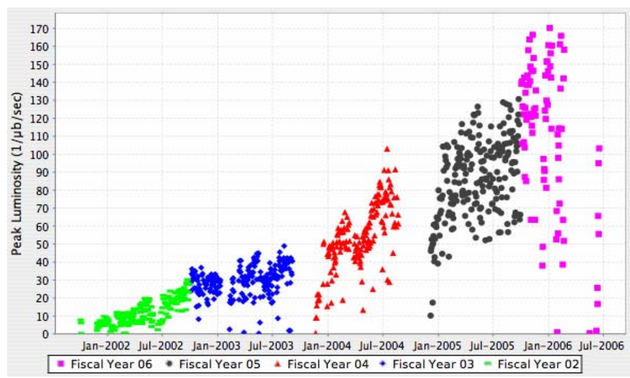

Figure 2: Run II peak luminosities (average of both CDF and D0 detectors).

Magnet quenches are the major reason of Tevatron downtime. Operational changes introduced after collider was commissioned reduced the number of quenches by a factor of two, resulting in about 8 quenches per month for the last 3 years and ≈30% of stores ending prematurely. Normally, quench recovery takes about an hour for mild quenches (magnet temperature raises to 10-15 K) and multi-hour recovery for major quenches (magnet temperature raises to ~100 K). But sometimes even a mild quench can cause a magnet failure resulting in multi-day repair. Table 1 presents major magnet failures of Tevatron magnets which resulted in significant downtime. While we were lucky in FY (fiscal year) 2005, when no major failures happened, three major failures occurred in the first five months of FY 2006 resulting in 5 weeks downtime and a week earlier start of 2006 shutdown. Two of these quenches happened due to failed pressure relief (Kautzky) valves. Considering this a systematic failure, we replaced the failed part in all of about 1200 valves during 2006 shutdown. One of worst failures happened on

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Dec. 20, 2003 when a hardware failure caused a beam loss with consecutive major multi-house quench with 2/3 of the beam lost in the ring before the beam was aborted. Magnets and beam collimators had to be repaired. This event was carefully analyzed and practical recommendations were drawn (see Ref. [6] for details.)

Table 1: Failures in Run II

Date	Time lost	Description	Sector
29-Apr-01		Cryostat vacuum leak	D13
21-May-01		Helium leak at corrector feed-through	F13
8-Jul-01		Helium leak on spool	F47
18-Aug-01		Helium leak	F44
1-Mar-03	12 days	Safety lead ground fault	A13
5-Dec-03	12 days	Helium leak at corrector feed-through caused by catastrophic beam loss	C19
20-Dec-03	10 days	Cryostat vacuum leak	B14
15-Mar-04	12 days	Helium leak	A44
21-Nov-05	3 weeks	Helium leak caused by stuck Kautzky valve	B17
14-Jan-06	2 weeks	Cryostat vacuum leak (air)	A44
22-Feb-06	1 week	Helium leak caused by stuck Kautzky valve	F47

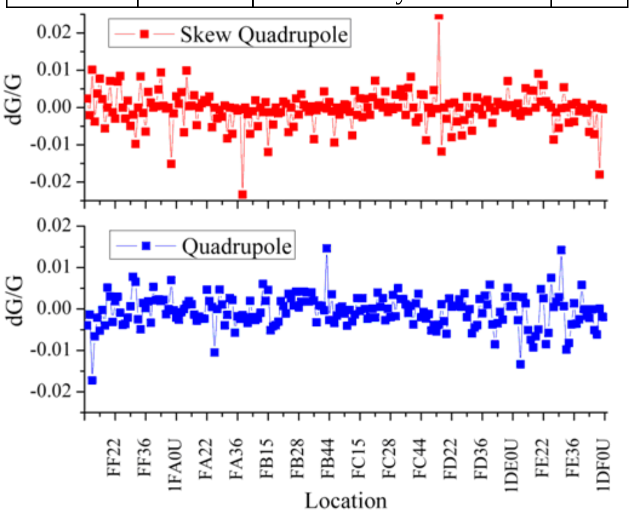

Figure 3: Distribution of relative normal and skew-quadrupole errors along the ring for collision optics in units of 10^{-3}

Table 2: Relative errors of focusing strength for the interaction region quadrupoles in units of 10^{-3}

NAME	Inj.	Low Beta	NAME	Inj.	Low Beta
B0Q3	4.34	-11.18	D0Q3	-1.01	-9.49
B0Q2	4.62	-1.87	D0Q2	21.58	-0.83
B0Q3D	-1.32	-0.09	D0Q3F	0.77	0.24
B0Q3F	-1.37	-0.47	D0Q3D	0.20	-1.84

New BPM system was commissioned at the beginning 2005. It significantly improved the accuracy of optics measurements and, consequently, led to better knowledge of linear and non-linear optics of the machine. The linear part of machine optics model has been built by fitting of large number of measured differential orbits to the model predictions [7]. Although initially the model included the results of magnetic measurements for all quadrupoles, the beam based measurements yield up to 2% corrections for quadrupole focusing. Figure 3 presents corresponding relative values of normal and skew quadrupole components. The largest fraction of the skew quadrupole component is related to the skew quadrupole fields of nearby dipoles. We do not know the reason for so large normal quadrupole component which exceeds the accuracy of the magnetic measurements by an order of magnitude. These focusing errors result in about 15% correction for beta-functions and quite strong coupling which cannot be neglected in any optics or optics related calculations. Both normal and skew-quadrupole errors depend on beam energy, further complicating the analysis and optics tuning. Although the final focus quadrupoles were manufactured and measured a few years later than other magnets they exhibit similar problems as becomes evident from Table 2; but their errors affect optics much stronger because they are located where the beta-functions are large (~1000 m). Note that all beam based measurements measure quadrupole strengths relative to the average dipole strengths determining the beam energy. This average misbalance is 0.179% at injection and 0.191% at collision energy. It is not shown in Figure 3.

Success of linear optics measurements inspired us to look for machine non-linearities. The study aimed to find a sextupole distribution at the injection energy was carried out in collaboration with CERN [8]. Although accuracy of the measurements does not allow us to ascribe sextupole strength to each magnet, the study pointed out major contributors. Analysis showed that all of them are related to regular machine sextupoles and that there is no one or few magnets with large sextupole components dominating ring non-linearity. That was good news given the fact that we did not have reliable data on the magnet non-linearities. Although a full set of magnetic measurements was carried out for each magnet before its installation in the tunnel, there is little trust in the measurements of sextupole component. At the time of the measurements it was unknown that the sextupole component strongly depends on time due to persistent currents in superconductor (see Ref. [9] and references there). Therefore the time of each measurement in the magnet hysteresis cycle was not specified and, consequently, sextupole strength at given time is unknown. Special sextupole circuits correct time dependent chromaticity of the entire ring but redistribution of sextupole component along the ring has not been known.

There has been a significant progress in simulation of the beam-beam effects for Tevatron [10], but further progress required comparison with experiment and was delayed by absence of accurate bunch-by-bunch tune measurements. Two tune monitors have been routinely used in Tevatron. The first one was inherited from Run I. It is based on resonant circuit built on the capacitance of pickup plates and operates at ~21 MHz. It has good sensitivity and good tune resolution but it cannot resolve tunes of separate bunches and can not independently see protons and antiprotons. Another tune monitor is based on microwave technology developed for stochastic cooling [11]. It operates at 1.7 GHz and can resolve separate bunches. However because of very high frequency it sees many synchro-betatron modes making tune line much wider than difference between horizontal and vertical tunes. There is strong coupling in Tevatron resulting that both horizontal and vertical modes contribute to the signals of horizontal and vertical monitors. Consequently, they report a mixture of both tunes making impossible to determine the real tunes. Recently we started development of another tune monitor based on a sub-micron resolution BPM and FPGA technology. After simple analog preprocessing of pickup signal electronics digitizes each bunch position and records it to memory. Then, FFT is performed for each bunch turn-by-turn position yielding bunch spectrum and tunes. Figure 5 presents results of the first tests of such tune monitor. Small vertical excitation is applied so as to see the signal clearly. It amplifies beam motion at betatron frequency by about 30 Db. In accordance with expectations, bunches 1 and 12 have different frequencies and different amplitudes.

Recently introduced Tevatron tune and orbit feedbacks resulted in more stable machine operation and minor improvement in the beam lifetime.

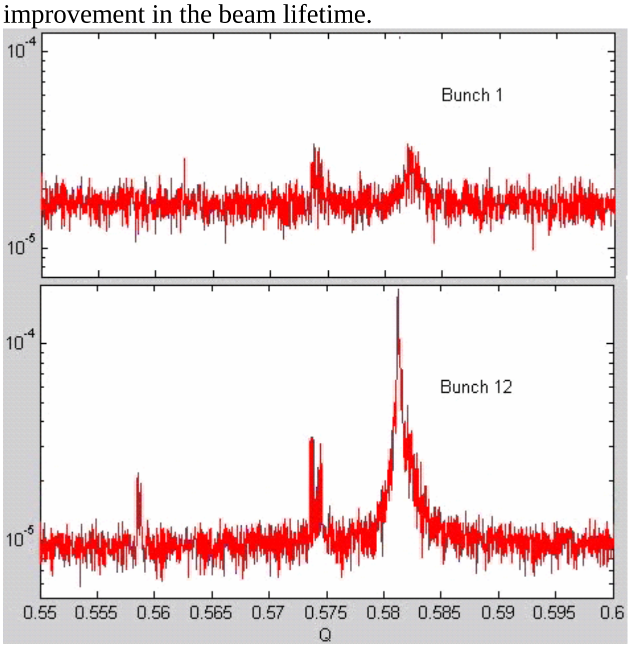

Figure 5: Bunch spectrum (mm per harmonic) for proton bunches 1 and 12 measured with new Schottky monitor. Data are taken during usual Tevatron store.

ANTIPROTON PRODUCTION

The success of Run II would not be possible without reliable work of Booster and Main injector (MI) - two proton synchrotrons used for injection of protons to Tevatron and antiproton production. In the spring of 2005, NuMI/MINOS beam operations were included into routine operation of Tevatron complex. This was achieved by adding 5 additional Booster batches to the two required for antiproton production. That put a strong pressure on minimizing beam losses in both Booster and MI. To address this problem and also increase number of protons on the target a team of about 20 people was created in the summer of 2005. The group was divided into four teams charged to improve performance of Booster, MI, Antiproton source, and instrumentation support.

The major task of the Booster team was to decrease longitudinal emittance in the Booster. There were a number of improvements, but the most significant was introduction of longitudinal quadrupole damper suppressing longitudinal oscillations after transition crossing. The work resulted in an increase of number of protons from $3.9{\cdot}10^{12}$ to $4.5{\cdot}10^{12}$ with simultaneous decrease of longitudinal emittance from 0.2 to 0.12 eV·s.

Presently, MI cycle includes two slip stacked Booster batches [12] for antiproton production and five Booster batches for NuMI. The task of MI team was to increase beam intensity on the antiproton production target and minimize beam losses. Improvements in beam loading and longitudinal matching, optimization of transverse and longitudinal dampers as well as a few other addressed problems yielded an increase of number of protons on the target from $6.2{\cdot}10^{12}$ to $7.6{\cdot}10^{12}$ and resulted in the total number of proton accelerated in one cycle to be $\sim 3{\cdot}10^{13}$.

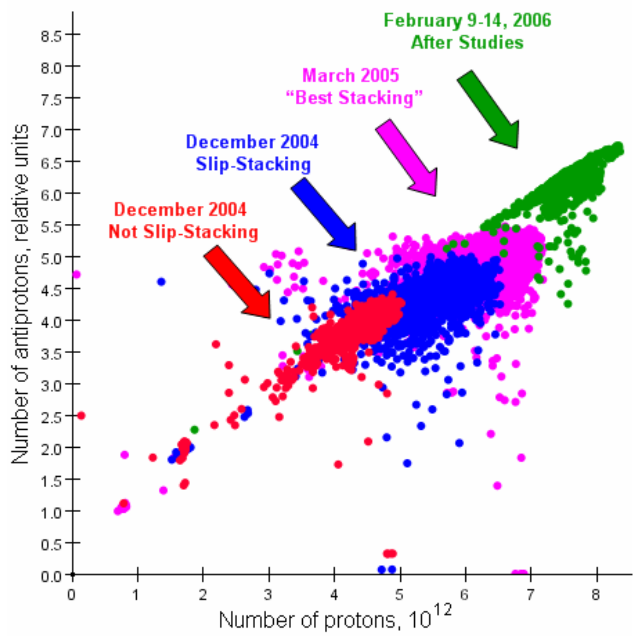

Figure 6: Historical data for the dependence of antiproton intensity on the number of protons on the target.

Two additional issues were addressed to maximize the phase density of antiprotons leaving the target. First, optics of MI-to-target transport line was redesigned to nullify both dispersions on the target. That allowed us to reduce the beam size on the target and to exclude its dependence on the energy spread. Presently, the minimum beam size is limited by the target damage. Rms size is ~150 μm for normal stacking and ~220 μm for slip stacking. The second harmful problem was slow uncontrolled beam position displacements on the target. They were suppressed by digital damper. Figure 6 presents data showing improvements in the number of protons on the target and corresponding increase in number of antiprotons at the end of Debuncher injection line.

ANTIPROTON COOLING

Five weeks of downtime spent for Tevatron repairs in FY2006 were lost for integrating the luminosity but they were exceptionally useful for studies in other machines resulting in significant improvements for Antiproton production. This time would be difficult to obtain under normal operating conditions. Most time consuming was orbit correction to the centers of quads for Debuncher and AP-2 line, which connects the target and Debuncher. It was complimented by the redesign of Debuncher optics aimed to minimize the beam size at places with limited aperture such as the stochastic cooling tanks, injection septum and extraction kicker [13]. Table 3 presents results of this work. One can see that the experimentally achieved acceptances are ~10% below design values and there is a potential for further improvements. Simulations show that the antiproton yield is proportional to the acceptance and for the acceptance corresponding to the new optics it should be about $30\cdot10^{-6}$ antiprotons/proton. Experimentally achieved value (target to Accumulator) is $21\cdot10^{-6}$. Comparison of measurements and simulations has shown that there is excessive beam loss in the middle of AP-2 line and also loss during Debuncher-to-Accumulator transfers. Both of them require better steering and optics improvements. Recently, additional vertical correctors were installed in AP-2 line to address the loss in the line.

Table 3: Improvements of Debuncher acceptances

	Initial design mm mrad	Initial, measured mm mrad	New design mm mrad	Present measured mm mrad
ε_x	34	30	40.5	35.3
ε_y	31	25	37.5	34.6

The growth of the stacking rate would not be possible without improvements in the stochastic cooling. First, we introduced gain ramps for Debuncher cooling. The ramps increase the gain for transverse systems and decrease it for the longitudinal ones maximizing cooling power for Debuncher cooling cycle of ~2.5 s. Second, we redistributed gains in the longitudinal core cooling system in Accumulator. Historically, main cooling was supplied by 2-4 GHz system while 4-8 GHz system was considered auxilliary. Using 4-8 GHz system as a main system and the 2-4 GHz as a helper we improved performance for the core cooling system. That suppressed the inverse particle flux from the core to the stack and resulted in faster stacking. Figure 7 presents historical data for the dependence of stacking rate on the stack size demonstrating steady growth for last two years.

As one can see in Figure 7 the stacking rate is decreasing with stack size and comes to zero for about $2.5\cdot10^{12}$ antiprotons. Before Recycler was commissioned we usually stacked $\sim1.5\cdot10^{12}$ antiprotons every 25-30 hours to fill the collider. With Recycler being operational we could split the stack between Recycler and Accumulator so that the collider would be filled from both machines – so called mixed mode operation. That allowed us to increase the total number of Antiprotons available for the collider fill to $(2\text{-}2.5)\cdot10^{12}$. But the phase density in both machines was not high. Just as in the Accumulator, the efficiency of Recycler stochastic cooling has been decreasing with stack size limiting the Recycler stack to $\sim1.5\cdot10^{12}$. Successful commissioning of electron cooling in the fall of 2005 addressed this problem [4, 14]. Gradual transition from the mixed mode operation to the Recycler only shots was carried out in the second half of 2005 (see Figure 8) and resulted in the record number of antiprotons available for the shot of $4.36\cdot10^{12}$.

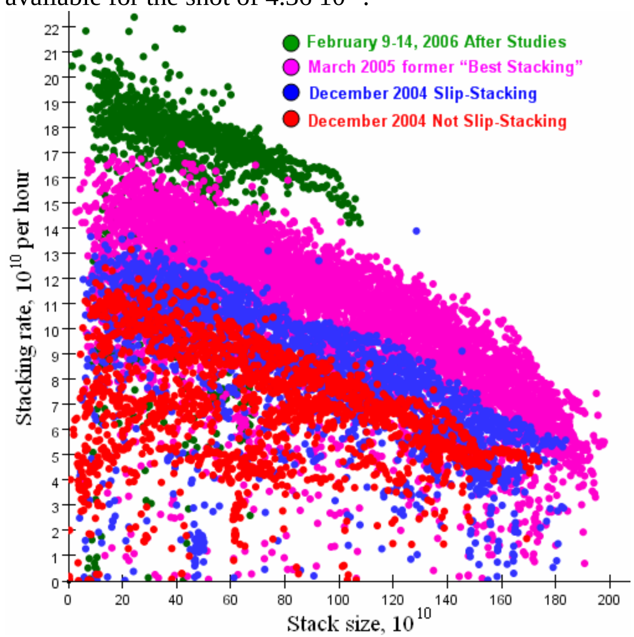

Figure 7: Historical data for the dependence of stacking rate on the stack size.

Main advantage of the electron cooling is that its efficiency does not depend on number of antiprotons. But deeper cooling makes the antiproton beam less stable. The first problem we encountered was the transverse resistive wall instability. It was suppressed by digital wideband damper with ~25 MHz bandwidth upgraded to ~90 MHz during 2006 shutdown [15]. That allowed us to increase the phase density by a factor of 2. Further increase of the phase density was limited by growth of tails in the bunch distribution with consecutive lifetime degradation. Measurements show that this loss is not accompanied by measurable dipole beam motion. That basically excludes dipole instabilities. The entire set of experimental data is quite controversial leaving us with a wide range of speculations. Three mechanisms were discussed. The first one is related to the development of transverse quadrupole instability due to interaction of antiproton beam with the electron beam [16]. Another possibility is storing electrons in the electron cooler with consecutive excitation of $e\bar{p}$-instability. There is also a possibility that the non-linear field of cold antiproton beam drives non-linear resonances for halo particles. We are discussing a set of experiments allowing us to find out the reason of particle loss and possible ways to mitigate it.

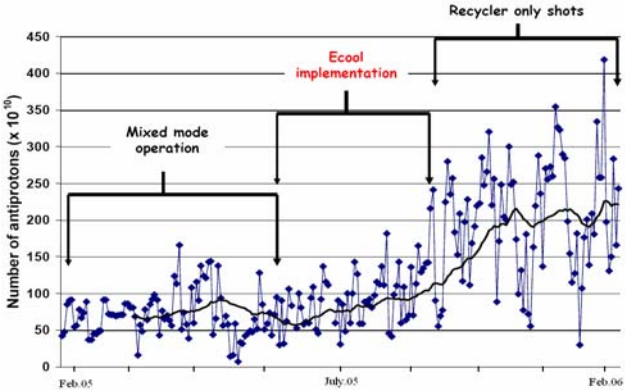

Figure 8: Changes in number of antiprotons available in Recycler for collider shots.

PLANS FOR THE FUTURE

Present DoE guidance is that Fermilab will operate the collider to the end of 2009 when LHC is expected to be fully operational. The design plan anticipates that by this time we will achieve the peak luminosity of $3\cdot10^{32}$ cm^{-2}s^{-1} and the total Run II luminosity integral of ~7 fb^{-1}. To achieve this we need to double the peak luminosity and the luminosity integral per week. That is a challenging task. For last three years we were able to follow the design plan and it supports our confidence that we can continue this trend in the future.

The antiproton production is a cornerstone of further luminosity growth. By the next summer we expect to increase the present peak antiproton production rate from $20\cdot10^{10}$ to $30\cdot10^{10}$ antiprotons per hour. The following upgrades are planned. First, better steering and optics corrections should yield acceptance increase in AP2 line and Debuncher resulting in 10-30% gain in antiproton yield. Second, replacement of RF tubes in Debuncher and the lithium lens upgrade should yield another 10-20% gain. Third, this growth needs to be supported by improved performance of stochastic cooling in Debuncher and Accumulator. Modeling and simulations show that with a few comparatively inexpensive hardware upgrades like gain correction and installation of additional notch filters it should support fluxes up to 35-40$\cdot10^{10}$ hour^{-1}.

Presently, total loss of antiprotons at beam transfers (Debuncher-to-Accumulator, Accumulator-to Recycler) and coalescing of antiproton bunches in Debuncher is in the range ~15-25%. At least half of this loss can be recovered with better machine tuning. Decreasing the Accumulator-to-Recycler transfer time from present 45 minutes to 15 minutes will increase the amount of antiprotons by additional ~15%. The maximum stack size of $436\cdot10^{10}$ achieved in Recycler is already close to the Run II goal of $600\cdot10^{10}$. Planned improvements of beam stability in Recycler should be adequate in achieving the final goal.

We already observe problems with beam-beam effects from antiprotons to protons. It is expected to be worse with further antiproton intensity increase. To alleviate problems with beam-beam effects we plan to change the working tune of the collider so that larger tune space would be available. Two working points have been discussed. The first one is located just above half integer resonance (like in KEKB collider), and the second one is near 2/3 resonance (like in SPS collider). Our present preference is with the first choice, but approaching closer to half-integer resonance amplifies chromaticity of beta-functions and, consequently, reduces momentum aperture to unacceptable level, if this chromaticity is not compensated. During the last shutdown Tevatron sextupoles were rearranged and new sextupole circuits were formed to control this chromaticity. Simulations show significant mitigation of beam-beam effects at the new working point if the beta-function chromaticity is suppressed. That also should allow us to increase the proton intensity by ~10%.

REFERENCES

[1] V. Lebedev, PAC'03, Portland, May 2003, p. 29.
[2] V. Shiltsev, EPAC'04, Lucerne, July 2004, p. 239.
[3] P. Bauer, *et. al*, PAC'05, Knoxville, May 2005, p.54.
[4] S. Nagaitsev, "Fermilab Recycler Performance with a Dual Cooling System, This conference.
[5] V. Lebedev, *et. al*, Proc. of the 8th Intern. Computational Accelerator Phys. Conf. (ICAP'04), June 2004; NIM-A, 558, No.1, Oct. 2005, p.299; M. Syphers – private communications, 2003.
[6] N. Mokhov, *et. al*, "Beam-induced damage to the Tevatron components and what has been done about it," ICFA-HB2006, Tsukuba, May 29-June 2, 2006, http://indico.kek.jp.
[7] A. Valishev, *et. al*, "Progress with Collision Optics of the Fermilab Tevatron Collider," This conference.
[8] F. Schmidt, et. al, "Measurement and Correction of the 3rd Order Resonance in the Tevatron," This conference.
[9] G. Velev, *et. at*, "New Measurements of Sextupole Field Decay and Snapback Effect on Tevatron Dipole Magnets," This conference.
[10] A. Valishev, *et. al*, PAC'05, Knoxville, May 2005, p. 4117.
[11] A. Jansson, *et. al*, EPAC'04, Lucerne, July 2004, p. 239.
[12] K. Koba, *et.al*, PAC'03, Portland, May 2003, p.1736.
[13] V. Nagaslaev, *et. al*, "Measurement and Optimization of the Lattice Functions in the Debuncher Ring at Fermilab," This conference.
[14] A. Shemyakin, *et. al*, "Performance of Fermilab's 4.3 MeV Electron Cooler," This conference.
[15] A. Burov, *et. al*, "Suppression of Beam Transverse Microwave Instability by a Digital Damper," This conference.
[16] A. Burov, *et. al*, "Transverse electron-antiproton instability in the recycler ring," ICFA-HB2006, Tsukuba, May 29-June 2, 2006, http://indico.kek.jp.