RECENT PERFORMANCE OF THE FERMILAB TEVATRON COLLIDER

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ABSTRACT

A year ago the Tevatron completed collider run Ia. This run was highly successful in terms of high energy physics results and accelerator performance. The various accelerator performance goals set before run Ia were either met or exceeded. Subsequently a Linac upgrade and a variety of other improvements were completed. After a very difficult start, run Ib is now well underway and the instantaneous luminosity goal set for this run has been achieved. This paper provides a brief survey of the accelerator upgrades which have contributed so far to the successful running of the Fermilab collider. The issues which have been identified as limiting accelerator performance are also presented.

1. Introduction

The Fermilab Tevatron began a three year program of colliding $p\bar{p}$ physics in May of 1992. The first phase of this program, designated run Ia, was an unqualified success. Several major improvements to the Fermilab accelerator complex were implemented prior to or during run Ia. The resulting collider performance exceeded the expectations of many. During the later half of run Ia, collider stores with initial luminosities of 5.4×10^{30} cm^{-2} sec^{-1} were typical. The end product was an integrated luminosity of 32 pb^{-1} delivered to the experiments in a period of 50 weeks. This luminosity, combined with the 1.8 TeV center of mass energy provided by the Tevatron, was sufficient to produce a statistically interesting sample of $t\bar{t}$ candidate events in the CDF detector[1].

After a nearly a year of running, the collider was shut down for the summer and fall of 1993 to install an energy upgrade to the Fermilab Linac[2]. The upgrade to the Linac consists of replacing high energy half of the old 201.25 MHz drift tube Linac with seven 805 MHz side coupled cavity structures with an average axial gradient of 7.5 MV/m. The upgrade increases the kinetic energy of the H^- beam injected into the Booster synchrotron from 200 MeV to 400 MeV thereby reducing the space charge tune shift by a factor of 75%. This permits the delivery of 75% more charge to the Booster, thus providing approximately 50% more protons for antiproton production and colliding beam physics.

The summer of 1993 shutdown was also used to install a low temperature upgrade in the Tevatron cryogenic systems[3]. The goal of this upgrade was to increase the beam energy of the Tevatron from 900 GeV to 1.00 TeV. Subsequently the Tevatron was started up and collider operation was established with a beam energy of 975 GeV. Higher energies were not achievable due to quenches in the low-β quadrupole magnets. The reliability of

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the cryogenic system at 975 GeV was somewhat degraded; therefore high energy operation of the collider was postponed. These reliability issues have since been resolved.

The success of run Ia and the anticipated improved performance from the Linac upgrade inspired ambitious goals of 2 pb^{-1}/week integrated luminosity and average initial luminosities of 1.0×10^{31} cm^{-2} sec^{-1} for the second phase of the run (Ib). Collider commissioning for run Ib began in January of 1994. In addition to the usual struggle to operate a machine that has been idle for many months, it was determined almost immediately that the Tevatron had markedly changed since run Ia operation. Among the problems encountered were: (1) transverse emittance dilution at every step of acceleration and low-β squeeze; (2) a large amount of transverse coupling in the injection and in the 900 GeV low-β lattices; (3) large oscillation of the Tevatron horizontal and vertical β functions relative to their design values; and (4) a distorted vertex distribution at the B0 interaction region detected by the CDF experiment. For the first six months of run Ib, these problems restricted the luminosity to half of that specified by the goals that had been set.

Recently (a week prior to submitting this paper) it was discovered that one of the low-β quadrupole magnets in the B0 insert was rolled by 7.5 mrad about its longitudinal axis. While the cause of the roll is not completely clear, fixing it has brought the Tevatron to very nearly its expected level of performance. The collider stores put into the Tevatron since this fix have all had initial luminosities in excess of 1.1×10^{31} cm^{-2} sec^{-1}.

In the remainder of this paper I will present the various components of the luminosity of the Fermilab Tevatron collider, the accelerator performance limitations associated with each component, and how these limitations have been dealt with during collider run I.

2. Limitations to Luminosity in the Tevatron

The luminosity in a $p\bar{p}$ collider has several ingredients. This dependence, for head on collisions, is expressed algebraically as:

$$\mathbf{L} = \frac{3g\, f B N_p N_{\bar{p}}}{b^*\left(e_p + e_{\bar{p}}\right)} \mathbf{F}\left(\frac{s_z}{b^*}\right) \tag{1}$$

where g is the Lorentz relativistic factor (959 at 900 GeV), f is the Tevatron revolution frequency (47.7 kHz), B is the number of proton or antiproton bunches (6), N_p is the number of protons per bunch, $N_{\bar{p}}$ is the number of antiprotons per bunch, b^* is the beta-function at the collision point, e_p and $e_{\bar{p}}$ are the normalized proton and antiproton 95% emittances, and $\mathbf{F}$ is a form factor that depends on the ratio of bunch length, s_z, to b^*. For the Tevatron, the value of $\mathbf{F}$ is approximately $\frac{1}{2}$. Equation 1 indicates that optimizing the instantaneous luminosity consists of delivering the largest possible numbers of colliding protons and antiprotons at the smallest possible emittances.

A good figure of merit by which to evaluate the performance of a $p\bar{p}$ collider is the number of $p\bar{p}$ interactions which occur at the detectors in a fixed interval of time. Thus, issues such as particle and emittance lifetime and system reliability are as important as optimizing the machine parameters that increase the instantaneous luminosity. At the present time the average luminosity lifetime is about 16 hours. The average proton and antiproton lifetimes are approximately 100 hours and 60 hours respectively. The emittance growth rate for both protons and antiprotons is 0.2 π mm•mrad/hour. System reliability issues are discussed in section 2.3.

2.1   Limitations to proton intensity and emittance.

The number of protons per bunch available for collisions is currently limited by the number of protons the Booster is capable of delivering to the Main Ring multiplied by the various efficiencies associated with each step in the chain of operations necessary to bring the protons from 8 GeV in the Main Ring to collisions in the Tevatron. The best proton intensity at collisions during run Ia was of order 1.3×10^{11} per bunch. With the advent of the Linac upgrade, there are approximately 30% more protons available from the Booster. There are several upgrades to the Booster that are currently being pursued (longitudinal and transverse dampers, ramped correctors, and aperture improvements) which could conceivably permit the full realization of the 50% proton intensity increase expected from the Linac upgrade[4].

A second important limitation to the proton intensity is time dependent persistent current effects in the Tevatron super conducting dipole and quadrupole magnets at the beginning of the Tevatron acceleration ramp[5]. These persistent currents are the result of magnetization of the super conducting filaments in the field of the magnet. These currents excite the higher order multipole fields allowed by the symmetry of the magnet. The excitation of the b_2 component (sextupole) from the dipoles is particularly severe. The time evolution of this effect depends on the history of the magnet bus current. The consequence of not correcting for this effect is a prompt loss of proton and antiproton intensity when the Tevatron ramp to 900 GeV is initiated. For reasons that are not well understood, the magnitude of the intensity losses is dependent on the injected proton intensity to the extent that no more than 1.1×10^{11} protons per bunch could be injected without significant loss. During run Ia a "b_2 unwind" procedure was successfully developed compensate for this effect using sextupole magnets in the Tevatron. After this procedure was implemented there were no further discernible proton or antiproton losses due to persistent current effects.

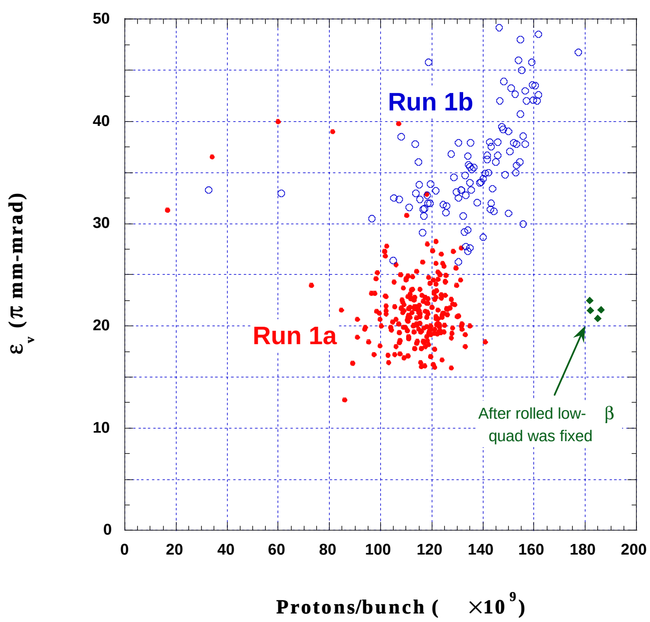

Fig. 1. Proton vertical emittance at collisions versus bunch intensity. The solid circles are run Ia data and the open circles are run Ib data.

There have been a variety of other intensity dependent effects which extract beam at various stages in the acceleration process from 8 GeV to 900 GeV. At injected intensities of just greater than 1.3×10^{11} protons per bunch the beam exhibited a longitudinal bunched beam instability in the Tevatron. This instability was cured using active damping. In addition, the proton emittance at collisions exhibits a strong dependence on proton intensity above intensities of 1.3×10^{11} per bunch (see Fig. 1). This emittance dilution at large proton intensities has been eliminated by correcting the rolled low-β quadrupole magnet.

The proton intensity at collisions in the Tevatron is ultimately limited by the beam-beam tune shift. In the case of the Tevatron the relevant shift is the tune shift experienced by the antiproton bunches due to the presence of the proton beam. This tune shift is given by:

$$\Delta n = \frac{3}{2}\frac{r_p N_p}{e_p} N_c \tag{2}$$

where r_p is the classical proton radius and N_c is the number of bunch crossings. The Tevatron working tune space is bounded by the $4/7$ and $3/5$ resonances. Therefore, to avoid sending the antiproton beam across a resonance on each crossing, the maximum allowable Δn is approximately 0.025.

For typical values of N_p (1.2×10^{11}) and e_p (20 π mm-mrad), the beam-beam tune shift per crossing is approximately 0.004. The number of bunch crossings for counter rotating beams occupying the same orbit is 12 ($N_c = 2B = 12$) yielding a net tune shift of 0.05 that is twice the beam-beam limit. One of the significant accomplishments of run Ia was the successful operation of electrostatic separators to separate the proton and anti-proton orbits everywhere except at the two interaction regions. The effect of this is to reduce N_c from 12 to 2. This allows for another factor of three increase in N_p/e_p before the beam-beam limit is reached. While the beam-beam tune shift no longer limits the proton intensity, it does use up available tune space as the proton phase space density is increased.

2.2 Limitations to antiproton intensity and emittance.

The predominate limit to collider luminosity is the ability to produce and deliver to the collider abundant quantities of antiprotons. The long time required to accumulate a usable number of antiprotons is a significant factor in the management of collider operations. At the most fundamental level, the problem of producing antiprotons is that of collecting $\bar{p}$'s from a production target and compressing them into a volume in phase space which is sufficiently small to be of use in the collider. The phase space compression is accomplished by several stochastic cooling systems in the antiproton source complex. As the accumulated $\bar{p}$ stack grows the effectiveness of the stochastic cooling systems is degraded. Thus, the rate at which antiprotons are accumulated is a function of the size of the stack circulating in the antiproton accumulator. Figure 2 illustrates the dependence of $\bar{p}$ stacking rate on the size of the stack. Presently, the antiproton accumulation rate is 5.0×10^{10} $\bar{p}$'s/hour at stacks smaller than about 50×10^{10} $\bar{p}$'s diminishing to approximately 3.5×10^{10} $\bar{p}$'s/hour when the stack reaches 150×10^{10} $\bar{p}$'s.

The antiproton intensity delivered to the collider depends on how many $\bar{p}$'s have been accumulated up to the time a new store is put in and the longitudinal and transverse emittances of the antiproton stack. The factor which limits the $\bar{p}$ accumulation rate is the stacktail cooling system. This is the system that merges newly injected $\bar{p}$'s with the rest of the antiproton stack.

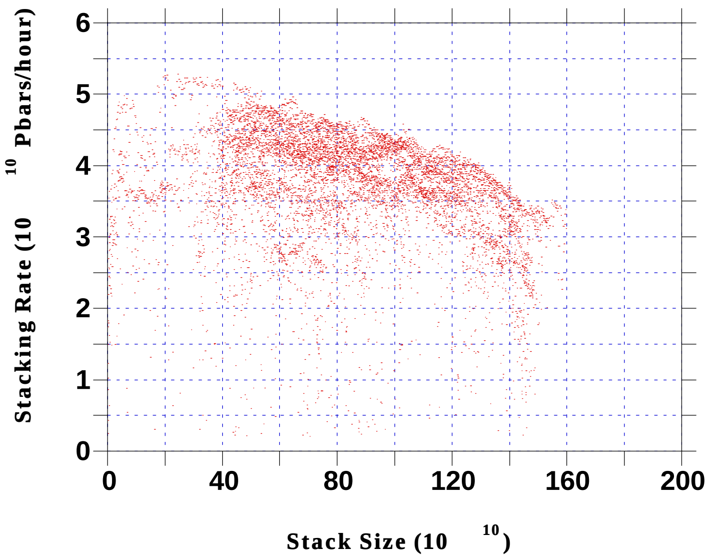

Fig. 2. Dependence of antiproton accumulation rate on the size of the $\overline{p}$ stack. Data for one month of running (June 1994) is included.

Minimizing the transverse emittance is important in achieving efficient transfer of the antiproton bunches from the antiproton accumulator into the Main Ring where the $\overline{p}$'s are accelerated to 150 GeV for injection into the Tevatron. Also, smaller $\overline{p}$ emittances in the antiproton source translate into smaller emittances at collisions in the Tevatron with the concomitant impact on luminosity indicated in Eq. 1. The longitudinal phase space density is significant because it determines how many $\overline{p}$'s are extracted from the $\overline{p}$ accumulator for use in the collider. Extraction of $\overline{p}$'s is accomplished by capturing some fraction of the stack in an RF bucket, accelerating the captured beam to an extraction orbit, and kicking it into the transfer line connecting the antiproton source to the Main Ring. The amount of beam that can be captured in the bucket area of the extraction RF system is proportional to the longitudinal phase space density of the $\overline{p}$ stack.

The most significant factor limiting the $\overline{p}$ phase space density is trapped ion induced transverse instabilities in the $\overline{p}$ accumulator[6]. Trapped ion problems were greatly alleviated in Run Ia with the an upgrade of the ion clearing electrode system and the development of a technique to clear trapped ions with RF[7].

2.3 System Reliability

There are two general categories of system reliability issues that have an impact on collider operation. The first category consists of failures that cause the loss of a collider store. These consist of failures such as super conducting magnet quenches, abort kicker prefires, power supply failures, site power fluctuations, and thunder storms. Approximately $\frac{1}{3}$ of all collider stores are lost unintentionally. The second category consists of the various faults that will cause the loss of the antiproton stack. These problems typically involve such things as power supply failures, magnet cooling system failures, site power fluctuations, and thunder storms as well as intentional stack dumps to repair vital equipment. The average time in between antiproton stack loss is about 7 days. Both categories of failure cause a significant interruption of collider operation due to the long time required to accumulate sufficient antiprotons for a new store (typically 10-20 hours). There is a serious effort underway to understand and mitigate against the causes of these diverse failures.

3. Summary

The outlook for the immediate future of the Fermilab Tevatron collider is very good. The initial luminosity and integrated luminosity goals of 1.0×10^{31} cm^{-2} sec^{-1} and 2.0 pb^{-1}/week set for run Ib have been achieved. Fermilab is in the early stages of recovery from a major mis-configuration of the Tevatron. There is therefore good cause to expect that the level of performance will continue to improve.

References

1. F. Abe et al. Fermilab-PUB-94/097-E. Submitted to Phys. Rev. **D** (1994).
2. C.W. Schmidt, Proceedings of the 1993 Particle Accelerator Conference, Washington D.C. 1655 (1993).
3. J.D. Fuerst and J.C. Theilacker, Submitted to the Proceedings of the 1994 European Particle Accelerator Conference, London (1994).
4. S. Shukla, this proceedings.
5. D.A. Herrup, et al. Phys. Rev. **E49** 5660 (1994).
6. S.J. Werkema, D.W. Peterson, and P. Zhou, Proceedings of the 1993 Particle Accelerator Conference, Washington D.C. 3573 (1993).
7. S.J. Werkema, K.D. Fullett, and P. Zhou, Proceedings of the 1993 Particle Accelerator Conference, Washington D.C. 3309 (1993).