THE TEVATRON COLLIDER - STATUS AND PLANS

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Abstract

The Tevatron Collider at Fermilab has set new peak luminosity records for a p-p-bar machine in the quest for the Top Quark and other high energy physics goals. In order to achieve these new luminosity levels, a number of improvements have been made which include separated Tevatron orbits, improved stability conditions in all machines and improved p-bar extraction techniques. However, the higher achieved beam intensities have led to a series of new issues which needed to be addressed in the achievement of high luminosity with sufficient luminosity lifetimes. In particular, the increased beam intensities have necessitated a re-examination of the beam stability in each of the accelerators which feed into the Tevatron as well as a careful optimization of the Tevatron operating point. An ambitious upgrade program has been laid out which should lead to a luminosity increase of an additional factor of ten over the next several years. An overview of the Fermilab accelerator complex will be given along with a description of the accelerator physics issues which need to be addressed in meeting the luminosity goals for the Collider.

1. INTRODUCTION

The Tevatron Collider is now in the second half of a three-year run serving two detectors and using new hardware which has permitted the achievement of new luminosity records for a p-p-bar collider. The first phase of this highly successful run was completed in May 1993 and the second phase begun in January 1994. The Tevatron Collider currently operates at 900 GeV with counter-streaming p and p-bar bunches (six each) on helically separated orbits. These are brought into head-on collision only at the two detector locations thereby minimizing the effect of beam-beam tune shifts on the available tune space for a given beam intensity. The resulting improvement in operation due to separated orbits amounted to a factor of five in both integrated and initial luminosities. Owing to the success of Run 1A, ambitious goals for luminosity were set for Run 1B at 2 pb^{-1}/wk and average initial luminosities of $1\times10^{31} cm^{-2}\ sec^{-1}$. While these goals have yet to be realized, significant progress has been made and the attempt to reach higher luminosity has led to the identification of specific problem areas which require further study.

In this paper, we summarize the performance of the Collider thus far and outline the accelerator physics issues which affect the the operation of the machine. Moreover, we discuss the planned improvements which are designed to ameliorate current operational problems and add machine capability for future runs. In particular, the plans leading to the expected luminosity increase to be realized from the Main Injector project will be described.

2. PERFORMANCE SUMMARY

The overall performance can be measured by the initial store luminosity, but more importantly by the weekly integrated luminosity delivered to the detectors, as shown in Fig. 1. The essential parameters of machine operation are described in terms of the familiar expression for luminosity given by

$$L = 3\, N_p N_{p\text{-bar}}\, B\, f_o \gamma / 2\, \beta^* \varepsilon_N \qquad (1)$$

where N_p and $N_{p\text{-bar}}$ are the bunch intensities, B is the number of bunches, f_o is the revolution frequency, β^* is the lattice function at the interaction point and ε_N is the 95% normalized emittance. Moreover, the integrated luminosity is directly related to the luminosity lifetime in the Tevatron, which is a function of machine operating conditions. The Collider is primarily limited by the ability to produce and accelerate sufficient quantities of p-bars, as shown in Fig. 2, which indicates a direct correlation between delivered luminosity and p-bar intensity achieved at low beta. The proton intensity does not appear to be limited in the Tevatron, but is effectively limited in the presence of p-bars by beam-beam effects. To avoid excess losses, the proton intensity is currently limited to about 2.1×10^{11} / bunch. The luminosity lifetime tends to decrease with the achieved luminosity, as shown in Fig. 3. This is suggestive of the fact that current operating conditions are limited by beam-beam effects [2]. P-bar production has been pushed to record levels, though the stacking rate, i.e. the ability to merge the newly-produced P-bars onto the stored p-bar beam shows a characteristic falloff due to fundamental limits in the stochastic cooling system. The primary new feature of Run IB was the Linac Upgrade which consisted of a new linac section designed to increase the delivered energy to the Booster by a factor of two. This was accomplished successfully and machine turn-on was completed by October 1993. In addition, new cold compressors were tested which will be required to lower the operating temperature of the bending dipoles sufficiently to permit an increase in energy to 1 TeV. In both cases, these upgrades have not yet led directly to an increase in luminosity, but will be required to achieve the planned luminosity goals for the Main Injector era.

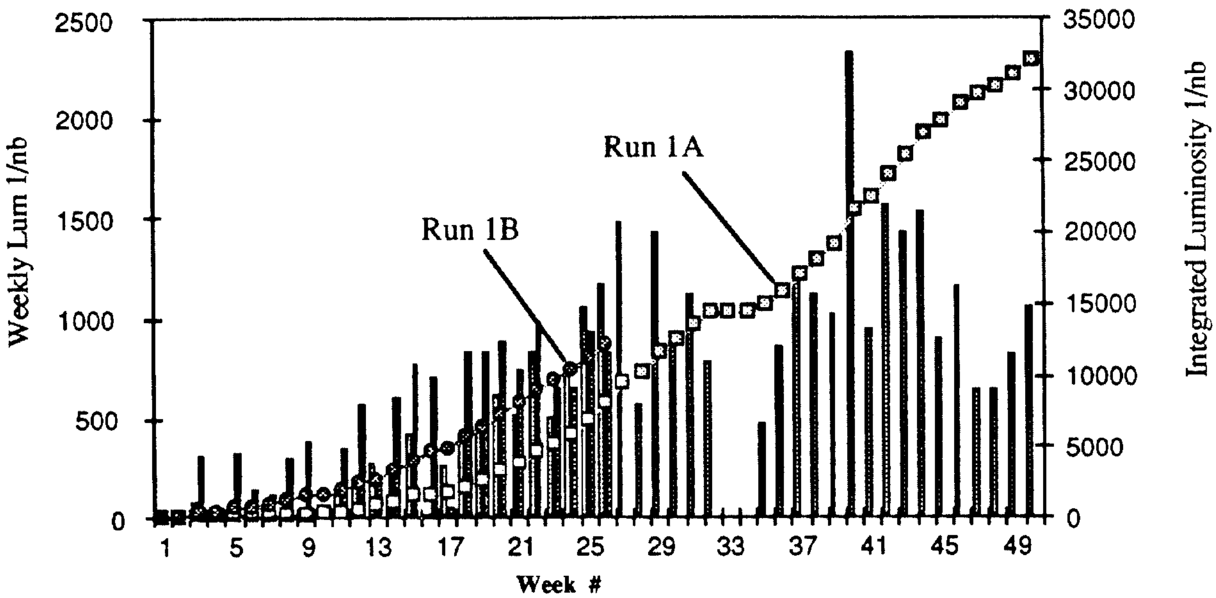

Fig. 1 Initial and weekly integrated luminosity for Runs 1A and 1B. Open bars are the initial luminosities for Run 1A and solid bars those for Run 1B.Thus far, 44 pb^{-1} has been delivered [1].

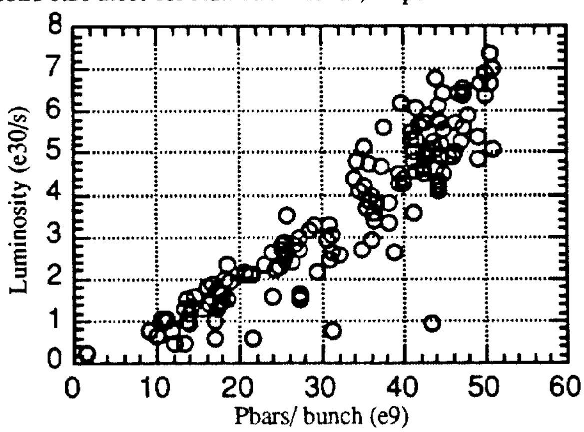

Fig. 2 Luminosity vs. Pbars/bunch at low beta.

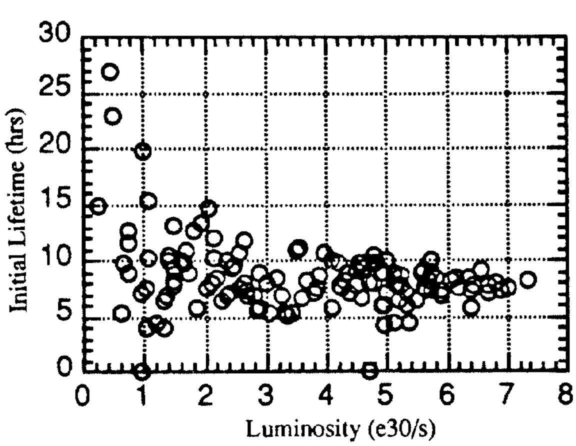

Fig. 3 Initial luminosity lifetime vs. luminosity for Run 1B.

3. OPERATIONAL ISSUES

With the successful commissioning of the Linac Upgrade, the Booster is now capable of accepting more charge at 400 MeV [3]. A commensurate increase in the Booster beam brightness at extraction has not yet been realized owing to the presence of both transverse and longitudinal instabilities. However, significant gains have been made in defining the causes of these instabilities and a program is underway to bring the instabilities under control. There has long been a longitudinal coupled-bunch mode in the Booster, however, a new, tracking longitudinal damper has been developed which has successfully demonstrated the suppression of longitudinal oscillations at one revolution harmonic. A program is underway to extend the damping capability to all unstable lines. In addition, a transverse, head-tail mode has been observed at high intensity which points to the need for better control over intrinsic chromaticity. A project has been initiated to implement transverse dampers and to refurbish the sextupole compensation in the Booster to remedy this problem. As a result of these ongoing improvements, the Booster has delivered a record intensity to the Main Ring of $4x10^{12}$ at 25 π mm-mrad.

With the advent of increased intensity from the Booster at modest emittances, the Main Ring has achieved new intensity levels and promises to improve as the Booster emittance is decreased further. The most significant intensity limit is due to a longitudinal coupled-bunch mode which decreases coalescing efficiency. Coalescing itself is a process by which eleven bunches from the Booster are phase-rotated by 90° and recaptured to produce a single bunch at higher intensity. However, since coupled-bunch oscillations can disrupt the recapture process, a fast process dubbed "snap coalescing" was devised to carry out the bunch rotation and recapture before the relatively slowly growing coupled-bunch instability could develop [4]. The result was an increase in available proton intensity delivered to the Tevatron. In addition, quadrupole oscillations were observed following transition in the Main Ring resulting in bunch lengthening and beam loss at 120 GeV. These oscillations were suppressed, however, by the installation of a quadrupole damper which has permitted still higher proton intensities. Up to 2.2 x 10^{11} per bunch has been achieved thus far. Overall, the Main Ring is operating at record intensities, although its restricted aperture (12 -15 π mm-mr) continues to be the bottleneck on higher beam intensity.

The P-bar Source, which realized large gains in Run 1A with the installation of improved ion clearing apparatus, has been operating at moderate p-bar stack sizes (100 mA) with good efficiency thus far in Run 1B. A new stacking record of 5.1x10^{10}/hr has been achieved. However, the stacking efficiency is observed to drop with stack size and is believed to be due to the current limit on available cooling efficiency in the stacktail system which cools and moves the p-bars into the stored beam. An upgrade for this system is being developed. The primary physics goal during Run 1B for the P-bar Source is to push to stack sizes to 200 mA or more to determine what new issues might surface under the conditions expected in future runs. Efforts are also underway to improve machine reliability.

In the Tevatron, six coalesced proton bunches are first loaded into the machine, followed by six coalesced p-bar bunches. One issue which arises in this process is the poor bunched-beam lifetime (1-2 hrs) in the period before the beams can be accelerated to 900 GeV. During this time, up to 20% of the potential luminosity can be lost. Some of these losses can be attributed to the relatively large chromaticity settings required at 150 GeV to avoid transverse instability of the beam, which, in turn, may be aggravated by the presence of coupling. It is also likely that the buckets are full from injection from the Main Ring, causing loss of large amplitude particles.

Overall, there is a relatively large increase in the transverse emittance of both beams during acceleration and the activation of the low beta quadrupoles (the "squeeze") which is responsible for the largest loss of potential luminosity, as shown in Fig. 4. The cause of this emittance growth is not known, but may be due to beam-beam effects. A significant difference in the emittance growth, and hence luminosity per particle, has been observed in Run IB relative to Run IA, and considerable effort has been expended trying to locate specific causes for this behavior. One reason for the differences is the fact that the lattice was altered slightly to correct errors observed in Run 1A. It is also possible that one or more of the low beta quads may have shifted slightly. Evidence for this conclusion is based on observed changes in the measured beta functions, coupling and vertex distributions provided by the experiments. The luminosity lifetime has also been degraded, associated with larger emittance growth rates, suggesting an altered interaction region. Efforts are now underway to localize and correct the problem.

In addition to these issues, in both Runs 1A and 1B, it was noticed that the collision orbit was subject to slow drifts by as much as 3-4 mm in some locations with characteristic times from four hours to several days. While the orbit

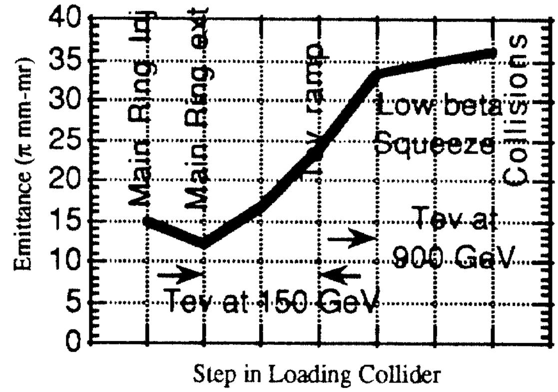

Fig. 4 Emittance growth during store loading in the Main Ring and Tevatron.

distortions appear to originate in a number of locations, the largest drifts have been localized to the low beta quadrupoles and the effect is especially pronounced following a quench of these magnets. Typical drifts are shown in Fig. 5, averaged over the entire ring. It is noted that the observed short-term drifts are predominantly vertical and may be associated with internal changes in the magnet support structure. Further studies are being carried out to determine the source of the observed drifts as they cause difficulty for the detectors and necessitate frequent orbit smoothing to correct the orbit oscillations.

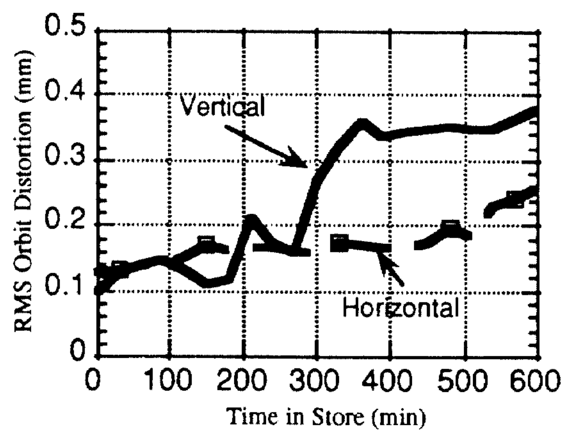

Fig. 5 Characteristic orbit drift during a store in terms of a ring-wide orbit distortion.

4. UPGRADE PLANS

The overall plan for delivering luminosity in the Collider is shown in Table 1, contingent on funding levels. A key improvement to be made before the Main Injector era is associated with the commissioning of a new fast kicker. This kicker is designed to have a 250 nsec rise time in order to accomodate the injection of bunches (batches) separated by 396 nsec. The total number of bunches will consist of, each, 36 proton and p-bar bunches, allowing also for adequate abort gaps. While the interactions per crossing will modestly increase, the overall luminosity is expected to increase by a factor of ten. The kicker itself consists of a ferrite-loaded, transmission line and is currently under development [5]. It is scheduled for prototype testing with beam in 1995. Provided the appropriate fast kickers can be developed, plans are also being made to consider a 72x72 scenario, or even 99x99, at 132 nsec bunch spacing.

As noted previously, work is being carried out to commission new cold compressor units which will enable the Tevatron dipoles to run at lower temperature thereby permitting the achievement of fully 1 TeV energy. This work is scheduled for completion in 1996 [6].

In the P-bar Source, a number of improvements are planned which are designed to increase the critical p-bar stacking rate by as much as a factor of five. As mentioned previously, the stacktail system is critical to maintain stacking at high stack sizes and a revamping of this system is planned. Other improvements including liquid-helium-cooled stochastic cooling pickups, rf system, and diagnostic upgrades are also under consideration. Moreover, significant redesign of the lithium lens and proton target systems is required to handle the increased repetition rates and higher beam intensities expected in the Main Injector era.

It is believed that the Main Ring is currently operating at near maximum intensity. Hence, the full luminosity gain to be realized must wait the arrival of the Main Injector. The Main Injector will replace the function of the Main Ring in a physically separate tunnel now under construction [7]. It is designed to have a large aperture (40 π mm-mrad) capable of receiving higher intensity from the Booster and will be able to cycle in 1.5 sec, delivering up to three times the protons for p-bar production than is currently the case. It will also have the capability for simultaneous delivery of high-intensity proton beams for fixed-target experiments. Details of this effort are reported elsewhere at this conference.

5. SUMMARY

An intensive study program is currently underway to determine the optimal operating conditions for the Collider. In particular, an investigation is being carried out to determine the optimal approach to improving operational stability through the use of feedback systems and improved hardware reliability. Beam instabilities at current beam intensities have been identified and steps are being taken to mitigate these problems. As part of these studies, attention is being focused on the operating point in the Tevatron and on finding reasons for the observed drift of operating conditions. Much of the effort is directed toward empirical determination of the machine lattice and on finding a suitable means of invoking dynamic orbit, tune and chromaticity control.

A long-term upgrade program is currently underway which will permit the use of more bunches for both protons and p-bars accompanied by a significant increase in the delivered luminosity. Critical in the achievement of these goals is the completion of the Main Injector project. Another key element is a commensurate increase in the p-bar production rate. A series of improvements in the p-bar source is planned which is designed to make the luminosity goals possible. With the above improvements, it is expected that the Collider will be at the forefront of physics productivity well into the next century.

* Operated by the Universities Research Association for the U. S. Dept. of Energy

6. REFERENCES

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Table 1 Planned Luminosity Upgrades for the Collider

	1989	1A	1B	II	Main Injector	
Protons/bunch	1.0e10	1.2e11	1.5e11	1.5e11	3.3e11	
Pbars/bunch	2.9e10	3.1e10	6.0e10	1.2e10	3.6e10	
Proton Emittance	25	20	24	24	30	π-mm-mr
β^*	0.55	0.35	0.35	0.25	0.25	m
Energy	900	900	900	1000	1000	GeV
Bunches	6	6	6	36	36	
Bunch Length	0.65	0.55	0.55	0.5	0.6	m
Typical Luminosity	1.6e30	5.4e30	1.0e31	1.7e31	8.1e31	1/cm2 1/sec
Integrated Luminosity	0.32	1.09	2.12	3.46	16.35	1/pb/week