TEVATRON STATUS

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Introduction

The Fermilab Tevatron is both the world's highest energy accelerator system and first large-scale superconducting synchrotron. Since Tevatron commissioning in July, 1983, the accelerator has operated in 1984, 1985 and 1987 with extracted beams of 800 GeV for three runs of fixed target physics, and in 1987, and 1988, with proton-antiproton colliding beams at 900x900 GeV. This paper will focus on the collider operation of the Tevatron: its present status and the outlook for its longer-term future evolution.

Improvements Since the 1987 Collider Run

Since the end of the 1987 collider run, there have been a number of significant improvements in the various accelerator subsystems. These improvements, which were crucial to the success of the present collider run, are briefly described below.

Antiproton Source improvements

The performance of the Accumulator transverse core cooling systems has been improved by suppressing undesirable parasitic waveguide modes in the pickup arrays with microwave absorbers. This has improved the emittance of the pbar beam sent to the Tevatron. In late 1988, microwave absorbers were also installed in the Accumulator stack tail system. The instabilities frequently seen in this system, which limited the system performance at high stack intensities, have been effectively eliminated. Additionally, an optical notch filter[18] has been added to the Debuncher transverse cooling systems, which allows the system to cope with the increased cycle rate required for "multi-batch" targeting (see below).

The Accumulator horizontal aperture at the core was improved by a reduction of the horizontal dispersion in the straight sections. This has resulted in an improvement in stacking rate at high stack intensities.

The voltage in the Debuncher bunch-rotation rf system has been increased by a factor of about 1.5, resulting in an increase in the pbar stacking rate of roughly 10-20%. In the Accumulator, a new rf cavity has been installed which allows more flexibility in the number of pbar bunches sent to the Main Ring.

Main Ring improvements

"Multi-batch" targeting refers to an operational mode of the Main Ring for pbar production. In this mode, three Booster batches are injected into the Main Ring, accelerated to 120 GeV, and extracted one at a time to the Pbar Source on a long flat-top. The purpose of this operation is to allow rapid-cycle operation of the Source, resulting in principle in an increased pbar stacking rate. Operation in this mode requires multiple bunch rotations in the Main Ring prior to extraction; these multiple rotations result in longitudinal emittance growth. This emittance growth, together with inefficiencies in the Pbar Source, have limited the effectiveness of this mode of operation to date. Further beam studies are planned to develop means to control these problems.

Significant improvements have been made in the efficiency of the bunch coalescing process in the Main Ring[1]. A lengthening of the Main Ring flat-top has allowed the bunch coalescing process to become more adiabatic, thus permitting a larger fraction of the initial 11 bunches to be coalesced into a single bunch. The result is not only an improvement in pbar transfer efficiency but also a reduction in unbunched beam and in the generally undesirable "satellite" bunches.

Finally, during the shutdown period prior to the current collider run, a major rework of the Main Ring lattice in the area of the DO overpass was undertaken[2]. This rework has had two consequences. The vertical dispersion wave around the ring, which resulted from a mismatch between the DO overpass and the rest of the lattice, has been largely eliminated. Moreover, the vertical dispersion mismatch between the Main Ring and the Tevatron at EO has been eliminated. The absence of this mismatch has resulted in smaller emittance beams at 900 GeV.

Tevatron improvements

Shortly after the end of the 1987 run, the modifications necessary to implement 6x6 bunch operation of the collider were begun. The major part of these modifications involved the Tevatron injection kickers. The kicker waveforms were modified to eliminate parasitic kicks delivered to stored bunches upon the injection of new bunches.

One of the principal contributors to the anomalous emittance growth observed during the 1987 collider run was identified in early 1988 as the charging power supplies for the proton and pbar abort kickers. Improved filtering of these power supplies has eliminated this problem. Filtering has also been added to the low-β quadrupole power supplies to help reduce additional emittance growth observed when the Tevatron is in the low-β configuration.

Large tune and chromaticity variations in the Tevatron at injection and acceleration were observed during the 1987 run. These effects are believed to be related to persistent currents in the superconducting Tevatron dipoles[3]. To address this problem, special progammable ramp generators were installed on the devices which control the Tevatron tune, chromaticity and coupling; these ramp generators are programmed to automatically compensate for the variations in the critical machine parameters[4]. The implementation of this scheme has provided sufficient control over the Tevatron tune and chromaticity that this problem, which was quite serious in 1987, is no longer of operational significance.

Finally, one of the undesirable features of the 1987 fixed-target run was the relatively large number of Tevatron dipole failures. Autopsies of these failures have revealed a correlation with certain fabrication flaws which can be discovered and fixed on existing magnets[5]. Prior to the 1988 collider run, all the dipoles in the 6 houses expected to contain the most unreliable magnets were examined for these flaws and repaired as necessary. About 140 magnets (50% of those examined) were repaired. The rest of the magnets in the ring will be examined and repaired as necessary after the end of the current collider run.

Performance During the 1988 Collider Run

Integrated luminosity

The run began on June 2, 1988 and has been in progress for about 38 weeks[6]. Examination of Fig. 1

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shows the substantial progress in integrated luminosity/week made since the start of the run. The total integrated luminosity delivered to date is 6.7 pb^{-1}.

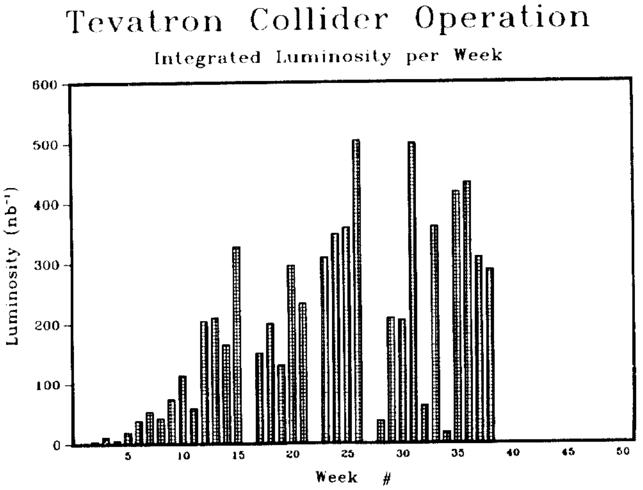

Figure 1

The major experiment in place during this run is the large general-purpose CDF experiment at B0. This experiment has logged about 3.2 pb^{-1} of integrated luminosity to date. Smaller experiments are also in place at C0, D0 and E0. At present, only the B0 straight section posseses a low-beta system. This system was designed to provide a β^* of 1.24x1.05 m (HxV) at the interaction point. However, for most of this run it has been operated in a mode in which the insertion optics are not matched to the rest of the ring, but a smaller β^* (0.53mx0.56m, HxV) is achieved.

Overall Collider Performance Parameters

The collider performance is summarized in the "performance parameters" listed in Table I. The first column corresponds to a typical good store in May, 1987. The second column presents the Tevatron I project design goals. The last column presents the parameters for one of the highest luminosity stores achieved to date.

Table I:
Collider Performance Parameters

Parameter	May 1987 Achieved	Tev I Des.	1988 Achieved
1. Number of bunches	3	3	6
2. Protons/bunch ($x10^{10}$) at low-β	5	6	7.2
3. Pbars/bunch ($x10^{10}$) at low-β	.8	6	2.9
4. Pbars extracted from core/bunch ($x10^{10}$)	2.3	6	4.5
5. MR transmission efficiency(%)	77	100	88
6. MR Coalescing efficiency(%)	70	100	80
7. Tev transmission efficiency(%)	65	100	95
8. Transverse emittance (95%, π mm-mrad)			
proton	24	24	23
pbar	36	24	18
9. β^* (m)	.74	1.1	.55
10. Pbar stacking rate (10^{10}/hour)			
(peak)	1.1	10.	2.0
(average)	.77	10.	1.4
11. Luminosity lifetime (hours)	8.	20.	10.-25.
12. Operational efficiency (%) (store hrs/total hrs)	40		65
13. Average stack before transfer ($x10^{10}$)	25.	40.	60-70.
14. Average stacking time (hours)	10		20.
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INITIAL LUMINOSITY ($X10^{29}/cm^2/sec$)	1.3	10.	20.7

Limitations to the Integrated Luminosity

Antiproton stacking rate: Table II shows the "missing factors" during the 1988 run[7] for each of the various quantities associated with the antiproton stacking rate. The "missing factor" is the factor needed to bring the observed value of the quantity up to the design level for the Tevatron I project. The largest single contribution to the missing factors is a factor of about 2.5 (included in "Pbars/proton into Debuncher") which appears to be due to an overestimate of the pbar production cross section on tungsten in the original design.

Table II: Pbar Source Stacking Rate
Missing Factors

Quantity	Value	Missing factor
1. Pbars/proton into the Debuncher($x10^{-6}$)	12.8	2.7
2. Pbars/proton bunch-rotated into 0.2% ($x10^{-6}$)	10.7	3.2
3. Pbars/proton injected into the Accumulator ($x10^{-6}$)	8.9	3.7
4. Pbars/proton stacked to the Accumulator core ($x10^{-6}$)	8.3	3.7
5. Protons/cycle on target ($x10^{12}$)	1.8	1.1
6. Targeting cycles/hour	1380	1.3
Overall: Pbars/hour stacked to Accumulator core ($x10^{10}$)	1.96	5.3

The "missing factors" in Table II correspond to stacking into an empty machine. In addition, there is a loss of beam from the Accumulator core which results in an effective stacking rate reduction as the Accumulator is filled. This effectively means that quantity 4 in the above table is a function of the stack intensity. For stacks of about $80x10^{10}$, quantity 4 is reduced to about $5x10^{-6}$.

The implementation of multi-batch targeting can in principle bring quantity 6 to the design value. Improvements in quantities 1, 2 and 3 are planned for the next collider run (see below). Implementation of 4-8 Ghz core cooling, and further improvements in the Accumulator aperture, can help reduce part of the roffoff in quantity 4 with stack intensity.

Antiproton transfer: Figure 2 shows the observed correlation between the number of antiprotons transferred to the Tevatron and the stack intensity. The rolloff seen at high stack intensities is principally due to two effects:

(a). The pbar transfer efficiency from the Accumulator to low-β in the Tevatron, which has been as high as 95% for transfers from small stacks, drops to about 60% for stacks in the 60-70x10^{10} range. This reduction is due to losses at pbar injection into the Main Ring: for large stacks, the core emittance begins to exceed the limited Main Ring transverse aperture.

(b). The fraction of the core which can be unstacked drops from about 60% for small stacks to 40% for large stacks. This drop is due to growth of the core longitudinal width as the intensity grows.

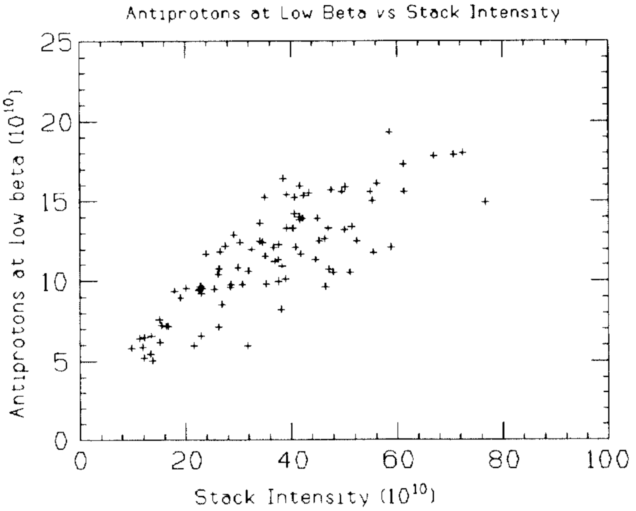

Figure 2

Both of these problems will be helped by the bandwidth upgrade to 4-8 GHz planned for the Accumulator core cooling system (see below).

Beam-beam interaction: The principal limitation to the proton transverse density (and hence the luminosity) in the 1988 collider run has been the beam-beam interaction. The beam-beam interaction can be parameterized by the linear beam-beam tune shift,

$$\delta\nu = 0.00733(N_p/\epsilon_p)n_x \ ,$$

where N_p is the number of protons per bunch (x10^{10}), ϵ_p is the proton 95% transverse emittance (in π mm-mrad), and n_x is the number of crossings (12 for this run). In terms of this parameter, we begin to see deterioration of collider performance at proton transverse densities corresponding to $\delta\nu > 0.02$; for $\delta\nu > 0.03$, the degradation is severe enough that we cannot operate there.

The performance deterioration observed in the range $0.02 < \delta\nu < 0.03$ is specifically:

1. Antiproton emittance growth at 150 GeV, during acceleration to 900 GeV, and during the low-β squeeze (typically on the order of 20-40%);

2. Antiproton losses during the same periods (typically 5-10%);

3. Reduction of the initial luminosity lifetime (see Fig. 3).

The influence of a 7th order resonance, located at a tune separation of $(\delta Q_x, \delta Q_y) = (0.018, 0.024)$ from the bare working point, is believed to be responsible for the observed effects. To control the beam-beam interaction during operation, it is routine practice to utilize the Tevatron transverse dampers as noise sources to deliberately increase the proton transverse emittance to bring $\delta\nu$ into the acceptable range. These dampers also are used to eliminate any satellites adjacent to the dense central bunch which may have resulted from imperfections in the coalescing process in the Main Ring.

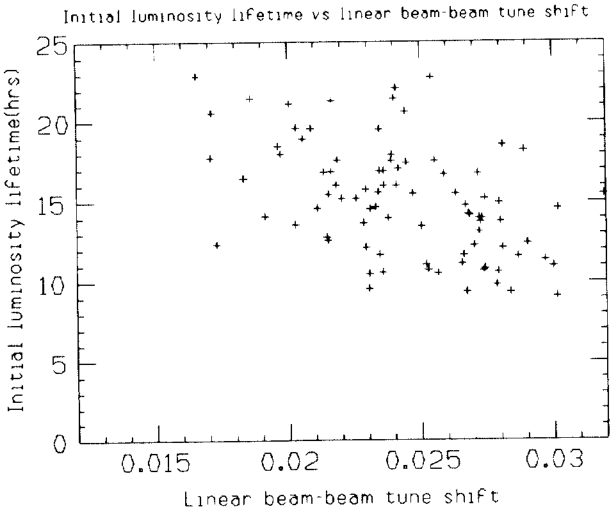

Figure 3

A program of direct measurements of the antiproton tune distribution[8] is underway to help understand this limitation in more detail. Studies have also begun to explore the possibility of using other regions of tune space which may provide areas freer of high-order resonances[9]. Ultimately, in the next collider run, the planned installation of a beam separator scheme will resolve this problem (see below).

Luminosity lifetime: The luminosity lifetime[10] is observed to grow from the initial values shown in Fig. 3, which depend on the proton transverse density, to values in the range of 25-35 hours after 15-20 hours into a store. At this point, the observed transverse emittance growth is about a factor of two greater than the expectation from intrabeam scattering and the effects of the Tevatron residual gas. Although studies are continuing to locate the source of this anomalous emittance growth, the luminosity lifetime is already sufficiently long that it is not a serious operational problem.

Reliability: As of 12 March 1989, there have been 218 stores in the 1988 collider run, of which 86 were ended intentionally (mean store length 21.8 hours) and 132 by failures (mean store length 9.7 hours). The mean store length for all stores is 14.5 hours. The largest single cause of unintentional store loss has been the spontaneous prefire of the Tevatron abort kickers (28 stores lost). There have been three Tevatron dipole failures, responsible for about 2.5 weeks of downtime. Several Main Ring overpass dipoles, and one Main Ring quadrupole, have failed and had to be replaced. There have also been a number of failures of the lithium lens (leaks in the lens cooling circuit) which have not caused substantial downtime because of the availability of numerous spares.

Outlook for the future: the Fermilab Upgrade

After the end of the current collider run, there will be a five month shutdown to complete the Tevatron dipole repairs started in the spring of 1988. Subsequently, the Tevatron will operate for fixed target physics for a nine month run. The energy will be 800 GeV and intensities of $1.5\text{-}2\times10^{13}$/pulse are planned.

Subsequent collider and fixed target runs will benefit from the substantial improvements planned in the Fermilab upgrade program[11]. This program is divided into three phases; in each phase, the collider initial luminosity is expected to increase by at least a factor of five. There will also be a substantial improvement in fixed target performance with each phase.

Phase I (1989-92)

Linac upgrade: The Linac upgrade[12] is a proposal to increase the Linac energy from 200 to 400 MeV in the same physical length, by a replacement of the last four drift tube cavities with more efficient, higher gradient cavities. The motivation for this upgrade is to reduce the space-charge induced emittance dilution presently suffered just after Booster injection for intensities above 1.5×10^{12}. This will have an impact on collider performance in two ways. First, the fixed intensity proton bunches used for collisions in the Tevatron should have their emittance reduced by 30-40%. Secondly, since Main Ring transmission efficiency is limited by the Main Ring transverse apertures, higher intensity beams (by a factor of 1.7) should be able to be accelerated and targeted for pbar production. This intensity increase will also benefit the fixed target program. If approved for construction in FY90, the Linac upgrade project could be complete by mid-1992. A related effort to reduce emittance growth in the low-energy end of the Linac is also underway.

Antiproton Source upgrade: In 1989, it is planned to increase the aperture of the Debuncher ring by opening up the Debuncher stochastic cooling system electrode gaps. Coupled with aperture improvements in the Debuncher injection line and an increase in the lithium lens operating gradient, this improvement should gain an overall factor of about 1.5 in pbar stacking rate.

At the same time, the TWT power in the Debuncher transverse cooling system will be doubled. This will compensate for the increase in the gap spacing. Additionally, in the Accumulator, the present 2-4 GHz core system will be upgraded to 4-8 GHz in 1989. The new 4-8 GHz core system[13] will improve the stacking rate at high stack intensities, and reduce the emittance of the pbars delivered to the Tevatron. Finally, a 2-4 GHz fast momentum cooling system is planned for the Debuncher in 1990-91. This system will make the momentum spread of the beam injected into the Accumulator both smaller and also less sensitive to variations in the longitudinal emittance of the proton beam. A prototype of this system may be implemented in late 1989.

In the area of targeting, a prefocusing lithium lens is under development for the 1989-1990 period, which will allow the proton spot size on the production target to be reduced. This will result in an increase in the pbar yield. To enable the target to survive with these small spot sizes, and with the higher proton intensities foreseen with the Linac upgrade, a target sweeping system is under design, with implementation expected in 1991-92. The ultimate overall gain in pbar yield expected from the targeting improvements is a factor of 1.3.

Tevatron upgrade: The principal improvements planned for the Tevatron in the near-term are a low-β system at D0, a new low-β system at B0, and a system of electrostatic separators to separate the beams everywhere except at B0 and D0. This system will relieve the constraints now imposed by the beam-beam interaction, and will allow operation with up to 44 bunches. A new abort system, and new injection kickers, will also be required.

R&D work will continue on cold compressors which will allow the ring-wide temperature to be reduced from its present 4.7° to less than 4.2°. If this work is successful, a ring-wide cold compressor system will be installed in 1990. This is the most feasible way to reach a ring energy in the collider mode of 1 TeV.

The new low-β system for B0 and D0 uses 12 new 1.4 T/m main quadrupoles of a cold iron, two shell design, and 6 new 0.7 T/m trim quadrupoles[14]. Nominally, the system can achieve a β^* of 0.25 m. Unlike the present system at B0, the insertion is completely matched to the Tevatron lattice, including the dispersion. The insertion design also provides warm spaces for separators. The system is planned to be completed in late 1990, in time for the first physics run of the D0 detector.

The separator system will be installed in 1990. The beams will be separated throughout the machine except at B0 and D0. The separated orbits[15] will be interlinked helices, providing a nominal separation of $>5\ \sigma$ at 1 TeV; separation is accomplished using 23 3-m long electrostatic separators operating at <35 KV/cm. A prototype system is currently under development; tests of the spark rate of a separator in the Tevatron environment will be conducted as soon as is feasible.

Overall collider performance in phase I: After the new low-β and separator installation, the beam-beam limitation will be relieved and operation with bunch numbers as high as 44 will be possible. By 1992, with the Linac and Pbar Source upgrades in place, the pbar stacking rate should reach about 7×10^{10}/hour. At this point, the major limitation to further improvements will be the performance of the Main Ring. With 22 bunch operation, a β^* of 0.5 m, and 10^{11} protons/bunch, and with optimal utilization of all the pbars the Source can provide (2.5×10^{10}/bunch in the Tevatron), it is expected that the collider can provide peak luminosities of about $10^{31}/\text{cm}^2/\text{sec}$, and integrated luminosities of >50 pb^{-1} per 10 month run.

Phase II: the Main Injector (1991-93)

Further progress in collider luminosity beyond phase I will require a major new initiative. The principal limitation to performance after the implementation of phase I is the Main Ring. This machine limits collider luminosity in at least four ways:

1. Because of the machine's limited apertures, proton intensity for antiproton stacking is limited to well below what is in principle available from the Booster;
2. For the same reason, the proton intensity for delivery to the Tevatron is limited to well below what the collider can take before the beam-beam limitation is reached on the separated orbits;
3. The machine's limited apertures results in poor antiproton transfer efficiency for large stacks.
4. The presence of the Main Ring beam in the vicinity of the collider detectors, requiring rigid control of losses while in pbar production, is a constant source of problems and dead time for the experiments and often provides a limitation to intensity.

The proposal for the solution of these problems is straightforward: replace the Main Ring with a new 8-150 GeV synchrotron in a new tunnel. This new machine is called the Main Injector. It has a radius about half that of the present Main Ring, and uses some of the same components. It will have adequate transverse and longitudinal admittance to handle efficiently all the beam that the Booster can deliver. Consequently, it will be able to provide intensities of $5\text{x}10^{12}$ protons/pulse, at a rapid cycle rate (0.67 Hz), to the Pbar Source for pbar production. It will be able to efficiently transfer large pbar emittances from the Source to the Tevatron. It has the capacity to provide proton bunch intensities of $>3\text{x}10^{11}$ to the Tevatron for collider operation. It will be able to deliver intensities of $6\text{x}10^{13}$ to the Tevatron for fixed target operation. Finally, because it is decoupled from the Tevatron, it will be able to deliver year-round 120 GeV test beams, and high intensity ($3\text{x}10^{13}$/pulse) 120 GeV production beams, to the experimental areas.

The overall impact of the Main Injector on collider performance is to increase both the number of protons and antiprotons sufficiently that the luminosity is expected to exceed $5\text{x}10^{31}/\text{cm}^2/\text{sec}$. If construction of the machine began in FY1991, it could be completed in late 1993.

Phase III: beyond 1993

The removal of the Main Ring from the Tevatron tunnel opens up the possibility of the installation of another superconducting synchrotron in its place. Current R&D work on high-field superconducting dipoles[16] offers the possibility of a 6.6T design with sufficient aperture to provide a 1.5 TeV replacement for the Tevatron. Moreover, the design admits of the possibility of operation at 8T (1.8 TeV) when cooled to 1.8° K.

Preliminary design work has established a lattice design[17] which reduces the required separator fields at the higher energy to a manageable level. The dispersion function has also been reduced substantially relative to the present Tevatron.

The collider performance gains inherent in this proposal are obvious. In addition to a luminosity increase to $>9\text{x}10^{31}/\text{cm}^2/\text{sec}$ (coming strictly from the reduced beam emittance at the higher energy), the physics reach of the 3.6 TeV CM energy is clearly substantially greater (equivalent to a factor of 10 in luminosity for some processes). Moreover, because this proposal does not require the removal of the existing Tevatron from the tunnel, the possibility of pp collisions at 2 TeV CM energy (and high luminosity) remains open.

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