THE TEVATRON: STATUS AND OUTLOOK

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Introduction

The Fermilab Tevatron is both the world's highest energy accelerator 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 with proton-antiproton colliding beams at 900x900 GeV for one run of collider physics. The next collider run will start in June, 1988 and is also planned for 900x900 GeV operation. This paper will focus on the collider operation[1] of the Tevatron: its present status, prospects for the immediate future, and the outlook for its longer-term evolution.

Performance During the 1987 Collider Run

a. Operational Features

The general operational parameters of the 1987 run[2,3] are summarized in table 1. The run extended roughly over the five month period from January to May; the weeks referred to in table 1 date from February 1, 1987. A comparison of the figures in table 1 shown for week 1 vs. week 14 indicates the degree of progress made in this first collider run of the Tevatron. This can also be seen in fig. 1, which shows the time development of the integrated luminosity at B0.

Table 1: General Operational Parameters of the 1987 Collider Run

Weekly Averages	Week 1	Week 14	Avg: Wks 1-14	Best Week
Pbar Stacking rate (10^{10}/hr)	0.51	0.59	0.63	0.93
Pbar transfer efficiency: Accum. to Tev low-β (%)	~1	28	15	28
Initial luminosity (10^{29}/cm^2/sec)	.0015	1.4	.33	1.4
Store duration (hrs)	8.3	9.8	8.9	13.3
Weekly totals				
Store hours	73	98	63	98
Number of stores attempted	9	10	6.6	8
Percent of stores terminated abnormally	67	40	33	13
Integrated luminosity (nb^{-1})	.12	16.9	5.2	16.9

In addition to the CDF experiment in the B0 straight section, experiments were also in place at C0, D0 and E0 during the 1987 run. At present, only the B0 straight section possesses a low-beta system. Normally, this system provides a β^* of 1.24x1.05 m (HxV) at the interaction point. Near the end of the run, a modified lattice was tried which provided a β^* of 0.77x0.71 m (HxV). Although the expected gain in luminosity was obtained, this lattice solution did not properly match the B0 insertion to the rest of the ring.

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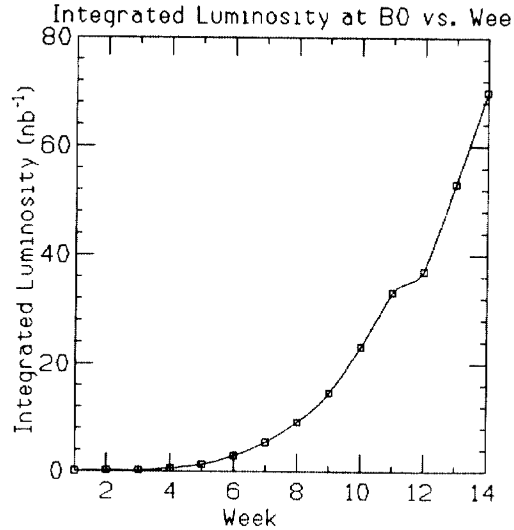
Figure 1



b. Limitations to the integrated luminosity

i. Antiproton stacking rate[4]

Table 2 shows the "missing factors" during the 1987 run for 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 over-estimate of the pbar production cross section on tungsten in the original design.

Table 2: Pbar Source Stacking Rate Missing Factors

Quantity	Missing factor
Protons/cycle on target	1.5
Targeting cycles/second	1.3
Pbars/proton into the Debuncher	3.1
Pbars/proton bunch-rotated into 0.2%	3.7
Pbars/proton injected into the Accumulator	4.4
Pbars/proton stacked to the Accumulator core	4.4
Overall: Pbars/second stacked to Accumulator core	8.2

The "missing factors" in table 2 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 reduction is about 30% for $3x10^{11}$ in the core.

ii. Antiproton transfer efficiency

Table 3 illustrates the problems encountered in the transfer of antiprotons from the Accumulator core to the Tevatron. The most severe losses occurred during the bunch coalescing process in the Main Ring[5], and during the first few seconds after injection at 150 GeV in the Tevatron. The variation in the Tevatron chromaticity after recovery from a store has been documented previously[6]. However, there were additional substantial variations in the Tevatron tune and chromaticity during injection and during acceleration. The loss of antiprotons during the first few seconds after Tevatron injection, and the antiproton emittance growth during acceleration (see below), has been attributed to these uncontrolled tune and chromaticity variations. The antiprotons are particularly sensitive to tune and chromaticity variations because of their large tune spread resulting from the beam-beam interaction with the protons.

Table 3: Antiproton Transmission Efficiencies

Transfer Step	Efficiency
Accumulator to Main Ring injection	87%
Main Ring: injection to 150 GeV	88%
Main Ring Coalescing	70%
Tevatron: injection to start of ramp	72%
Tevatron: acceleration to 900 GeV	99%
Tevatron: Low-β squeeze	90%
OVERALL	34%

iii. Beam emittance growth during Tevatron filling

Table 4 illustrates the history of the normalized transverse emittance of the proton and antiproton beams from 8 GeV to 900 GeV during Tevatron filling. Both beams almost double in emittance at injection into the Tevatron. This is understood to be due to a mismatch of the vertical dispersion at Main Ring to Tevatron transfer. Part of this mismatch results from the vertical dispersion introduced into the Main Ring by the overpasses at B0 and D0. There is a further growth of the antiproton emittance in the Tevatron during acceleration and the low-β squeeze. This is due to the poor control of tune and chromaticity mentioned above, resulting in emittance blowup from the encounter of parts of the large antiproton tune distribution with beam-beam driven resonances.

Table 4: 95% Invariant Transverse emittance during collider filling
Typical values, averaged over both planes
Units: π mm-mrad

Transfer Step	Protons	Antiprotons
Booster	12	--
Antiproton Source	--	12
Main Ring	12-15	12-15
Tevatron: injection	20-25	20-25
Tevatron: 900 GeV, low-β	20-25	30-45

iv. Beam emittance growth during Tevatron storage

The luminosity lifetime observed during the 1987 run[7] was substantially poorer than expected from beam-gas and intrabeam scattering effects. It was dominated by a growth of the transverse emittance of both the proton and antiproton beams, in both planes. The emittance and emittance growth rates are shown in table 5; the data are averaged over the last 80 stores of the run. For these stores, the initial luminosity lifetime was typically 8 hours, increasing to 14 hours after about 10 hours into the store.

Table 5: 95% Invariant Emittances and Emittance growth rates during storage

Parameter	Protons	Antiprotons
Horizontal transverse emittance (π mm-mrad)	27	42
Vertical transverse emittance (π mm-mrad)	25	33
Longitudinal emittance (ev-sec)	4.2	5.0
Horizontal growth rate (π mm-mrad/hr)	5.3	4.9
Vertical growth rate (π mm-mrad/hr)	3.2	4.3
Longitudinal growth rate (ev-sec/hr)	0.11	0.07

Prospects for the 1988 Collider Run

Since the end of the 1987 collider run, there have been a number of significant improvements in the various accelerator subsystems. Some of these improvements were made during the fixed-target run, and tested in two four-day "mini-collider" runs in December, 1987 and February, 1988. Other improvements were implemented during the shutdown period which started in March, 1988 and has just ended. Taken together, these improvements are expected to result in significantly improved collider performance in 1988.

a. Antiproton Source Improvements[4]

In the area of stochastic cooling, 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 will improve the emittance of the pbar beam sent to the Tevatron. Additionally, an optical notch filter has been added to the Debuncher transverse cooling systems, which will allow the system to cope with the increased cycle rate required for "multi-batch" targeting (see below).

In the area of machine apertures, the Accumulator horizontal aperture at the core has been improved by a reduction of the horizontal dispersion in the straight sections. This should result in an improvement in stacking rate at high stack intensities.

In the area of RF, a program of doubling the voltage in the Debuncher bunch-rotation RF system has begun. This program, when completed in late 1988, should result in an improvement factor of 1.3 in the pbar stacking rate. In the Accumulator, a new RF cavity has been installed which will allow more flexibility in the number of pbar bunches sent to the Main Ring.

b. 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 procedure is to allow rapid-cycle operation of the Source, resulting in principle in an increased pbar stacking rate. Operation in this mode was commissioned in October, 1987 and exercised in December, 1987. During that period, although the mechanics of the operation were fully debugged, the stacking efficiency suffered, so that no real improvement in the absolute stacking rate was realized. Further work on the optimization of this mode of operation will continue during the 1988 collider run.

Significant improvements have been made in the efficiency of the bunch coalescing process in the Main Ring[8]. 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 8-10 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. These improvements were made in the summer of 1987, tested in the "mini-collider" runs, and will be fully operational for the 1988 run.

Finally, during the shutdown period which has just ended, a major rework of the Main Ring lattice in the area of the D0 overpass was undertaken[9]. This rework has had two consequences. The vertical dispersion wave around the ring, which results from a mismatch between the D0 overpass and the rest of the lattice, has been reduced. Moreover, the vertical dispersion mismatch between the Main Ring and the Tevatron at E0 has been eliminated. The absence of this mismatch should result in smaller emittance beams at 900 GeV.

c. 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 improved to the point that parasitic kicks delivered to stored bunches upon the injection of new bunches were sufficiently small that the existing transverse dampers could handle them. The mechanics of 6x6 operation was tested successfully in both "mini-collider" runs.

The principal problem which is expected in 6x6 operation is the beam-beam tune shift, especially since the proton beam emittance (95%) is expected to be under 20 π mm-mrad with the elimination of the vertical dispersion mismatch at Tevatron injection. Based on the available tune space at the normal Tevatron working point, the maximum beam-beam tune shift which can be tolerated is about .02. This corresponds to 6 bunches of 6×10^{10} protons per bunch with an emittance (95%) of 24 π mm-mrad. It is planned to explore other regions of tune space near the integer stop-band which provide in principle larger regions free of resonances.

One of the major accomplishments of the studies performed during the "mini-collider" runs was the identification[7] of one of the principal contributors to the anomalous emittance growth observed during the 1987 collider run. The culprits were the capacitor-bank charging power supplies for the proton and pbar abort kickers. During a store in February, 1988, the proton horizontal emittance growth rate was observed to shrink from 3.5 π mm-mrad/hr to 0.75 π mm-mrad/hr when the horizontal abort kicker system was de-energized. Improved filtering of the power supplies for these kickers is expected to eliminate 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.

The large tune and chromaticity variations in the Tevatron at injection and acceleration observed during the 1987 run are expected to have an even larger impact on performance with 6x6 bunch operation. To address this problem, special programmable ramp generators have been installed on the devices which control the Tevatron tune, chromaticity and coupling; these ramp generators will be used to automatically compensate for the variations in the critical machine parameters. The ramp generator software for chromaticity control during Tevatron acceleration is based on the results of measurements of the fast time variation of the sextupole component of a superconducting magnet similar to a Tevatron dipole. A preliminary test of this scheme, carried out during the last "mini-collider" run, resulted in a substantial reduction in the chromaticity variation usually observed during the first part of the Tevatron acceleration cycle.

A new solution for a "mini-beta" lattice, which provides a β^* of 0.78x0.61 m (HxV) at B0 will be tried in the 1988 run. Unlike the 1987 "mini-beta" lattice, this solution is properly matched (except in dispersion) to the rest of the ring.

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. During the recent shutdown period, 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. This work should improve the Tevatron reliability, which in any case can be expected to be better for a collider run than for the fixed-target run, with its continual magnet ramping.

d. Overall Collider Performance Goals in 1988

The collider performance is summarized in the "performance parameters" listed in table 6. The first column corresponds to a typical good store in May, 1987. The second column presents estimates of the best values one might expect to achieve for each of these parameters during the 1988 run. These estimates are based on the experience of the last run and the improvements discussed in the previous sections. The last column presents an estimate of what one might expect for the average values of these parameters to be achieved simultaneously in an operational situation. The last two lines of Table 6 show the initial and average luminosity achieved at the end of the 1987 run, and expected operationally for the 1988 run.

Table 6:
Collider Performance Parameters

Parameter	May 1987 Achieved	1988 Goal	1988 Operational
1. Number of bunches	3	6	6
2. Protons/bunch ($\times10^{10}$) at low-β	5	6	5
3. Pbars/bunch ($\times10^{10}$) at low-β	.8	1.1	.85
4. Pbars extracted from core/bunch ($\times10^{10}$)	2.3	2.5	2.1
5. MR inj. and accel. efficiency(%)	77	75	70

6. MR Coalescing efficiency(%)	70	85	80
7. Tev transmission efficiency(%)	65	75	70
8. Transverse emittance (95%, π mm-mrad)			
proton	24	15	20
pbar	36	20	30
9. β^* (m)	.74	.70	.70
10. Pbar stacking rate (10^{10}/hour)			
(peak)	1.1	2.5	1.6
(average)	.77	1.75	1.1
11. Luminosity lifetime (hours)	8.	20.	12.
12. Operational efficiency (%) (store hrs/total hrs)	40		45
13. Average stack before transfer ($x10^{10}$)	25.		26.
14. Average stacking time (hours)	10		12.
INITIAL LUMINOSITY ($X10^{29}/cm^2/sec$)	1.3		3
AVERAGE LUMINOSITY (nb^{-1}/week)	15		35

Outlook for the Future: Beyond the 1988 Collider Run

Given the average luminosity expectations shown in table 6, and assuming a two month start-up period, a collider run of 10 months should deliver about 1 pb^{-1} of integrated luminosity. The goals for subsequent runs, as dictated by the need to sustain a viable collider physics program, correspond to a doubling of the accumulated integrated luminosity with each running period. The improvement program outlined below is focused on achieving this goal.

a. Near-Term Improvements (1989-1992)

i. Linac upgrade

The Linac upgrade[10] 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[11] presently suffered just after Booster injection for intensities above $1.5x10^{12}$. 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. 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.

ii. Antiproton Source upgrade[4]

In the area of apertures, 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.

In the area of stochastic cooling, three projects are planned. First, the TWT power in the Debuncher transverse cooling system will be doubled. This will compensate for the increase in the gap spacing. Secondly, 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 will improve the stacking rate at high stack intensities, and reduce the emittance of the pbars delivered to the Tevatron. Finally, a 4-8 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.

In the area of targeting, a prefocussing 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, or with higher proton intensities, a target sweeping system is under design, with implementation expected in 1991. The ultimate overall gain in pbar yield expected from the targeting improvements is a factor of 1.5.

iii. Tevatron upgrade

The principal improvements planned for the Tevatron in the near-term are a low-β system at D0, an upgrade of the low-β system at B0, and electrostatic separators to permit multibunch operation with bunch numbers greater than 6. Injection and abort kicker modifications will also be required. R&D work will continue on cold compressors which will allow the ringwide temperature to be reduced from its present 4.7° to less than 4.2°. This is the most feasible way to reach a ring energy in the collider mode of 1 TeV.

The D0 low-β system[12] 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. 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 1989, in time for the first physics run of the D0 detector.

When the D0 system is installed, new trim quadrupoles will also be installed at B0. This will allow simultaneous and independent operation of the B0 and D0 low-β systems. At a later date, the B0 system will be upgraded with the new main quadrupoles, and the systems will be identical.

The installation of the trim quadrupoles at B0 will also open up the warm spaces needed in this insertion for separators. Thus, provided that the separator development progresses well, separated beams will be possible after 1989. The beams will be separated throughout the machine except at B0 and D0. The separated orbits will be interlinked helices, providing a nominal separation of 12 σ at 1 TeV; separation is accomplished using 18 3 m long electrostatic separators operating at 50 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.

iv. Overall upgraded collider performance

After the new low-β and separator installation, operation with bunch numbers in the range of 6 to 32 is foreseen in the years between 1990 and 1992. By 1992, with the Linac and Pbar Source upgrades in place, the pbar stacking rate should reach about 10^{11}/hour. At this point, the major limitation to further improvements will be the antiproton stack intensity limits in the Accumulator. With 32 bunch operation, a β^* of 0.5 m, and 6×10^{10} protons/bunch, and with optimal utilization of all the pbars the Source can provide, it is expected that the collider can provide peak luminosities of about $5 \times 10^{30}/cm^2/sec$, and integrated luminosities of about 8 pb^{-1} per 10 month run.

b. Long-Term Improvements (Beyond 1992)

Further progress in collider luminosity beyond 1992 will require a major new initiative. 1992 is still well before the expected advent of the SSC, and further improvements will therefore be required to avoid a hiatus in particle physics research at the energy frontier. Two principal directions for this new initiative are presently under consideration at Fermilab.

One direction leads to the enhancement of the pbar-p collider luminosity to a maximum of $5 \times 10^{31}/cm^2/sec$. The collider would utilize the separators discussed above to operate with 80 bunches. The Main Ring will use "multi-batch" targeting with 6 batches to achieve a 1 Hz average targeting rate. A major upgrade to the Antiproton Source cooling systems will be required to cope with this increased rate. In addition, two new synchrotrons operating in the 8-20 GeV energy range must be added to the Fermilab complex. One of these synchrotrons, a storage ring for antiprotons with stochastic cooling, will receive antiprotons periodically from the Accumulator. Its existence is required by the fact that the Accumulator cannot hold a sufficient number of antiprotons to fill the Tevatron at the required luminosity. This machine will also accelerate the antiproton beam to 20 GeV and inject into the Main Ring, thus avoiding Main Ring losses at 8 Gev and at transition. Additionally, it will serve to recover and recool diffuse antiproton beams from the Tevatron. The other synchrotron will accelerate 8 Gev proton beams from the Booster to 20 GeV, and inject into the Main Ring. Proton injection at 20 GeV should allow a significant increase in Main Ring beam intensity for pbar production.

The other direction for a major increase in the luminosity is essentially to build another Tevatron and form a pp collider. This scheme involves the construction of a new tunnel with about half the circumference of the present Main Ring. Existing Main Ring components (magnets, power supplies, RF, etc) would be moved to this tunnel to form a new Main Injector ring operating from 8 to 150 GeV. In the existing tunnel, a second superconducting storage ring would be built in order to form a pp collider with the existing Tevatron. Operation with about 1000 low-intensity bunches and a β^* of 0.25 m would provide a maximum luminosity in excess of $10^{32}/cm^2/sec$. In order to bring the beams into collision within the constraint of the existing tunnel, the 4.4 T dipoles near the straight sections will have to be replaced with new 6.6 T dipoles. The total number of new 6.6 T dipoles needed for both rings is about 120.

This latter direction would require on the order of a year of downtime for installation, and would be more expensive than the first option. Nevertheless, because of the lack of dependence on antiprotons, compared to the first option it is considerably more straightforward, will provide more luminosity, has less risk of not attaining its goals, and will probably have a higher degree of reliability. Both options (and other options not mentioned here) are under discussion at the moment, and will probably continue to be debated for some time. What is clear is that some major initiative, starting about 1990, is needed to bridge the time span between 1992 (when the present Tevatron collider will reach effective saturation of its capabilities) and the advent of SSC operation for physics in the late 1990's.

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