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Tevatron Collider: Status and Prospects *

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TEVATRON COLLIDER: STATUS AND PROSPECTS

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Abstract During the 1988-89 run, the Fermilab Tevatron proton-antiproton collider exceeded the design luminosity goal of $10^{30}/cm^2/sec$ and delivered 9.6 pb^{-1} of integrated luminosity at 1800 GeV to the CDF experiment. Based on the operational experience accumulated during this collider run, the performance of the Tevatron collider will be reviewed. This review will treat not only the Tevatron itself, but also the auxiliary accelerator systems necessary for collider operation. The performance and the limitations in each of the accelerator subsystems will be discussed and analyzed. The plans to overcome some of these limitations in the next collider run will also be discussed. Finally, the status of longer-term upgrade proposals for the early 1990's focused on increased luminosity will be presented.

INTRODUCTION

The Fermilab Tevatron is the world's highest energy accelerator system and the 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 fixed target physics; and in 1987, and 1988-89, with proton-antiproton colliding beams at 1800 GeV. This paper will focus on the collider operation of the Tevatron: its performance during the 1988-89 run and the outlook for its future prospects.

PERFORMANCE IN THE 1987 COLLIDER RUN AND SUBSEQUENT IMPROVEMENTS

The 1987 collider run was the first full-scale run of the Tevatron collider. During that 5-month run, the peak initial luminosity reached $1.3 \times 10^{29}/cm^2 sec$; about 70 nb^{-1} of integrated luminosity was delivered to the CDF experiment at B0. Some of the important performance parameters of this run are displayed in Table 1 below. The details of the performance of the Tevatron and its injectors during this run have been presented in earlier papers[1,2].

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[*] Operated by the Universities Research Association, Inc., under contract with the U. S. Department of Energy.

After the end of the 1987 collider run, a number of improvements were made in various accelerator subsystems, both in the injectors and in the Tevatron itself. These improvements, which were based on the experience of the 1987 run, were crucial to the success of the 1988-89 collider run. They have been discussed in detail in previous reports[3].

PERFORMANCE DURING THE 1988-89 COLLIDER RUN

Integrated luminosity and overall collider performance

The run began on June 20, 1988 and ended on June 1, 1989[4]. The maximum integrated luminosity delivered in the best week (week 44) exceeded 0.5 pb^{-1}. The total integrated luminosity delivered was 9.6 pb^{-1}.

The collider performance is summarized, and compared with the 1987 run and the design parameters, in Table 1.

TABLE 1: Collider Performance Parameters
All emittances are 95%, in π mm-mrad
All intensities are in units of 10^{10}
Column (1): Achieved in 1987 collider run
Column (2): Achieved in 1988-89 collider run
Column (3): Tevatron I design

Parameter	(1)	(2)	(3)	Parameter	(1)	(2)	(3)
Number of bunches	3	6	3	β^* (m)	.74	.55	1.1
Protons/bunch at low-β	5	7.2	6	Antiproton stacking rate (10^{10}/hr) peak	1.1	2.1	10.
Antiprotons/bunch at low-β	.8	2.9	6	average	.77	1.4	10.
Antiprotons extracted from the core/bunch	2.3	4.5	6	Luminosity lifetime (hrs)	8.	10-25	20
MR transfer efficiency(%)	77	88	100	Operational efficiency(%) (store hrs/total hrs)	40	65	
MR coalescing efficiency(%)	70	80	100	Average stack before transfer	25.	60-70	40
Tev transfer efficiency(%)	65	95	100	Average stacking time (hrs)	10.	20.	4.
Transverse emittance proton	24	23	24				
antiproton	36	18	24				
Initial luminosity ($\times 10^{29}/cm^2/sec$)	1.3	20	10				

The major experiment in place during this run was the large general-purpose CDF experiment in the B0 straight section. This experiment recorded about 4.6 pb^{-1} of integrated luminosity. Smaller experiments were also in place at C0, D0 and E0. At present, only the B0 straight section posseses a low-beta system. For most of this run, the system was operated in a mode in which the insertion optics were not matched to the rest of the ring, but a β^* of 0.53mx0.56m (HxV) was achieved.

Limitations to the integrated luminosity

Antiproton stacking rate

Table 2 shows the various quantities associated with the antiproton stacking rate. The table shows the values achieved for each of these quantities and the Tevatron I design value. The largest single discrepancy arises in the first item ("Antiprotons/proton collected in the Debuncher") and is due to an overestimate of the antiproton production cross section on tungsten in the original design by a factor of about 2.5.

TABLE 2: Antiproton Source Stacking Rate

	Quantity	Achieved Value	Tevatron I Design
1.	Antiprotons/proton collected in the Debuncher ($\times 10^{-6}$)	12.8	35
2.	Antiprotons/proton bunch-rotated into $\delta p/p = 0.2\%$ ($\times 10^{-6}$)	12.1	35
3.	Antiprotons/proton injected into the Accumulator ($\times 10^{-6}$)	10.5	35
4.	Antiprotons/proton stacked to the Accumulator core ($\times 10^{-6}$)	8.4	28
5.	Protons/cycle on target ($\times 10^{12}$)	1.8	2
6.	Targeting cycles/hour	1380	1800
7.	Overall: Antiprotons/hour stacked to the Accumulator core ($\times 10^{10}$)	2.1	10

The achieved values 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 means that quantity 4 in the above table is a function of the stack intensity. For stacks of about 80×10^{10}, quantity 4 is reduced to about 5×10^{-6}.

Improvements in the antiproton yield per proton, the number of protons on target, the cycle rate, and the rolloff of stacking rate with stack intensity are planned for Phase I of the Fermilab upgrade (see below).

Antiproton transfer

Fig. 1 *shows the observed correlation between the number of antiprotons at* low-β in the Tevatron and the stack intensity. The rolloff seen at high stack intensities is principally due to two effects:

(a). The antiproton transfer efficiency from the Accumulator to low-β in the Tevatron drops from 95% for small stacks to about 60% for stacks in the 60-70×10^{10} range. This reduction is due to losses at antiproton injection into the Main Ring: for large stacks, the core emittance exceeds the limited Main Ring transverse aperture.

(b). The fraction of the core which can be unstacked with a fixed RF bucket 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.

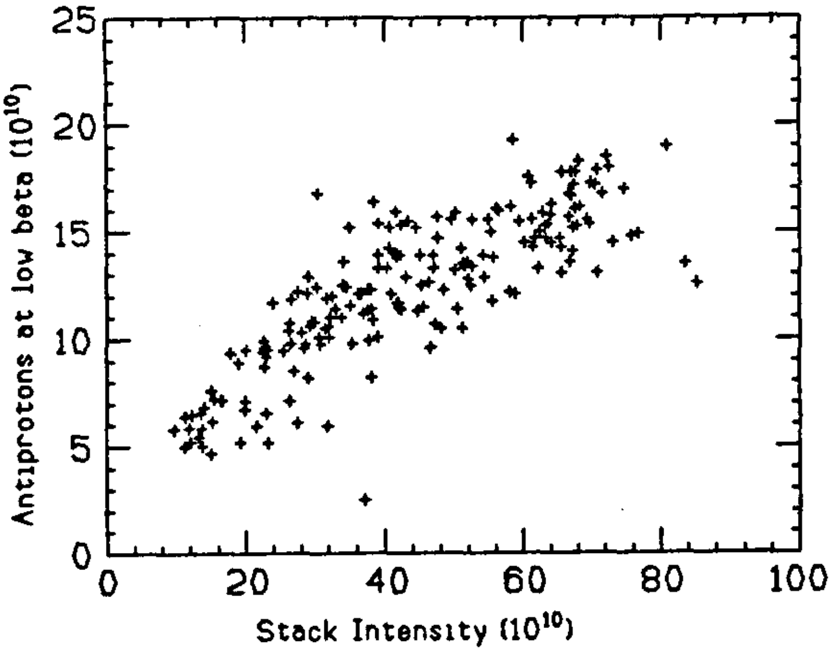

FIGURE 1: Antiprotons at Low Beta vs Stack Intensity

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

Beam-beam interaction

The principal limitation to the proton transverse density (and hence the luminosity) in the 1988-89 collider run was the beam-beam interaction. The beam-beam interaction can be parameterized in terms of the linear beam-beam tune shift per crossing,

$$\delta\nu_c = 0.00733(N_p/\epsilon_p) \ ,$$

where N_p is the number of protons per bunch ($\times 10^{10}$) and ϵ_p is the proton 95% invariant transverse emittance (in π mm-mrad). The principal effect of the beam-beam interaction is on the antiprotons, because the proton transverse density is so much larger than that of the antiprotons. For twelve crossings per revolution, corresponding to operation with six proton bunches, the total tune shift experienced by the antiprotons is approximately

$$\delta\nu = 12\delta\nu_c.$$

In terms of this parameter, we begin to see deterioration of collider performance at proton transverse densities corresponding to $\delta\nu > .02$; for $\delta\nu > .03$, the degradation is severe enough that we cannot operate there.

The performance deterioration observed in the range $.02 < \delta\nu < .03$ is twofold. The first effect is antiproton emittance growth (typically 20-40%) and particle loss (typically 5-10%) in the Tevatron at 150 GeV, during acceleration to 900 GeV, and during the low-β squeeze. The second effect is a reduction of the initial luminosity lifetime (see fig. 2).

The influence of a 7th order resonance, located at a tune separation of $(\delta Q_x, \delta Q_y) = (.018, .024)$ from the bare working point, is believed to be responsible for the observed effects. To control the beam-beam interaction during operation, it was routine practice to deliberately increase the proton transverse emittance utilizing the Tevatron transverse dampers as noise sources to bring $\delta\nu$ into the acceptable range.

The installation of a beam separator system in Phase I of the Fermilab upgrade (see below) is expected to eliminate this limitation.

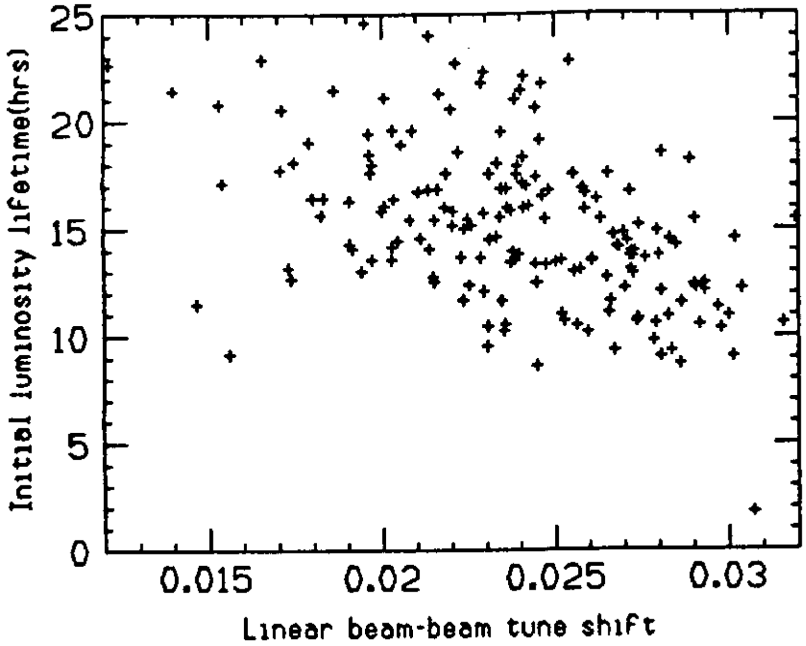

FIGURE 2: Initial luminosity lifetime vs beam-beam tune shift

Luminosity lifetime

The luminosity lifetime was observed to grow from the initial values shown in fig. 2 to values in the range of 25-35 hours after 15-20 hours into a store. In general, the luminosity lifetime was sufficiently long that it was not a serious limitation to the integrated luminosity.

Reliability

During the 1988-89 collider run, there were 295 stores, of which 133 were ended intentionally (mean store length 20.5 hours) and 162 by failures (mean store length 9.5 hours). The mean store length for all stores was 14.4 hours. The largest single cause of unintentional store loss was the spontaneous prefire of the Tevatron abort kickers (31 stores lost). There were three Tevatron dipole failures, responsible for about 2.5 weeks of downtime. Several Main Ring overpass dipoles, and one Main Ring quadrupole, failed and had to be replaced. There were also a number of failures of the lithium lens which did not cause substantial downtime because of the availability of numerous spares.

PROSPECTS FOR THE FUTURE: THE FERMILAB UPGRADE

Subsequent collider and fixed target runs will benefit from the improvements planned in the Fermilab upgrade program[5]. This program is divided into three phases; in each of the first two phases, the collider initial luminosity is expected to increase by at least a factor of five. There will also be an improvement in fixed target performance with each phase.

Phase I (1989-92)

Linac upgrade

The Linac upgrade[6] is a proposal to increase the Linac energy from 200 to 400 MeV 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 growth[7] presently suffered just after Booster injection for intensities above $1.5\text{x}10^{12}$. The overall impact on collider performance will be a reduction in the transverse emittance of the protons used for collider operation in the Tevatron and an increase in the intensity of the protons used for antiproton production from the Main Ring. 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.

R&D efforts to date have concentrated on the development of the prototype high gradient accelerating structure and power source. The first prototype structure has been power tested successfully to gradients roughly 10% higher than will be required in the Linac.

Antiproton Source upgrade

In late 1989, it is planned to increase the aperture of the Debuncher ring by increasing the separation of the Debuncher stochastic cooling system electrode gaps; at the same time, the cooling power will be doubled to compensate for the increased gap spacing. Coupled with aperture improvements in the Debuncher injection line and an increase in the lithium lens gradient, the overall gain expected is a factor of about 1.5 in antiproton yield.

In the Accumulator, the present 2-4 GHz core momentum and betatron systems will be upgraded to 4-8 GHz in the summer of 1989. The new 4-8 GHz core systems will improve the stacking rate at high stack intensities, and reduce the emittance of the antiprotons delivered to the Tevatron.

In the 1990-91 period, a 2-4 GHz fast momentum cooling system is planned for the Debuncher. A prototype of this system will be implemented in late 1989.

In the area of targeting, a system of fast kickers to sweep the proton beam across the production target during the beam spill will be implemented. This system will reduce the peak beam energy density deposited in the target, enabling it to survive with the higher proton intensities forseen with the Linac upgrade and the Main Injector (see below). The target sweeping system is currently under design, with implementation expected in 1991-2. A prefocusing lithium lens will also be used in connection with this system to simplify the proton optics upstream of the target.

Main Ring upgrade

At present, the Main Ring cannot cycle more rapidly than 0.38 Hz for antiproton production. "Multi-batch" targeting refers to a new operational mode of the Main Ring for antiproton production which has the potential to increase the average production cycle rate to 0.5 Hz. To date, beam loss from the Main Ring and inefficiencies in the Antiproton Source cooling systems have limited the effectiveness of this mode of operation. Further studies in the next collider run will be required to determine whether this mode of operation can be made practical.

Two other improvements are planned for the Main Ring in the near future. These are a system of ramped correction dipoles which will allow orbit correction through transition and a system of new quadrupoles which will provide a reduction in the peak horizontal dispersion. These improvements should be beneficial not only for overall acceleration efficiency but also for control of losses which are detrimental to the collider detectors during collider operation.

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. A new abort system, and new injection kickers, will be required. Cryogenic improvements are also under consideration to boost the ring energy.

The new low-β systems for B0 and D0 can provide β^* in the range of 1.7 m to 0.25 m. Both insertions are completely matched to the Tevatron lattice and provide warm spaces for separators. The systems are planned to be completed and installed in early 1991.

The separator system[8] will also be installed by early 1991. 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 $>5\ \sigma$ at 1 TeV; separation is accomplished using 23 3 m long electrostatic separators operating at <35 KV/cm. This system will relieve the constraints now imposed by the beam-beam interaction, and will allow operation with up to 36 bunches.

Successful beam tests of a simple separator system in the Tevatron were carried out during a study period in June of 1989. Two separators, one in each plane, were used. With 6 intense proton bunches and 1 antiproton bunch separated on the helical orbits, the antiproton bunch lifetime at 150 GeV was observed to be substantially improved over the non-separated orbit situation with similar proton bunch densities. Although extremely preliminary and incomplete, these beam tests are very encouraging for the eventual success of the separated orbit scheme.

Finally, R&D work will continue on cold compressors[9] which will allow the ringwide temperature to be reduced from its present 4.7° to less than 4.2°. Together with a program of replacement of weak magnets, this is the most feasible way to reach a ring energy in the collider mode of 1 TeV.

Collider performance in Phase I

By 1992, with the Linac and Antiproton Source upgrades in place, the antiproton stacking rate should reach about $7\text{x}10^{10}$/hour. With the completion of the Tevatron upgrades discussed above, it is expected that the collider can provide peak luminosities of $> 10^{31}/\text{cm}^2/\text{sec}$ at $\beta^* = 0.5$ m, and integrated luminosities of $>60\ \text{pb}^{-1}$ per 8 month run.

Phase II: the Main Injector (1991-94)

The principal limitation to performance after the implementation of Phase I is the Main Ring. This machine limits collider luminosity primarily because of its restricted aperture, which limits the proton intensities which can be delivered for antiproton production and for Tevatron collisions. In addition, the presence of the Main Ring beam in the vicinity of the collider detectors, requiring rigid control of losses while in antiproton production, is a constant source of problems and dead time for the experiments.

The proposal for the solution of these problems is straightforward: replace the Main Ring with a new 150 GeV synchrotron in a new tunnel. This new machine is called the Main Injector[10]. With a radius about half that of the present Main Ring, it will have adequate transverse and longitudinal admittance to provide intensities of $5\text{x}10^{12}$ protons/pulse, at a rapid cycle rate (.67 Hz), to the Antiproton Source for antiproton production. It will have the capacity to provide proton single 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 in a separate tunnel from the Tevatron, it will allow 120 GeV test beams, and high intensity ($3\text{x}10^{13}$/pulse) production beams, to be delivered to the experimental areas year-round.

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 begins in FY1991, it could be completed in mid-1994.

Phase III: beyond 1995

The upgrades associated with Phase II will allow the Fermilab collider and fixed target programs to continue forefront research at the high energy frontier into the middle of the 1990's. The next phase of the upgrade program must evolve from Phase II in a direction which maintains the capability for operation at the energy frontier for as long as this capability is unique, but at the same time is consistent with Fermilab's role in the US high energy physics program after the energy frontier passes to the SSC Laboratory. The specific details of Phase III remain to be worked out. Whatever direction is ultimately taken, however, it is certain that Fermilab's accelerators will continue to play a crucial and pivotal role in carrying out the Laboratory's mission for the foreseeable future.

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