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The Fermilab Pbar-P Collider; Present Status and Future Plans*

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THE FERMILAB PBAR-P COLLIDER; PRESENT STATUS AND FUTURE PLANS

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Abstract

The Tevatron Collider is performing beyond expectations for its first physics run. The peak luminosity is already 1.6 times the design goal of 10^{30} cm^{-2} s^{-1}. The anticipated integrated luminosity recorded by the major detector, CDF, is 3 inverse picobarns which should be sufficient to see the top quark if its mass is less than 110 GeV. The next two Collider runs will have improved performance with luminosity approaching 10^{31} at two interaction regions. In the years between 1993 and 2000, the Collider energy will be increased by using the highest field superconducting magnets then available, where 8.8 T would give 2 TeV on 2 TeV pbar-p collisions with a luminosity above 10^{31}. To facilitate this possibility and to improve the general Collider capabilities, a new 150 GeV Main Injector is now being designed.

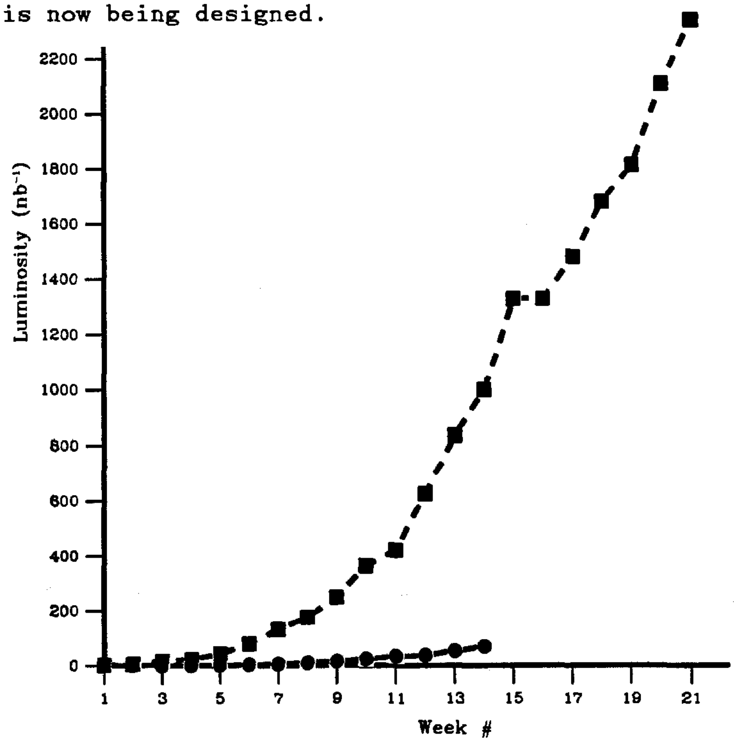

Figure 1. Comparison of integrated luminosity for the 1987 and 1988 runs. The 1988 run is scheduled to continue another 22 weeks, until May 1989.

Introduction

Historical Perspective

In 1983 the superconducting Tevatron was installed in the same tunnel as the 500 GeV Main Ring synchrotron. The Tevatron was then operated only as an 800 GeV fixed target machine until 1985 when the first antiprotons were available from the source for use in the Collider. Heroic efforts were required to achieve a luminosity of a few times 10^{24}. The first engineering run took place in 1987 and the circles on figure 1 show the integrated luminosity as a function of time during this period. The boxes show the luminosity progression of the run which is now underway.

While the Tevatron is not the first pbar-p collider, it is the first superconducting accelerator and storage ring. And as such it has the advantage of a storage energy of 900 GeV compared to CERN's 315 GeV, even though the radius of the Tevatron is 10% smaller than that of the SPS. We hope that this energy advantage will be significant, especially considering that CERN has been in the Collider business since 1981 and has developed a formidable expertise.

Project Description

Figure 2 shows a schematic of the Tevatron Complex. Proton beams start at the source located in the 750 keV Cockroft-Walton accelerator. H^- ions are accelerated to 200 Mev in the Linac and injected into the Booster synchrotron using a multiturn charge exchange technique. Protons are accelerated to 8 GeV and transferred to the Main Ring where they are either accelerated to 120 GeV for pbar production or to 150 GeV for injection into the Tevatron.

The pbar production cycle involves a bunch rotation to make each of the 82 rf bunches as short as possible just before the beam is extracted from the MR at 120 GeV. Short bunches of 8 GeV pbars are thus produced on a copper target, focused by a lithium lens, and injected into the Debuncher ring. The first stage of cooling is effectively the rotation of these short bunches in the Debuncher to reduce the momentum spread by a factor of 15. The next stage is the stochastic cooling of the emittances in both transverse planes prior to the transfer to the 8 GeV Accumulator storage ring. In the 2.6 seconds between injection cycles, the transverse emittances are reduced from 20π mm-mr to 7π.

In the Accumulator several stochastic cooling systems are used to merge the pbars into the circulating stack (the stack tail system) and to reduce the emittance of the stack in all three planes. When enough antiprotons have been accumulated, it is possible to initiate a fill of the Tevatron Collider.

The filling procedure involves loading the Tevatron with six high intensity proton bunches and then six pbar bunches. While these injections are underway, and during tests necessary to insure the proper setting of the transfer lines, the Tevatron is required to be at a constant energy of 150 GeV. A rediscovered characteristic of superconducting cable called "flux creep" is responsible for a decay of the sextupole component of the field of the 772 dipoles during this period, and continuing corrections to the chromaticity correcting sextupoles are required. Understanding this phenomenon and the subsequent variation in the sextupole component as the magnets are ramped has been one of the reasons for our ability to preserve the transverse emittances of the beams during the present run. Also essential in preserving the emittances was a modification at the D0 overpass to the MR lattice to provide a better dispersion match at the MR to Tevatron injection point.

The MR rf allows a maximum bunch area of about 0.4 eV-s between 17.6 and 30 GeV. Since 3 eV-s are needed to provide the needed bunch intensity, each high intensity bunch starts out as 11 rf bunches (53 MHz) at 8 GeV which are injected into the MR, accelerated to 150 GeV, and then coalesced into a single bunch using a 2.5 MHz rf system. One very impressive improvement for the present run is the ability for this procedure to be almost 100% efficient.

Once the 12 bunches have been injected, the Tevatron is ramped to 900 GeV and the low β insertion at B0 is turned on. In going from the injection optics to the low β optics, (the squeeze), 30 function generators control power supplies through 30 separate optics solutions. Care is needed as an error in betatron tune of 0.01 can cause losses and emittance growth of the pbar beam.

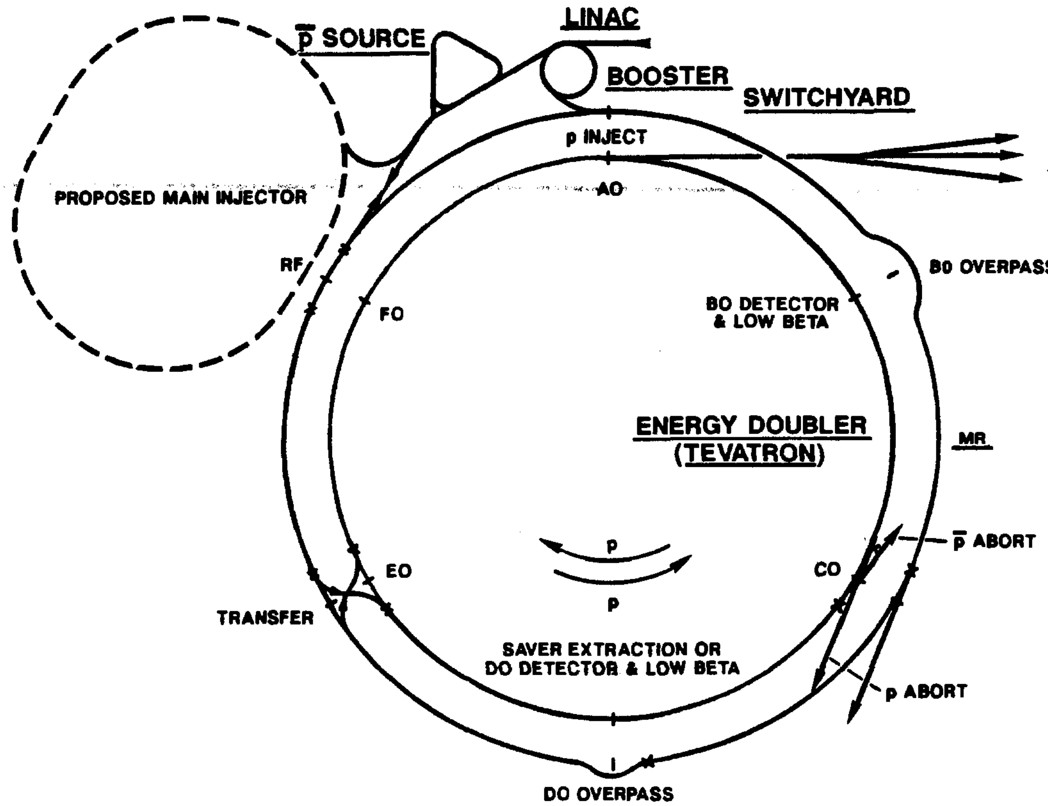

Figure 2. Schematic of the Fermilab accelerator complex. The MR is 0.6m above the Tevatron except in the overpass regions. The average radius of the Tevatron and MR is 1 km, the average radius of the Accumulator, Debuncher, and Booster is about 75 m. Colliding beam operation and fixed target operation should alternate every 3/4 year. Major detectors are at B0 and D0. The experiment at C0 shares the straight section with the MR and Tevatron abort systems, the one at E0 shares the straight sections with the MR to Tevatron p and pbar transfer systems. There is a low β insert at B0. D0 will have one next year. The location and size of the proposed 150 GeV Main Injector is indicated. Direct transfers from the MI to the Tevatron eliminate the need for the MR.

The store generally lasts until it is ended by some malfunction or the luminosity has decayed to an unacceptable level. The present run has been aided by increases of both the luminosity lifetime and the mean time between failures for the Tevatron components. Typical initial luminosity lifetimes are 20 hours, growing to 30 or 40 hours after 10 hours. Even so, the luminosity lifetime is dominated by transverse emittance growth caused by some unknown heating mechanism (power supply noise is suspected). There is no evidence for significant intrabeam scattering. The emittance growth rate is too large to be due to gas scattering based on measured pressures as well as on the relative intensity versus emittance lifetimes.

Figure 3 shows the evolution of the peak luminosity at the CDF detector for the run in 1987 and the present run. Generally, the initial luminosity has been near to 10^{30} for the the more recent stores due to the lack of pbars and also the fact that the CDF detector is rate limited and not much is gained from higher luminosities. The trigger and data acquisition systems of the CDF detector have shown steady improvement; the experiment has recorded >70% of the available data even at luminosities of 10^{30}.

The maximum initial luminosity is presently determined from beam-beam interaction effects. The details of the limiting mechanism depend on the relative emittances of the proton and pbar beams. The present operating mode is one in which the proton bunch intensity is lower than it could be and the transverse emittances are artificially doubled by intentionally missteering the beam injected into the Tevatron. These factors reduce the head-on beam-beam tune spread suffered by the pbars to the point where the pbar tunes fit between the 2/5 and 3/7 resonance lines.

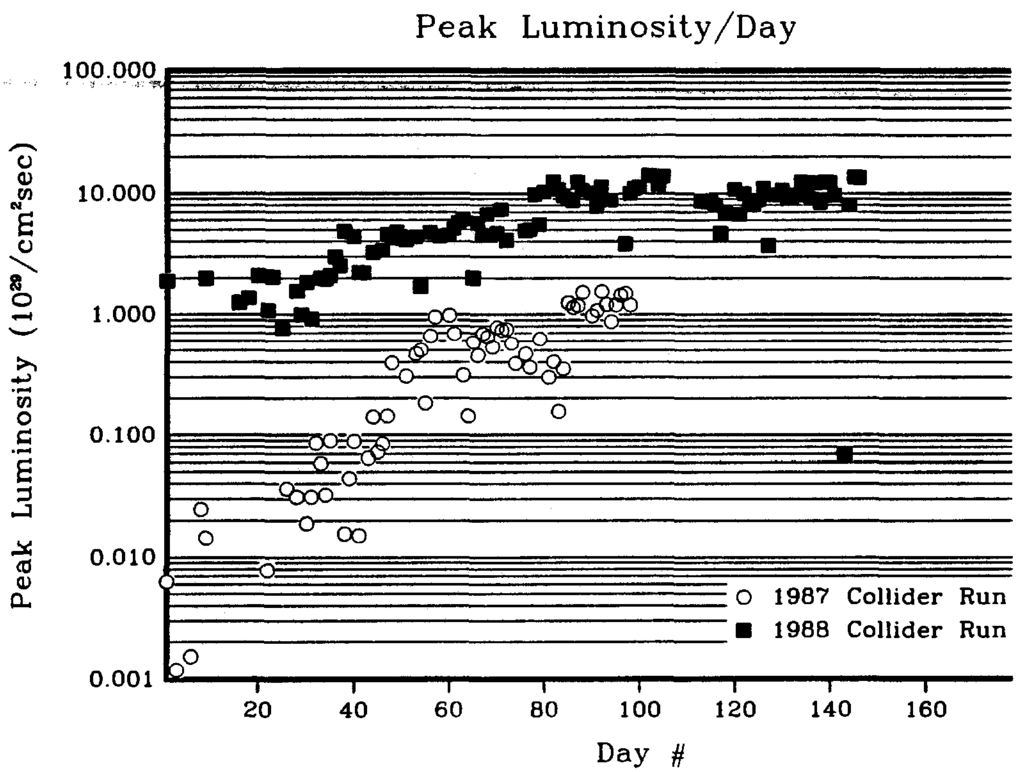

Figure 3. Comparison of initial luminosity for each store in 1987 and 1988.

If more protons are used or if the proton emittance is reduced, the pbars are shifted onto the resonances which cause beam loss and emittance growth. More recently, as the pbar stacks have grown larger and the pbar bunch intensities correspondingly larger, the pbar induced beam-beam tune shift has caused the proton beams to be damaged. As well, there is evidence that the beams are being lost on the 5/12 resonance lines. Indeed, all loss mechanisms are consistent with the picture that the non-linear transverse forces at the edge of the bunches drive traditional sum resonances. We hope to try other working points with more area free of lowest order resonances.

Present Status

The performance of the various components of the Collider are shown in Table I (pbar source) and Table II. As can be seen, major improvements for the present run have come from the MR. The increased transmission efficiency and the smaller emittances for protons and pbars have been important. Doubling the number of bunches and reducing the B0 β^* have also contributed to the improved performance. The improved perfomance of the control system is very significant. In particular, there are new programs and systems which monitor transfers and stores for easy diagnosis of problems and optimization of operating conditions.

For normal operation, the proton emittance is intentionally enlarged and the intensity of the proton bunches is restricted to reduce the beam-beam tune shift. I believe that if the effects of the beam-beam forces could be minimized either by a new working point or the use of electrostatic separators, the luminosity could be increased by at least a factor of 3.

Table I, Pbar Source Stacking rates

stage	Design	End'87	Nov'88
per cycle			
P's on target	2E12	1.3E12	1.9E12
To Debuncher	7E7	1.46E7	2.30E7
After Rotation	7E7	1.23E7	1.92E7
Into Accum.	7E7	1.04E7	1.60E7
Pbars in core	6E7	0.99E7	1.50E7
overall			
cycles/hour	1800	1400	1380
Stacking rate	10.8E10	1.2E10	1.8E10
Maximum stack	4.2E11	4.0E11	8.1E11

Table II, Collider Perfomance

	Design	End'87	Nov'88
Antiprotons			
From Accum./bunch	6.0E10	3.6E10	3.3E10
MR transmission	100%	50%	>95%
Coalescing Eff.	100%	65%	>95%
MR to low β Eff.	100%	80%	>95%
Overall transmission	100%	30%	>90%
Number stored/bunch	6.0E10	1.2E10	3.0E10
Protons			
Coalescing Eff.	100%	65%	>95%
Number stored/bunch	6E10	5E10	>7E10
Collisions			
Number of bunches	3X3	3X3	6X6
$\epsilon_{H,V}$ 95% Normalized			
(p)	24π	25π	14π
(pbar)	24π	35π	14π
B0 β^* (m)	1.1	.75	.55
Max luminosity 10^{30}	1.0	.15	1.6

With the possible exception of attempting to run at a new working point, there are few hopes for significantly improving the machine performance this run. Work is under way to prepare a new operating point near the integer stopbands, similar to the way the ISR was operated for high luminosity. Some ideas to use octupoles to stabilize the emittance growth caused by the beam-beam interaction are being investigated. There is also some work being done to develop the capability to accelerate several Booster batches simultaneously for pbar production cycles.

Plans Through 1993

After the present run, which ends in May of 1989, there will be two more Collider runs before major changes to the Tevatron Complex are contemplated. The Collider runs last about 9 months and alternate with fixed target runs of a similar duration.

Perhaps the most significant upgrade for the 1991 run will be the addition of another low β insertion with a second major detector at the D0 straight section. The new insertion will be an improved one, with more quadrupole circuits which will allow better matching to the lattice functions of the arcs, a β^* of 0.25 m, and a much simpler transition from the injection optics to the low β optics. At some point, the insertion at the B0 straight section will be upgraded to be the same as at D0.

Also for 1991 will be the first attempts to use electrostatic separators to reduce the number of head-on beam-beam collisions. At present there is a design which calls for the installation of 21 electrostatic separator modules (each 3 m long, gradients up to 50 kV/cm) to provide separation of the proton and pbar beams at all crossing points except B0 and D0. This double helix scheme will eventually allow 22 bunches of protons and 22 bunches of pbars, although some subset of the scheme should allow 6 on 6 operation at considerably higher luminosity than is now possible.

Additional cryogenic components will be added to allow Tevatron magnets to be run at a lower temperature (4.0 vs. 4.6 degrees K) which will allow the operating energy to be raised from 900 to 1000 GeV. The last four tanks of the present 200 MeV Linac will be replaced with higher frequency cavities to allow 400 MeV injection of the H^- beam into the Booster. The minimum emittance being determined by the Laslett tune shift in the Booster, this higher injection energy will lead to brighter proton beams. To cope with the higher pbar flux and bigger core intensities, some of the stochastic cooling systems of the source will be upgraded to higher frequencies (4 to 8 GHz).

Plans for the Rest of the Millennium

In order to make significant advances at Fermilab in the period before the SSC or UNK Collider are producing physics results, some improvements to the Tevatron have been considered. The first was a plan to increase the luminosity of the present 900 GeV pbar-p collider by adding two 20 GeV rings to the Tevatron complex in order to increase the pbar stacking rate and the maximum stack size. This plan would have increased the peak luminosity to 5 10^{31} and cost about $124 million. A second option which was studied was the addition of a second superconducting ring to the Tevatron tunnel with the idea of creating a proton-proton collider at 1 TeV on 1 TeV with a luminosity of 2 10^{32}. This would have required placing the MR injector in another tunnel and would have cost $285 M. One difficulty with this scheme is that the straight sections at the interaction regions are too short to bring the proton beams in two separate rings into collision without special 6.6 T magnets. That is, one has to develop high field magnets just to have 1 TeV collisions.

2 TeV on 2 TeV pbar-p Collider

A third plan also involves removing the MR from the Tevatron tunnel and replacing it with a new superconducting ring but using pbar-p collisions in the new, higher energy ring. At present, a new Main Injector is being designed which would replace all of the functions of the present MR and add the capability of slow spill for tuning up the fixed target experiments during collider runs. The location of this proposed 150 GeV synchrotron which would be in a new tunnel 1/2 the size of the Tevatron is shown in Figure 2.

The ultimate step is to install a new superconducting ring in the place of the old MR which would be of the most modern technology and the highest possible field (e.g. 8.8 T at 1.8 degrees K). The luminosity should scale with the energy, giving a factor of 2 over whatever is achieved in the next two runs; we expect to have over 10^{31} by the end of 1992. The new 2 TeV on 2 TeV collider could turn on in 1994 with a luminosity more than 2 10^{31}. As an additional benefit, the magnets which are capable of 2 TeV in collision mode will also add the capability of fixed target physics at 1.5 TeV. The fixed target energy could be higher, but is limited by the length of the extraction straight section.

This third plan with higher energy collisions has been adopted because it preserves the detectors at D0 and B0. The upgrades of the detectors to allow luminosities in the 10^{32} range are more costly than the accelerator upgrades.