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The Fermilab Tevatron and Pbar Source Status Report *

H. Edwards

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THE FERMILAB TEVATRON AND PBAR SOURCE
STATUS REPORT*

H. EDWARDS
FERMI NATIONAL ACCELERATOR LABORATORY
BATAVIA, IL 60510

Fermilab is now in the final construction and commissioning phase of the Tevatron and Pbar Source. With the completion of the construction at the DØ Colliding Detector Hall and the MR BØ Overpass, the Tevatron program initiated in 1979 with the Energy Saver project and in 1981 with the TeV I project will reach completion. The DØ colliding detector and low-β quads which are not part of the TeV I project are planned for completion in 1989. Thus with the superconducting ring capable of accelerating and storing beams to about 900 GeV, extensive modification to the Main Ring and with the two new Pbar Source rings, Debuncher and Accumulator, we are on the threshold of $\bar{p}p$ collider operation as well as the fixed target operation begun in 1983. Initial commissioning of all Collider systems culminated in October 1985 with the successful detection of collisions in the BO CDF detector. (Figure 1.) The construction and operational activities of the past few years outlined in Fig. 2, illustrates the staged conversion of the lab complex from conventional 400 GeV fixed target facility to the technologically and scientifically exciting $\bar{p}p$ superconducting collider. With the recommissioning this fall, year-round operation (except for about two months each year) for collider or fixed target is expected to begin and, hopefully, continue for the next four to five years uninterrupted. Initial Collider operation will be with three small experiments at CØ, DØ, and EØ in addition to the large BØ CDF detector.

The present Fermilab accelerator complex is illustrated in Figs. 3a, b. The Main Ring and Tevatron are in the same tunnel and have an average radius of 1000m. The Debuncher and Accumulator are in the same tunnel and have average radii of 80.4 and 75.45m respectively. The Booster also has a radius of 75.45m and all three of these rings operate at 8 GeV kinetic energy, with the Booster accelerating beam from 200 MeV kinetic energy. The Main Ring, which was originally built as a 400-500 GeV fixed target accelerator, has now been modified with two overpasses at the two major colliding detectors which elevate the ring by 6m at BØ and 2m at DØ respectively.[1] This last running period operation with the DØ overpass was successfully carried out. In addition, other modifications at F17 have permitted extraction of 120 GeV beam to the pbar target. These modifications have called for replacements of some regular Main Ring dipoles with other magnets such as vertical bends -which has necessitated doubling the excitation in adjacent magnets to twice nominal. Thus, Main Ring peak excitation is now ~200 MeV and operates at 120 GeV for the $\bar{p}$ production targeting and 150 GeV for injection into the TeV. Extensive work on Main Ring RF has also been done to facilitate the manipulations required for bunch rotation prior to extraction for $\bar{p}$ target production and for bunch coalescing prior to injection of single bunches into the Tevatron for storage.

The TeV I Collider operation has been described in numerous references[2] and can be broken down into the Pbar Production operation and the Tevatron Collider operation.

I. PBAR PRODUCTION OPERATION

Pbar Production Cycle (at the Main Ring repetition rate, nominal 0.4 Hz).

a) Injection of one Booster batch (84 RF bunches, full circumference of the booster) into the Main Ring and acceleration to 120 GeV.
b) RF bunch rotation,[3] in the Main Ring to produce narrow time spread bunches (~0.8 ns full width at base). This is done by first lowering the RF to minimize the momentum spread then quickly raising it and allowing the mismatched beam to undergo 1/4 synchrotron oscillation prior to extraction.)
c) Extraction from the Main Ring, targeting of the beam on a tungsten target, and focussing of the secondaries by a lithium lens. (See paper this conference.)
d) Injection of secondaries into the Debuncher ring and a continuation of the bunch rotation[4] of the secondaries which have narrow time spread and large momentum spread, $\Delta p/p = 3\%$ full width, by a 1/4 synchrotron oscillation followed by adiabatic debunching to produce a debunched beam with $\Delta p/p = 0.25\%$.
e) The 7×10^{-7} particle $\bar{p}$ beam is then betatron cooled from 20π to 5π emittance for the duration of the cycle. The cooling system for each plane has 500W power with a gain of 135 db at 2-4 GHz.
f) The beam is transferred to the Accumulator, bunched at 53 MHz[5] and decelerated to the stack tail, where the stack tail cooling[6] moves the beam away from the stacking orbit in 2 sec and into the core at 6 MeV/sec initial rate. The stack tail gain is exponentially decreasing toward the core which is 60 MeV away. It takes two hours for beam to reach the core. The stack tail system has 1600 watts for momentum cooling with 150 db gain at 1-2 GHz. The betatron cooling system has 210W horizontal and 20W vertical power with a gain of 125 db at 1-2 GHz.
g) The stack core system, using stochastic stacking developed by Vander Meer, continuously builds up the higher density stack and after about four hours densities of 10^{11}/MeV with about 4×10^{11} particles with $\Delta p/p \sim 0.07\%$ are expected. Betatron cooling has reduced the transverse emittance to 2π mmmr.

The core cooling system has 30 watts of power for momentum cooling and ten each for betatron cooling with gain of 105 db at 2-4 GHz. (The operation of the Debuncher and Accumulator cooling systems is given in a separate paper at this conference.)

Pbar Source Commissioning.

Commissioning of the Pbar Source started January 17, 1985 and was carried out parasitically to High Energy Physics operation until the end of August when dedicated time was devoted to the final source and Collider commissioning that lasted until October 13. Cross talk between the Main Ring and Tevatron power supplies and magnetic fields produced some operational difficulties, which hopefully have been rectified during the past shutdown. The commissioning activities used primary protons at 8 GeV or secondary protons at 8 GeV produced from 120 GeV primaries, or secondary 8 GeV $\bar{p}$'s. Protons were used extensively to check all systems of the transport, Debuncher, and Accumulator with beam proceeding in the same direction as the final $\bar{p}$ beam but with opposite magnet polarity. The final $\bar{p}$ bunching, extraction from the Accumulator and transport to the Main Ring, was checked by sending 8 GeV protons from the Main Ring backward into the Accumulator.

Since October, a new line (AP4) from the Booster to the Pbar Source had been commissioned in February 1986, and allows operation of the Debuncher and Accumulator without the Main Ring. This mode cannot be used to study the production targetry or the AP1, AP2, and AP3 transport lines and their transfer into the rings, but has been used to measure the admittance of the rings.

The Pbar Source commissioning milestones are listed in Table I. Major obstacles to the commissioning process were as follows.

a) A piece of cardboard had been left on one of the vacuum pieces during installation.

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

b) Collapsed bellows restricted the aperture and made stacking difficult, and the reluctance of the commissioners to open the vacuum system and check.
c) The failure of the transformer for the lithium lens which required operating a factor of two below design.
d) The required care needed in tuning and aligning the Accumulator cooling system.

TABLE I
Antiproton Source Commissioning Milestones

August 16, 1983	Groundbreaking for Pbar Source enclosure.
January 29, 1985	Beam transported from Main Ring to target.
March 17	120 GeV beam focussed at the target location.
April 12	Beam transported to end of AP2.
April 15	Debuncher installation complete.
April 21	Circulating beam in the Debuncher.
May 15	Antiproton yield measured at end of AP2.
May 22	Accumulator installation complete.
May 25	Secondary proton beam debunched.
June 6	30 turns observed in Accumulator (via AP3).
June 15	Beam cooled in Debuncher.
June 19	Piece of cardboard found and removed from Accumulator.
June 20	Circulating beam in the Accumulator.
June 23	Accumulator beam decelerated to stacking orbit.
July 20	Beam transferred from Debuncher to Accumulator.
August 23	Replace six collapsed bellows in the Accumulator.
August 30	Core cooling system commissioned.
September 3	First stochastic stacking of protons.
September 7	Reverse polarities. First antiprotons seen in Debuncher.
September 8	10^8 antiprotons accumulated.
September 9-14	CDF detector installed.
September 25	10^9 antiprotons accumulated.
October 3	First antiprotons extracted.
October 5	First antiprotons observed in Main Ring.
October 8	9×10^9 antiprotons accumulated at 10^9 antiprotons/hr. 1.3×10^9 antiprotons accelerated in the Main Ring and observed in the Tevatron.
October 13	First proton-antiproton collisions at 1.6 TeV.

Table II indicates the performance of the Source at the end of the commissioning period and the goal for the 1986/87 test run. As can be seen from Table II there was an overall reduction factor of 150 from the designed $\bar{p}$ production rate.

The major missing factor, 2)&3) (~10), was in the flux of $\bar{p}$'s transported from the target and captured in the Debuncher. This is due to aperture restrictions in the AP2 transport line and the injection devices into the Debuncher, in emittance dilution due to poor matching and injection oscillations, and to the acceptance of the Debuncher which was measured to be $(10\text{-}12\pi\times10^{-6}\ \text{m})^2$ instead of the design $(20\pi)^2$.

Since the commissioning run in October, the Debuncher has been operated with beam from the Booster and AP4 line. All but the essential small aperture devices were removed and the acceptance was improved to $23\pi\times27\pi$ over the whole 4% momentum aperture. The small aperture devices; kickers, pickups, Lambertson magnets, μwave cut off, etc, have since been reinstalled with motorized stands and the acceptance is now $22\pi\times22\pi$ over 3 1/2% momentum aperture. In addition, potential aperture restrictions in the AP2 line have been identified and larger aperture magnets installed. Unfortunately this line and transfer into the Debuncher cannot be checked until the Main Ring is operational again.

The second largest missing factor 1)&8) (~5) came from the Main Ring intensity and repetition rate. Intensities greater than 10^{12} were not effective because of longitudinal emittance growth in the Main Ring and Booster which caused the bunch length at targeting time to be too long. This resulted in a momentum spread too large for the injection orbit aperture of the Accumulator. During the past shutdown, modifications have been made to the Main Ring vacuum chamber impedance which should reduce the longitudinal growth and the Booster is being outfitted with a pulsed quadrupole γ_t jump.

The Main Ring cycle time averaged about 5 sec whereas the design called for 2 sec. Actual time between $\bar{p}$ production cycles was 4 sec and these were interspersed with other types of ramps in the supercycle to give the 5 sec average. For the most part operational convenience dictated the cycle time which can easily be cut to 3 sec, and possibly with care to 2.2 sec.

An easier way to improve the average targeting rate may be to load three Booster batches into the Main Ring on each cycle and target them individually on Main Ring flattop. As this will require going through the bunch rotation process multiple times and consequently may dilute the longitudinal phase space, it must be studied before being adopted. If successful then the time duration between targeting pulses on flattop will be limited by the lithium lens heating and the Debuncher cooling rates.

Of the remaining missing factor of 3, most is associated with decelerating to the stack tail orbit. The speculation here is that there was a rather large octupole tune vs. momentum variation which may have caused losses on the 0.625 resonance as the beam was moved from the injection to stack tail orbit. Since commissioning, strong octupole corrections have been added.

The Accumulator aperture has recently been measured using the Booster and AP4 line after small aperture devices were removed. It was found to be $9\pi\times8\pi$ (10^{-6}m h, v) on the injection orbit and $14\pi\times9\pi$ on the central orbit. This is to be compared with the design aperture of $10\pi\times10\pi$. During the commissioning test the effective apertures may have been considerably smaller, but this did not affect operationbecause the long cycle time and low intensity allowed for Debuncher cooling of the beam to 3π instead of the design 7π. A new closed orbit system with additional vertical steerings from large dipoles is being implemented and the small aperture devices will be put on motorized stands for remote positioning. With these modifications and with alignment of the vacuum chamber it is expected that the Accumulator aperture will be adequate.

The stochastic cooling systems could not be rigorously checked because the $\bar{p}$ flux entering the accumulator stack was about a factor of 40 below design.

Recommissioning studies this coming fall will concentrate on stochastic cooling studies in the Accumulator and targeting injection studies into the Debuncher.

II. TEVATRON COLLIDER OPERATION

In order to load the Tevatron with three bunches of protons and three bunches of pbars for Collider operation the following steps must be performed.

Loading Procedure

a) Check out of all transfers as outlined in Check Out Procedure.
b) Load the three proton bunches into locations in Tevatron separated by 1/3 of the ring circumference. In this operation the Main Ring is cycled from 8 to 150 GeV three time and on each cycle:

i. About 9-11 RF bunches of protons are extracted from the Booster to the Main Ring and accelerated to 150 GeV.
ii. The Main Ring and Tevatron are phase locked and the relative circumferential position of the Main Ring beam to its desired position in the Tevatron is measured.
iii. The Main Ring is then "cogged" by a programmed change in RF frequency or radial position such that $\int 2\pi\Delta R dn = \Delta C$ makes up the desired circumference adjustment and phase lock is restored.
iv. The RF bunches are coalesced into one bunch.[7] In this

process the normal 53 MHz, h=1113, RF voltage is lowered or paraphased to .1 kV to reduce the Δp/p. The 2.5 MHz, h=53, and 5 MHz, h=106, are turned on quickly so that the 9-11 bunches undergo as a unit 1/4 synchrotron oscillation of 2.5 MHz frequency in a mismatched bucket, and are recaptured in a single 53 MHz bucket when this RF is turned up again at the end of the 1/4 oscillation.

v. The single bunch of beam is then transferred to the Tevatron at 150 GeV.

c) Loading the three $\bar{p}$ bunches into the Tevatron then takes place in three separate Main Ring cycles.

i. In the accumulator an h=2, 1.2 MHz system with one suppressed bucket is used to extract a fraction of the beam (up to about 1/3) from the core.

ii. When the one bunch of beam has been accelerated to the extraction orbit, a second h=2 RF system is turned on with higher voltage and the bunch in the bucket is shortened.

iii. This bunch is then adiabatically bunched at 53 MHz (h=84) into approximately nine bunches.

iv. The antiprotons are then extracted from the accumulator, injected into the Main Ring, captured in the 53 MHz Main Ring RF system, and accelerated to 150 GeV where they are cogged and coalesced and transferred to the Tevatron in a way similar to the proton operation, except now the pbars must be injected mid-way between the proton bunches so that the injection kicker does not disturb the protons.

v. The accumulator stack must be recooled for a few minutes before another set of bunches can be extracted from the accumulator.

d) Once three bunches of protons and antiprotons are in the Tevatron, they are accelerated to 800-1000 GeV and stored.

e) The low-β quads at BØ[8] are then turned on and the β* at the Colliding Detector (CDF) is squeezed to 1m from the normal optics of 70m.

f) Finally, the protons and pbars, which are controlled by two orthogonal 53 MHz RF systems, are "cogged" or rotated with respect to one another to bring them into collision at the center of the detector. This final step is necessary because of their relative spacing required during injection.

Collider Commissioning.

Commissioning of the Main Ring and Tevatron for Collider operation started in 1984 after installation of the low-β quads at BØ, though tests and storage of the bunch coalescing had started even earlier.

Development and accelerator studies in four areas were necessary: Main Ring RF manipulations; controls and applications software support to carry out the orchestration of various types of accelerator cycles, and sequences of cycles; Tevatron storage and low-β squeeze sequence; and finally the study time testing of various beam transfers, storage steps and sequences. Table III lists the milestones associated with the Tevatron and Main Ring Collider commissioning.

Main Ring RF. Extensive work on the Main Ring RF has been carried out over the past few years. Considerable effort has gone into the low level system and controls so that: low intensities, i.e. just a few bunches, fewx10^{10} particles can be accelerated without difficulty; so that the 18 MR cavities which produce 4MV of RF can be programmed (paraphased) in two sets of nine cavities, such that the vector sum voltage can be precisely lowered to .1-2 kV, while the 2.5 and 5 MHz systems are performing the bunch rotation. A digitally controlled frequency generator was developed for use on Main Ring flattop to lock the beam to the Tevatron RF and perform the precise cogging operation. The same type of hardware is used in the Tevatron[9] for the final collision cogging. All this is coordinated with beam sync clock marker system which specifies where azimuthally the beam bunches should be in each of the accelerators at any time.

TABLE III
TEV COLLIDER AND MAIN RING COMMISSIONING MILESTONES

1983	
July 3	First beam accelerated to 512 GeV in Tevatron.
August 19	First stored beam, 400 GeV, 13 minutes.
November 9	Beam stored for three hours.
1984	
February 15 - April 2	BØ low-β installation and 800 GeV commissioning.
April 18	β*=2m at 400 GeV.
May 16	β*=1m at 400 GeV.
July 16 - January 5, 1985	Shutdown F17-DØ overpass construction.
1985	
February 11	β*=1m at 800 GeV.
June 6	Reverse injection TeV to MR.
June 18	Coalesced beam to TeV.
August 28	Stored coalesced bunches.
August 22	Used Sequencer program.
August 29	Start dedicated $\bar{p}$ studies, TeV off.
September 9-13	CDF Detector installed, TeV on.
September 19	Injected three coalesced proton bunches. MR cogging operational.
October 5	First antiprotons injected in Main Ring.
October 8	First complete system check out. Pbars accelerated in MR.
October 10	$\bar{p}$ beam to TeV.
October 12-13	$\bar{p}$ to 800 GeV - collision point cogging - low-β - collisions detected.

Controls and Applications Programs. Flexible control to accommodate different types of accelerator beam cycles, sequences of cycles, and a variety of beam transfers had to be developed. In particular, the Main Ring has become the workhorse accelerator and can be programmed to carry out a number of different types of cycles, such as 150 GeV accelerated beam for injection into the TeV for fixed target physics, 120 GeV beam to the $\bar{p}$ target for $\bar{p}$ production, 8 GeV beam to $\bar{p}$ rings for tune up, proton and $\bar{p}$ acceleration for injection into the Tevatron for Collider storage, and a reverse injection cycle where protons are taken from the Tevatron to the Main Ring for check out of the transfer of pbars from the Main Ring to the Tevatron.

A Time Line Generator[10] was developed which allows an arbitrary variety and repetition of these types of cycles within a supercycle which itself can be the standard TeV fixed target ramp, or dc storage at 150 GeV or at flattop. The software for control of the Tevatron had to be developed so that it could be frozen at the injection level, ramped to peak energy and frozen at that level. The magnets associated with turning on the low-β optics (four low-β quad supply circuits supply 20 steering elements and five global tune and chromaticity supplies), had to be programmed through 28 steps in order to get to the 1m β* optics.

Finally, a Sequencer[11] was developed which controls the other application programs and can load different Time Line Generator files, Tevatron ramp files, or low-β squeeze files, and it can also activate lists of data base "set" requests. Thus, once the Sequencer files are set up the operator has only to request the particular sequence to be performed next instead of loading numerous files and settings himself. Types of sequences which are supported are:

1. Test reverse injection Main Ring to Accumulator.
2. Test Reverse injection TeV to Main Ring.
3. Set at 150 GeV/inject protons.
4. Store protons - 150 GeV.
5. Inject antiprotons.
6. Store antiprotons - 150 GeV.
7. Ramp to 800 GeV and store.
8. Turn on low-β.
9. Vary parameters.

10. Recover from low-β.
11. Recover from store.
12. Prepare for fixed target.

Low-β Quads and Storage. The low-β quads were installed in early 1984 so that sufficient time could be devoted to accelerator studies involving programming them through the 20 steps necessary to reach the 1m β* optics condition.[8] Prior to the dedicated studies which started September 1985, there were a total of 39 study periods devoted to storage and low-β quad squeeze programming adjustments. During these studies a total of 21 stores lasting greater than one hour were achieved.[12]

Beam Transfer. The orchestration and checking of various transfer schemes was developed during this time so that during the final dedicated commissioning a check out procedure used prior to injecting pbars was developed. A simplified version of this procedure is outlined below. The first time it was tried, on October 8, it took about 18 hours to complete the check out because of timing problems uncovered during the testing.

Check Out Procedures

1. Establish a normal Main Ring to TeV proton injection cycle followed by a reverse injection TeV to Main Ring cycle, and tune up Main Ring to TeV forward transfer and TeV to Main Ring reverse transfer (for pbars).
2. Replace the reverse injection cycle by a pbar injection cycle, but with using protons injected into the Main Ring. Inject protons into the TeV. Check that proton beam in the Tevatron is unaffected by the pbar injection kicker and has a good lifetime, and that the Main Ring proton beam on the pbar cycle is kicked out by the pbar injection kicker.
3. Discontinue pbar production cycles and change the AP1 line to 8 GeV, and tune up the Main Ring to Accumulator transfer using protons.
4. Set kicker timing appropriate for pbars instead of p's and check that diagnostic devices are properly set up and operating.
5. Proceed with the loading procedure.

The final tests with antiprotons were carried out in four sessions: October 5, 8-9, 10-11, 12-13 (Fig. 4). In total 2×10^{10} antiprotons were used in about 23 shots. Thus in total about 1/3 the number of pbars were used as would be in a single design intensity bunch of 6×10^{10} particles. Collision events were detected by the CDF detector on three of the last shots at an estimated luminosity of few$\times10^{24}$.

It is obvious that the pbar transfer, acceleration and coalescing processes were not optimized in the two dozen shot attempts. Table IV gives a very approximate summary of the efficiency of the various processes. The pbar bunch intensity was, of course, the major factor, however, transmission coalescing efficiencies in the Main Ring were equally bad when combined and deserves some remarks (Fig. 5).

First, because the available number of pbars was uncertain, it was decided to configure the Main Ring RF so that a pilot pulse of protons could be used to run the low level RF frequency feedback loops and any use of feedback from pbar signals could be eliminated. In order to do this the Main Ring RF cavities were configured in two groups; one to accelerate the protons and one to accelerate the pbars, similar to what is done in the Tevatron. Antiprotons followed by protons were then injected at 8 GeV while the RF was locked to a fixed frequency, feedback from protons was then turned on and the beams accelerated. At transition there was no phase feedback on the antiprotons and a number of them were lost. In a couple of more days this problem could have been rectified. With more antiprotons available this mode of acceleration will not be used.

Second, the RF cavity paraphasing for bunch coalescence relies on precise cancelation of vector voltages independently from two sets of proton and pbar cavities to the order of a fraction of a percent in amplitude and a fraction of a degree in phase. Dead reckoning this sensitive alignment is not possible to the accuracy required without beam for the final adjustment. Here again there was not sufficient time with pbars. Unfortunately protons can not be used for this procedure because of their different direction through the cavities. Thus, the lack of efficient coalescence lead to a description of the antiproton longitudinal phase space emittance without increasing the bunch intensity.

The other major factor in Table IV is the proton coalescing efficiency which unlike the pbars had been carefully tuned but still remained inefficient. Bunch coalescing has been recognized as the most unsuccessful of the operations needed in the Main Ring or TeV for Collider operation. The design calls for bunch intensities of 6×10^{10} after coalescings. Maximum intensities obtained were $\sim4\times10^{10}$ with considerable momentum spread, and satellite bunches typically of the order of 1/3 the intensity of the main bunch, and a loss of up to half of the total particles that were being coalesced. Not only is this inefficient but the bunch length during collisions is longer than desirable for the experiments, and the large momentum spread produces a transverse mismatch and dilution upon transfer into the Tevatron because of the vertical dispersion in the Main Ring which is not matched in the Tevatron.

Two possible causes for the difficulties in coalescence have been addressed during the present shutdown. First, during the RF paraphasing process when the beam is debunched it is possible that micro-wave instability could be blowing up the momentum spread. Microwave signals have been seen during the coalescing process, and estimates of the vacuum chamber impedance also indicate the possibility of longitudinal instabilities. A large fraction of the chamber impedance comes from the transition joints at the ends of the magnets, and sleeve inserts have now been installed at the 1000 or so locations around the ring.

The other probable cause for inefficient coalescing is the lack of precise control of the RF sum voltage during the paraphase procedure. To rectify this during the next run, the final paraphasing will be done with two cavities and the rest will be turned off. In addition, more 2.5 and 5 MHz RF for bunch rotation has been added to make the capture back into the 53 MHz bucket more efficient.

Another difficulty encountered in the Main Ring, which does not show in Table IV, but was very evident during the commissioning, was a beam instability that occurred during the cogging operation. Presumably this was a head tail instability aggravated by the fact that the chromaticity could not be tuned near positive zero for all radial positions that were encountered on a statistical pulse-to-pulse basis during the cogging or azimuthal rotation of the beam. This will be corrected with stronger sextupole circuits.

A summary of Tevatron proton stored beam measurements is given in Table V. This is compiled from the studies[13] with the proton beam alone and indicates adequate lifetimes and growth rates at low bunch intensity. The transverse emittance varied tremendously from store to store and probably reflected dilution from coherent oscillation as well as mismatches at transfer to the Tevatron.

A number of studies of the Tevatron beam admittance, sensitivity to operating point, x-y coupling and nonlinear fields were made, as well as measurements of the β function at specific locations. These measurements[12,13] will not be discussed here except to mention that the chromaticity ($\Delta\nu=\xi\Delta p/p$) at injection was found to be 40 units different from expected. This could be explained by a time dependent change in the superconducting dipoles of about 1 unit of b_2 (sextupole field$\times10^4$ of dipole field at one inch). Since then this order of change has been measured by magnetic measurement in the dipoles, but as yet a consistent explanation of the exact cause has not been found.

Present Status

Turn on and recommissioning of the Accelerator complex is under way at this time. The Main Ring must be recommissioned with both the B0 and DØ overpasses as well as a new injection line from the Booster, and after extensive vacuum work to insert the impedance vacuum sleeves. A number of components have been changed in the Tevatron in an attempt to replace magnets with low quench currents, voltage to ground breakdown or vacuum leaks. It is hoped that the Tevatron will run at 900 GeV during the next year. The Collider test run is expected to start in December and during that time severe demands will be put on the reliability of the whole complex. It is hoped that by the end of the run in March 1987 that antiproton production rates of 1.5×10^{10}/hr and peak luminosities of 10^{29} $cm^{-2}sec^{-1}$ can be achieved.

III. LONG RANGE UPGRADE PROGRAM

In order to maintain a vital long range colliding beam physics program, it is necessary that the luminosity increase significantly each running period so that effectively higher energy constituent collisions can be explored. A rule of thumb adopted by the physics community is that with each yearly run the cumulative integrated luminosity should double in order that new physics potential can be effectively explored. It seems probable that the Fermilab Collider luminosity will reach saturation in 1990-1991 without a substantial upgrade to be completed by 1992. Intermediate steps, such as the low-β quad design and a Linac energy upgrade, should benefit Collider and fixed target physics on a shorter time scale.

The upgrade program presently under evaluation has three goals.

a) Luminosity to 5×10^{31} $cm^{-2}sec^{-1}$.
b) Pbar production rates to 4×10^{11} pbar/hr.
c) Intensity increase for fixed target operation.

All areas of the accelerator are impacted. The injector and main ring are being analyzed to determine an appropriate emittance improvement program. The pbar source is being evaluated to determine the optimum plan for pbar production, and the feasibility of many bunch operation in the Tevatron is being evaluated in order to reach the luminosity goal.

The Injector and Main Ring Upgrade

The injector and Main Ring upgrade program is focused on improvement of the beam quality, i.e. lower emittance for present intensities, and increased intensity for presently obtained emittances. These goals should help both fixed target and collider operation.

The Booster Space Charge Limit. It is believed that the transverse beam emittance is set by the space charge tune spread limit in the Booster at the start of acceleration after the beam has been bunched. The tune spread for a given bunch intensity divided by normalized emittance can be reduced by increasing the beam energy or decreasing the accelerator radius. After some consideration, it has been decided to pursue an upgrade of the energy of the linac rather than the construction of an additional prebooster ring. A prebooster at say 1/3 the radius of the booster would require three times the length of time to fill the main ring and add one more accelerator in an already complicated chain. A linac upgrade, especially if it can be done in stages, can benefit the program over a relatively short time period and in the long run lead to the total replacement of dated equipment.

The Linac Upgrade can proceed in stages. Most important is the initial step of replacing the last half of the 200 MHz Alvarez accelerating tanks with 800 MHz side-coupled structures for an increase in kinetic energy from 200 MeV to about 420 MeV. This change can be done in the existing building and without extensive modification to the injection line to the Booster. Sections of the side-coupled structure can be installed during normal maintenance and development periods with a somewhat longer period (six weeks) for the final conversion. A change in $\beta\gamma^2$ from 0.833 to 1.516 would predict an increase in N/ε_n of 1.8 based on tune shift depression due to space charge.

The second step would call for replacement of the preaccelerator with an RFQ and the replacement of the lower energy 200 MHz tanks and RF power supplies with a 400 MHz system and an improved RF power source. The higher gradients achievable with the 400 MHz system would allow the side-coupled structure to be moved upstream. Additional side-coupled cavities could then be added to make a 600 MeV linac of about the same length as the present 200 MeV linac. The transverse emittance would be 3π normalized (90%), or about one half the present value. This step would require considerable rework of the booster injection line.

The Main Ring. As extensive modification of the Main Ring has just been completed and as yet there is no operating experience, any discussion of possible Main Ring or Booster upgrade programs will be deferred at this time. The issue here is whether a smaller radius Main Ring with higher injection fields could substantially improve the overall performance. Such a proposal must be weighted against issues such as filling times for the Tevatron and targeting rep rates for $\bar{p}$ production. An alternative might be a fast cycling post Booster to inject into the present Main Ring above transition.

The Pbar Source Upgrade. The Pbar Source upgrade program has a goal of increasing the production rate by a factor of four from 1×10^{11}/hr to 4×10^{11}/hr. In order to achieve this the source targeting cycle rate would be increased a factor of 2 to 1 Hz average, and the number of pbar's entering the debuncher would also have to be increased a factor of two.

Main Ring rep rate improvements can be achieved by multiple Booster batch acceleration and single batch extraction to the pbar production target. If six batches were accelerated together and extracted on flattop every 0.7 sec, an average of 1 Hz could be obtained.

The Pbar Production Target and Lithium Lens. At the pbar production target higher yields can be obtained if either the proton beam size is reduced or the beam current increased. In both cases the peak energy density will increase beyond allowable limits unless the beam is swept across the target such that the peak energy density is no larger than the current rate. While such an approach is in principle feasible, it is technically quite difficult. If pbar's can be recovered from the Tevatron and recooled in a recovery ring, this might be a way of supplementing the $\bar{p}$ production. If 50% of the pbar's can be recovered and recooled, there would be no need to demand more from the target system aside from the higher repetition rate.

The lithium lens cycle time can be increased from 0.5 Hz to 1.4 Hz without reduced efficiency if the lens radius, R_o, is reduced while the gradient is increased such that magnetic field at R_o is unchanged.

Cooling Systems. Cooling times in both the Debuncher and Accumulator will be reduced by the development of higher bandwidth systems (4-8 GHz or 8-16 GHz instead of 1-2 or 2-4 GHz). In addition, cooling power requirements in the Debuncher and Accumulator can be reduced by changing the gap of the pickups and kickers as the transverse beam emittance shrinks.

In the Debuncher the transverse cooling rate can also be increased by increasing $\eta=1/\gamma_t^2-1/\gamma^2$. This can be accomplished with a γ_t jump scheme that would preserve η and the RF voltage requirement at injection time. An η increase of 1.5 times seems possible.

In the Accumulator $\eta\Delta p/p$ must be reduced by a factor of 4 so that Schottky bands at the revolution harmonic cannot overlap in the bandwidth of the cooling system, since the bandwidth must increase by four to accommodate the faster stacking rate. Here η can be reduced a factor of 2 by using different gradients in the lattice quadrupoles. Reduction of $\Delta p/p$ of the stack by a factor of 2 is feasible although it will require precooling of the injected beam.

Accumulation rates of 4×10^{11}/hr will build up to the design instability threshold of 10^{12} particles in about two hours. Thus fills should be transferred from the accumulator to the Tevatron (or a high quality storage ring) at about this time interval. It is planned that the beam will be unstacked and extracted in two loads of 12 bunches spaced at the 7th subharmonic of 53 MHz. Each bunch will contain 3×10^{10} particles or a total of 0.7×10^{12} particles per fill. A fill sequence will take place once every two hours and consists of replacing all of the protons and 1/6 of the antiprotons.

The Tevatron Collider Upgrade

The Collider upgrade has a goal of 5×10^{31} $cm^{-2}sec^{-1}$ luminosity. Table VI lists the tentative parameters. The main features of the design are as follows:

Low-β^* of 1/2 meter or less. High gradient 20 kG/cm quadrupoles will be designed with a 3-inch inside diameter. Research on NbTi superconductor with ternary tantalum (Ta) will be developed. The quadrupoles will be designed to operate at 2K with a fall back to 14 kG/cm at 4.2K. The appropriate cryostat and refrigeration system must be developed. If β^* of less than 1/2m can be obtained this will reduce requirements on pbar production.

Separators. Electrostatic separators, on either side of each IR, must be used to reduce the number of collision points and the head on beam-beam tune shift. The separators might be placed in the region of the low-β quads, but even so there will be three collisions at each IR region, one at β^* and two adjacent satellites. Separation will be in both planes producing a "Double Helix" of counter-rotating beams spiraling about one another. The long range beam-beam tune shift and multipole fields produced by the Coulomb field must be evaluated.

TABLE VI UPGRADE PROGRAM

N_p	5×10^{10}
$N_{\bar{p}}$	$2\ 1/2\times10^{10}$
ϵ_T^p (95%)	$12\pi\times10^{-6}$m with growth to 20π
ϵ_L	0.5-1.0 eV-s with growth to 3 eV sec
σ	20-30 cm with growth to 60 cm
Bunches B	144
β^*	1/2-1/4 m
$\mathcal{L}$/hit (10^{25})	1 max reduction with growth
(10^{30})	68 max reduction with growth
Design goal (10^{30})	50
Bunch spacing	132 ns
Harmonic number	1113/7=159
BNp (10^{13})	0.7
BNpbars (10^{13})	0.35
$\bar{p}$ Accumulation rate	4×10^{11}/hr
p Accumulation time to refill	10 hr minimum
Accumulator intensity	10^{12} max
Fill interval	~2 hr (24 pbar bunches)
Beam-beam tune shift head on	0.018 3 crossings per IR

Intra-beam Scattering growth times will be important. The bunch length growth especially is expected to be rapid. One feature of the parameters chosen is the unequal proton and antiproton bunch intensities and the plan that all protons will be replaced every fill cycle (~2 hours), whereas pbars must last for six cycles. Thus, though protons are twice as intense they should suffer less degradation. The potential of a pbar recovery ring or bunch beam cooling will be evaluated.

Summary

At this time the upgrade program is in its infancy. Feasibility studies and real design work is yet to begin. Cost benefit evaluations as well as technical difficulty will be important in determining which options are pursued. For the present the first priority must be the recommissioning and increasing of the luminosity by the factor of 10^6 to reach the present TeV I design goal.

The Antiproton Source and Collider commissioning time last year was a most exciting, if exhausting, experience. The enthusiasm and expertise of all of the Antiproton Source Department and Accelerator Division personnel, as well as the CDF experiments, was most impressive. A paper like this can only reflect the ideas, work, and accomplishments of the whole team and in no way should be construed to be a personal effort. In particular, material for this paper was obtained from G.Dugan, J.McCarthy, J.Peoples, J.Marriner, R.Johnson, D.Finley, P.Martin and D.Edwards.

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TABLE II PBAR PRODUCTION MISSING FACTORS AND GOALS

		Design	Oct 85	Missing Factor Stages+	Goal Winter 86-87	Missing Factor+
1)	MR Intensity	2E12	1E12	2/2	1.5E12	1.33/1.33
2)	Flux of p to 1Q728 4.8% Δp/p 55×30πx10⁻⁶m	(22E7	3.8E7	3/6)	8E7	
	Flux of p to 1Q728 into 20πx10⁻⁶m	7E7	2.3E7	1.5/3	5E7	1/1.33
3)	$\bar{p}$ Captured in Debuncher	7E7	3.5E6	7/20	4E7	1.33/1.77
4)	$\bar{p}$ in Debuncher After Transverse Cooling	7E7	3.1E6	1.13/22		
5)	$\bar{p}$ to Accumulator on Inject Orbit	7E7	3E6	1.04/23	3E7	1.33/2.35
6)	$\bar{p}$ Decelerated to Stack Tail	7E7	1.7E6	1.8/41	2.4E7	1.25/2.9
7)	$\bar{p}$ Cooled into Core in Accumulator	6E7	1E6	1.35/60	1.2E7	1.67**/4.9
8)	Number Target cyc/hr	1800 (2 sec cyc)	720 (5 sec)	2.5/150	1200* (3 sec cyc)	1.5/7.3
	Total $\bar{p}$/hr	11E10/hr	0.7E9/hr		1.5E10/hr	
	Total p	5E11	1 E10		10E10	

+Individual/Cumulative
*More if multiple target per MR cycle.
**Depends on cycle time and intensity

TABLE IV TEV COLLIDER HISTORY AND GOALS

	Design	Oct 85	Approximate Factor	Goals Winter 86-87
Pbar Extracted from Accumulator/Bunch		~E9	60	2.7E10
Pbar MR Transmission		0.1	10	3/4
Pbar Coalescing Efficiency		~0.15	6	1/2
Pbar Transmission from MR to TeV 800 GeV		1/2	2	1
P Coalescing Efficiency		0.2-0.4	3	1/2
P Stored/Bunch	6E10	2E10	3	4E10
Pbar Stored/Bunch	6E10	Few E6	~E4	1E10
Number of Bunches	3×3	1×1	3	3×3
Transverse Emittance 95% Normalized (π×10⁻⁶m)	24	15-50	1.4	24
Bunch Length Luminosity Reduction		0.8	1.2	0.9
Luminosity	E30	Few E24	Few E5	E29
Pbar Accumulation Rate	11×E10/hr	E9/hr		1.5×E10/hr
Average Minimum Storage Time Required from Pbar Production Rate	2 hr			5-6 hr

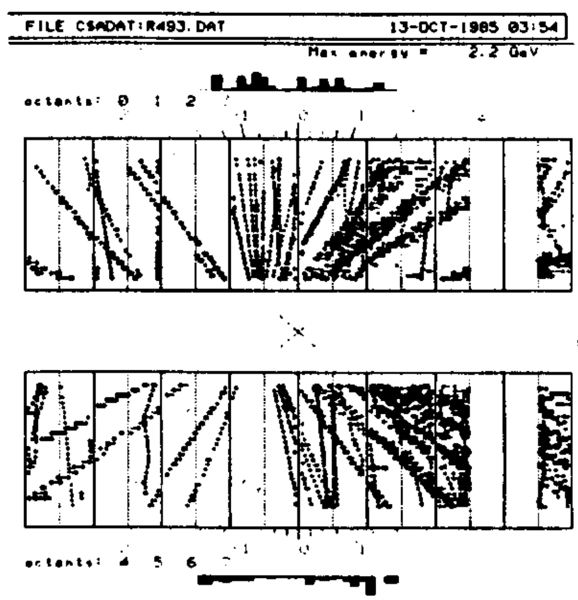

Figure 1 BØ Colliding Detector event.

TABLE V TEV PROTON STORAGE DATA

	150 GEV	800 GEV	LOW-BETA	DESIGN
Bunch Lifetime	2.6 hr (2E10)		>70 hr (0.7E10)	
Total Current Lifetime	>6 hr			
Bunch Intensity	4E10 max	2E10 Typical		6E10
Bunch Length (FWHM)			5 ns (2E10)	3 ns
Longitudinal Growth σ_p/p			5% hr	2%
Vertical Emittance Growth	<6%/hr	<12%/hr	<2.3%/hr	5%
Horizntl Emittance Growth			<10%/hr (2π/hr)	5%
E_N (10^{-6}) Horizontal			30-60π	24π
(95%) Vertical			15-50π	24π

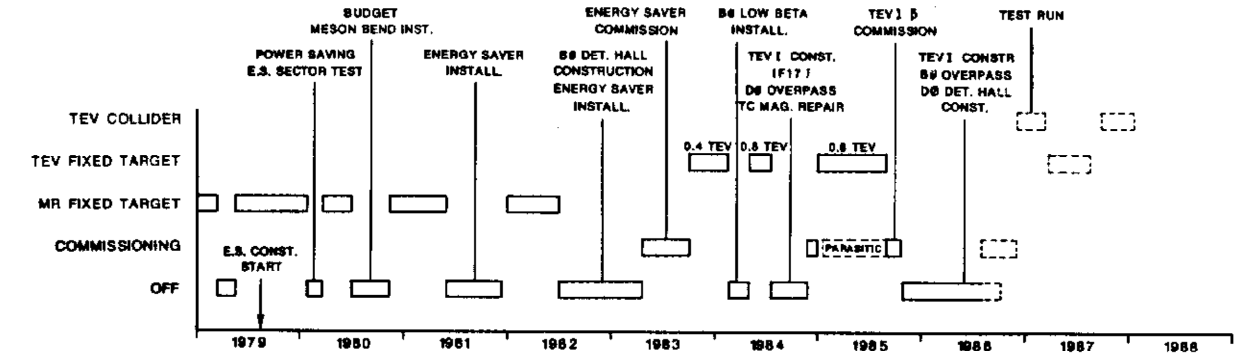

Figure 2 Operations activity showing construction and commissioning time for the Tevatron.

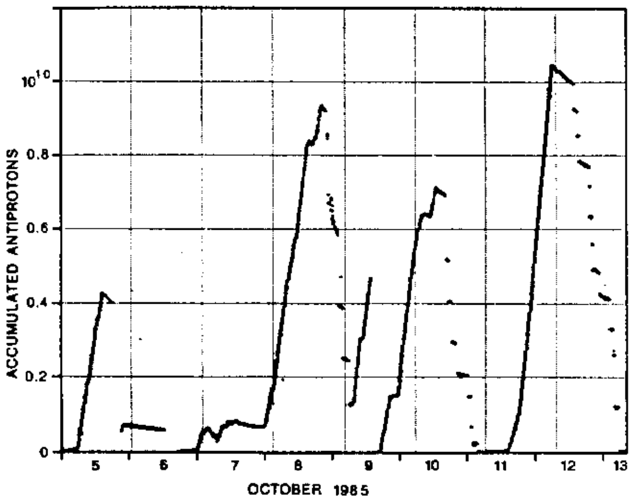

Figure 4 Antiprotons in the Accumulator showing accumulation rate and shots extracted for Collider commissioning.

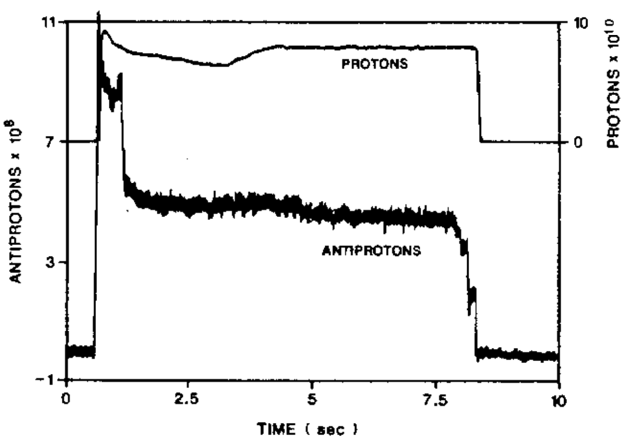

Figure 5 Simultaneous acceleration of protons and antiprotons in the Main Ring with loss of antiprotons at transition and coalescence time.

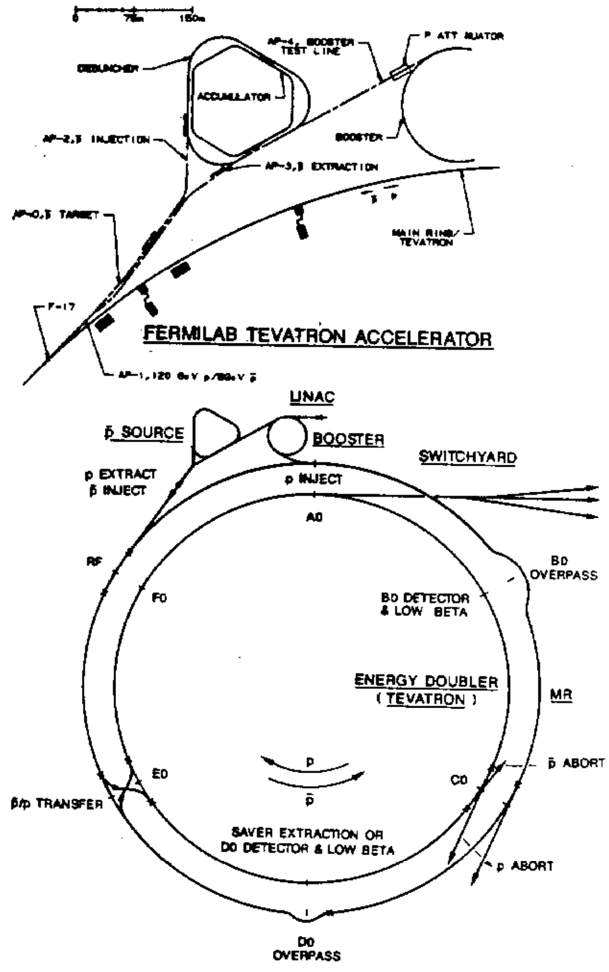

Figure 3. The Fermilab Tevatron and Antiproton Source.