TEVATRON I: ENERGY SAVER AND $\bar{p}$ SOURCE

G. Dugan
Fermilab, P.O. Box 500, Batavia, IL 60510*

Introduction

The aim of the Tevatron I project is the construction of a proton-antiproton collider at Fermilab. The design goals of the collider are a center of mass energy of 2 TeV and a luminosity of greater than $10^{30}/cm^2/sec$. The collider will be utilized by two large experiments located in the long straight sections B0 (the CDF detector) and D0; and by three specialized experiments at C0, E0 and F0. The first operation for colliding beam physics is scheduled for 1986.

The Tevatron I project encompasses a host of accelerator systems in the Main Ring and Energy Saver, as well as the Antiproton Source, which is the complex in which the $\bar{p}$'s are made, collected and stored. At the time of this writing, the construction and installation phases of the project are essentially complete, and the commissioning phase has recently begun. In this report, no attempt will be made to discuss the design of each subsystem, since this information has been extensively documented elsewhere[1,2,3]. A brief overview of the project will be presented for orientation; then, the present status of each system will be reported, in the order in which they will be required to operate for colliding beams. At the conclusion, the goals for completion of the commissioning of the project will be discussed.

Overview of Tevatron I

To produce antiprotons, once every 2 seconds a booster batch of $2x10^{12}$ protons is accelerated to 120 GeV in the Main Ring, extracted at the F17 medium straight section, transported to the Antiproton Source target station and focussed to a σ=0.4 mm spot on a production target. The extracted beam consists of 82 53 MHz bunches, each of whose time spread has been narrowed to 0.7 nsec by RF manipulations at flattop in the Main Ring. 8 GeV antiprotons are produced at the target, focussed by a lithium lens and transported along a secondary beam line to the Debuncher. The transverse emittance of the secondary beam injected into the Debuncher is 20π mm-mrad, with a momentum spread of 3%; this corresponds to about $7x10^7$ $\bar{p}$'s. The Debuncher is an 8 GeV storage ring of circumference 503 m. In this ring, the beam is debunched, exchanging the narrow time spread of the injected $\bar{p}$'s for a reduced momentum spread (0.2%); it is also stochastically cooled for 2 sec, reducing its transverse emittance to 7π mm-mrad. After 2 sec, the beam is extracted to the Accumulator, and the next $\bar{p}$ pulse enters the Debuncher. The Accumulator is also an 8 GeV storage ring, of circumference 474 m. In this ring, a system of 4 stochastic cooling systems (two transverse and two longitudinal) allow the longitudinal density of the beam to be increased by two orders of magnitude (to 10^5/ev), and the transverse emittance to be decreased to 2π mm-mrad, over a period of 4 hrs. During this time, $4.3x10^{11}$ $\bar{p}$'s are accumulated in the "core".

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To start colliding beam operations, $.6x10^{11}$ $\bar{p}$'s are displaced by an RF system from the core to an extraction orbit, bunched, and extracted from the Accumulator using a shuttered kicker. The $\bar{p}$ beam is transported to and injected into the Main Ring at F17, and accelerated to 150 GeV. At flat top, the 13 bunches are coalesced into a single bunch with a longitudinal emittance of 2.4 ev-sec. Previously, three proton bunches of similar emittance have been prepared in a similar way and injected into the Energy Saver. The $\bar{p}$ bunch in the Main Ring is synchronized with the proton bunches in the Energy Saver and injected. The above procedure of extracting a $\bar{p}$ bunch from the Accumulator and delivering it to the Energy Saver is repeated twice more, to get three $\bar{p}$ bunches with a total of $1.8x10^{11}$ $\bar{p}$'s. The assembly of 6 bunches is then accelerated to 1 TeV, and the collision point adjusted appropriately. The low beta quads are energized to bring beta down to 1 m at the intersection region, and colliding beam experiments can begin.

Main Ring Systems for $\bar{p}$ production

During the summer shutdown last year, an overpass[4] was installed in the Main Ring at D0. This is one of two overpasses required to be able to operate the Main Ring for $\bar{p}$ production simultaneously with colliding beam experiments in the Tevatron. The overpass was commissioned successfully last year, making the Main Ring the world's first non-planar synchrotron. Since the startup of HEP in January of this year, the Main Ring has operated simultaneously as an injector to the Tevatron for the fixed target physics program, and as a source of beam for parasitic accelerator studies of the systems which will be required for colliding beam operations.

The parasitic studies associated with $\bar{p}$ production have been aimed at 3 goals:

1. Main Ring studies of the operating mode required for $\bar{p}$ production: a Main Ring ramp with a 2 sec cycle time and a 120 GeV flat-top.

2. The commissioning of the 53 MHz bunch narrowing system.

3. The commissioning of the F17 extraction/injection system.

The Main Ring has been run with a 120 Gev flat-top with no significant problems. The minimum cycle time achieved to date has been 3.5 sec; further reductions have been limited by power supply regulation problems which are expected to be solved in the near future.

The bunch narrowing procedure in the Main Ring[5] involves reducing the size of the RF bucket by counterphasing two RF cavities, until the bunches have a small momentum spread; then the RF voltage is abruptly raised to a large value (> 3 MV), creating a large bucket in which the mismatched bunch rotates. After one-quarter of a synchrotron oscillation, when

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the time spread of the bunch is least, the beam is extracted at F17 for $\bar{p}$ production. Commissioning of this system is well underway; the time spreads achieved to date are typically 0.5 nsec (FWHM). Figure 1 presents recent data showing bunch narrowing, followed by extraction at F17.

The F17 extraction/injection system was installed in the Main Ring during January of this year and commissioned by the middle of February[6]. It consists of a kicker at E17 (used for 120 GeV proton extraction), a kicker at E48 (used for 8 GeV $\bar{p}$ injection), and an extraction channel (two Lambertsons and two C-magnets) at F17.

Figure 3 presents a single turn measurement of the last turn before extraction of the 120 GeV beam in the Main Ring. Although the figure corresponds to beam with normal bunches, bunch-narrowed 120 GeV beam, with a momentum spread of ± .15%, has also been extracted with no measurable losses. The 8 GeV $\bar{p}$ injection system has been successfully commissioned, by using it to extract 8 GeV protons in the reverse direction from the Main Ring. As will be discussed below, this mode of operation has been very useful in providing a low emittance 8 GeV beam for commissioning of the beam lines and rings of the Antiproton Source.

Antiproton Source

Fig. 2 is a layout of the Antiproton Source, showing the beam lines which connect the rings to the Target Station and the Main Ring.

Beam Lines (AP-1, AP-2, AP-3, D to A) and the Target Station

The AP-1 beam line[7] transports the 120 GeV proton beam to the target station, and focuses it to a small spot on the target. It consists of 10 dipoles and 14 quadrupoles, extending over a length of about 152 m. Together with AP-3[8], it also transports cool $\bar{p}$'s from the Accumulator back to the Main Ring for injection at F17. This beam line, together with its terminus (the Target Station[9] beam dump), was installed during December and January, and commissioned during February and March. Fig. 4 shows the beam profile of the focussed 120 GeV beam at the target, as measured by a high-resolution secondary emission monitor.

The AP-2 beam line[8] transports the $\bar{p}$'s from the production target to the Debuncher. The first elements in this line are part of the Target Station[9]: the lithium lens[10] and a pulsed 3° dipole. This beam line, consisting of 8 dipoles and 33 quadrupoles, and extending a distance of 262 m., was installed during February and March. For commissioning, the target and lithium lens have been removed, and the polarity of the line reversed; 8 Gev protons, transported from the Main Ring along AP-1, were used to study the line. Beam was transported successfully to the Debuncher, with the beam line lattice functions roughly as expected.

The AP-3[8] line, which transports $\bar{p}$'s from the Accumulator to the matching point with AP-1, consists of 9 dipoles and 30 quadrupoles. It has just recently been installed, and its commissioning (with 8 GeV protons) is in the early stages. To date, beam has been transported most of the way to the Accumulator, to a temporary beam stop located near the Accumulator extraction point. Studies of the beam line characteristics are underway.

Also in the earliest stages of commissioning are the principal components of the $\bar{p}$ production system, the target[9] and lithium lens[10]. During the last week of April, beam was targetted for the first time and the lithium lens was used to focus the secondaries into AP-2; measurements of the secondary yields collected into AP-2 were made using an RF intensity monitor located about 150 m. from the target station. A Cerenkov counter was also used to measure the $\pi/\bar{p}$ ratio. With the lithium lens at 300 kA, a yield of roughly 3×10^{-5} $\bar{p}$/p was measured, with a momentum bite of 6%. This is consistent with yield calculations[11] for 8 GeV $\bar{p}$'s.

Debuncher Ring

The Debuncher ring[12] consists of 66 dipoles and 114 quadrupoles, with 138 sextupoles and 28 trims. There are three RF systems in the ring: 53 MHz for debunching[13] and two h=4 systems: broad-band for gap preservation[14] and narrow band for diagnostic purposes. There is also a transverse stochastic cooling system[15], composed of 128 pickup and kicker pairs, operating in the 2 to 4 GHz frequency range. For noise reduction, the pickup preamps and terminating resistors are cooled to liquid nitrogen temperature. The kickers are driven by 16 TWT's. This system will be installed in early May.

The beam diagnostics include a BPM system[16] capable of both single and multiple turn measurements, Schottky pickups and DC beam current monitors. Injection and extraction are done utilizing fast kickers[17] and current septa[18].

The construction of the guide field magnets for the Debuncher (and for the Accumulator and the beam lines) was carried out at the Fermilab Magnet Factory over the last two years. The installation of all the major components of the ring (except for the stochastic cooling system) was complete by mid-April, and commissioning was begun using 8 GeV protons transported along AP-1 and AP-2. During the second week in April, 8 GeV beam was successfuly injected into the Debuncher. Fig. 5 shows the first turn in the Debuncher, as measured by the BPM system. Coasting beam was established in the machine shortly thereafter; to establish a bunch structure, the beam was captured using the narrow band h=4 system. Figure 6 shows the closed orbit after several seconds. The quad busses were adjusted to acheive tunes of about 9.75 in each plane. After the sextupole families were energized, the tune spread was measured to be less than .002, for a momentum spread of about .1%. The momentum aperture (without the stochastic cooling system in) was measured to be 6% for injected beam, and 4.7% for circulating beam. The circulating beam lifetime (1/e) was measured to be 83 minutes.

Accumulator Ring

The Accumulator ring[19] contains 28 dipoles, 78 quadrupoles, 24 sextupoles and 30 trims. As for the Debuncher, the magnets were fabricated at the Fermilab Magnet Factory. The nature of the Accumulator as a large aperture storage ring imposes stringent field quality requirements on the magnets: fig. 7 illustrates the field quality of a typical Accumulator large dipole.

The Accumulator features shuttered injection and extraction kickers[17], and three RF systems: 2 h=2 systems for capturing the core for extraction[21] and a 53 MHz (h=84) system for injection stacking[20] and bunching prior to extraction. There are four stochastic cooling systems: stack-tail[22] momentum and betatron, and core momentum and betatron. The stack-tail systems operate at 1-2 GHz; the momentum system uses 172 pickup pairs with cooled preamps and 160 kicker pairs driven by 40 TWT's. The betatron system uses 64 pickup and kicker pairs. The core systems (both momentum and betatron) operate at 2-4 GHz, using 80 pickup pairs and 48 kicker pairs. The diagnostic systems are similar to those of the Debuncher.

The installation of all the major components of the Accumulator was completed during April, including the stochastic cooling systems. Initial commissioning of the ring, to establish closed orbits and circulating beam using 8 GeV protons from AP-3, is planned for May. Shortly thereafter, tune, chromaticity and dispersion measurements will be made, as a preliminary to the commissioning of the stochastic cooling system.

Main Ring and Energy Saver Systems for Colliding Beams

The ability to coalesce 10-15 bunches in the Main Ring into a single bunch, both for protons and antiprotons, is required for colliding beam[21,23] operations. This coalescence is done by reducing the size of the 53 MHz buckets slowly, thus increasing the length of the bunches until they nearly overlap; then, the bunches are captured in a single 2.6 MHz bucket created by special RF cavities in the Main Ring. The bunches (now essentially a continuous distribution) are allowed to rotate in an enlarged h=53 bucket through 1/4 of a synchrotron oscillation; at this point, the 53 MHz system is turned on to capture the beam in a single h=1113 bucket. All the hardware required for this system has been installed, and preliminary tests of the technique have been carried out using the parasitic study facility mentioned above.

The status of the system required for injection of the $\bar{p}$'s into the Main Ring has been described above. A beam synchronization system has been developed and brought into operation, which will allow control of the RF bucket into which the beam is injected, both in the Main Ring and the Tevatron. This system is required in order to be able to control the azimuthal locations of the three $\bar{p}$ (or p) bunches relative to one another. Additional systems, both in the Main Ring and the Tevatron, are required to control the azimuthal locations of $\bar{p}$ bunches relative to p bunches. Both of these systems are currently under development.

To transfer the $\bar{p}$'s from the Main Ring to the Tevatron, a reverse injection system is required[24]. The system was installed during April; it consists of an extraction/injection channel at E0 (two Lambertsons in the Main Ring and two in the Tevatron, connected by a short vertical transfer line), a kicker at E17 in the Main Ring and a kicker at D48 in the Tevatron. The reverse injection system will be commissioned during May, by extracting protons from the Tevatron to the Main Ring through the injection channel.

An antiproton abort system for the Tevatron has also been designed and partially fabricated. Three abort kickers at C17 will kick the $\bar{p}$'s into a beam dump at C0. This system will be installed when required.

The final major systems required for colliding beam operations are the low beta quads at B0 and D0. The low beta system at B0[25] was installed during the early part of last year. Additionally, of course, the Tevatron has to operate as a storage ring. The operation of the Tevatron as a storage ring, together with the operation of the low beta system[26], has been the subject of a number of dedicated studies periods over the last year.

These studies have been quite successful. The B0 low beta system has achieved a $\beta^*=1$ m at 800 GeV (the present Tevatron operating energy). Fig. 8 is a meaurement of the beam profile at B0 during the low beta squeeze. Proton storage periods of as long as 4 hrs have been achieved with the low beta system on. Gradually, the reliability of the Tevatron as a storage ring has been improved. Measurements of tunes and chromaticities and the influence of the low beta system, have been made. Emittance growth and dynamic apertures for the stored beam have been measured. The chromaticity of the Tevatron with the low beta system on has been measured to be -5 units higher than expected.

Future Commissioning and Operations Goals

An ambitious commissioning schedule has been adopted. Commissioning of the Accumulator has just started; the aim is to complete the commissioning of all systems except stochastic cooling by the end of May. During June, the stochastic cooling systems would be commissioned, with the goal of a stored and cooled $\bar{p}$ beam in the Accumulator by July. Subsequently, the first attempts to bring these $\bar{p}$'s to the Main Ring and Energy Saver will be made. If this is successful, $\bar{p}p$ collisions may be achieved in the Energy Saver in late summer. In this event, some components of the CDF detector will be installed at B0 and attempts made to observe $\bar{p}p$ collisions at 1.6 TeV in the center of mass.

This initial operation will undoubtedly be at a much reduced luminosity from the design goal. Nevertheless, by 1986, when the first official colliding beam runs are scheduled, it is expected that Tevatron I will acheive its design goals.

Acknowledgements

The work discussed in this paper represents the dedication and effort of hundreds of people in the Fermilab Tevatron I Section and the Accelerator Division, as well as collaborators from Argonne, Lawrence Berkeley Laboratory, INP at Novosibirsk and the University of Wisconsin.

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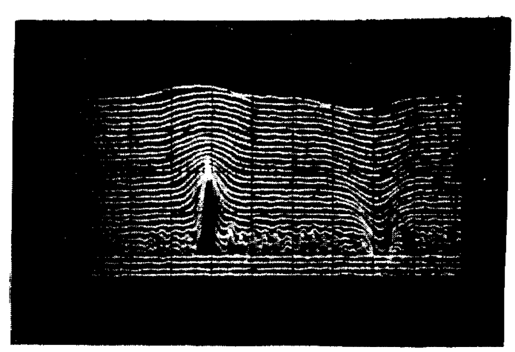

Figure 1. Bunch narrowing of 120 GeV beam in the Main Ring, followed by extraction at F17. Each trace corresponds to a successive turn; horizontal scale is 2 nsec/cm. Bunch intensity was 10^9 protons/bunch.

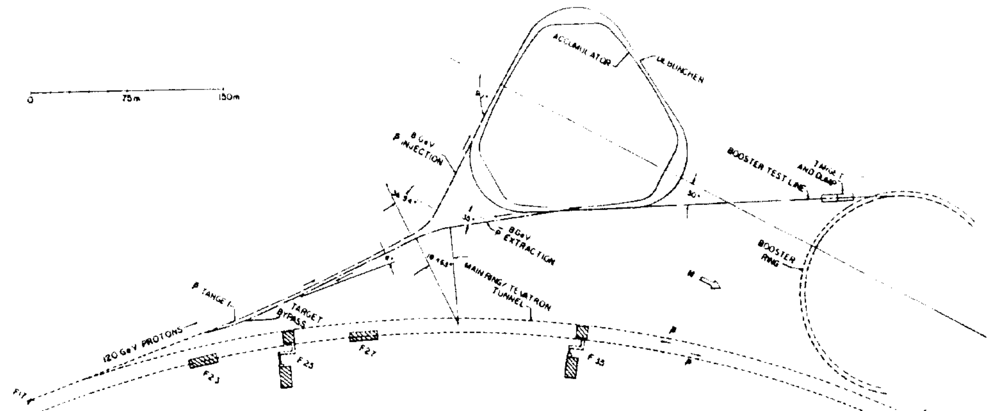

Figure 2. Layout of the Antiproton Source.

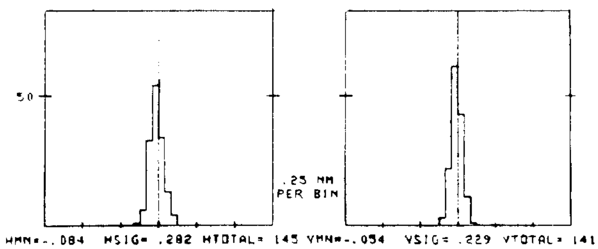

Figure 4. Beam profile of 120 GeV beam at the $\bar{p}$ production target. Resolution of the secondary emission monitor is 0.25 mm; beam intensity was ~10^{11}/pulse.

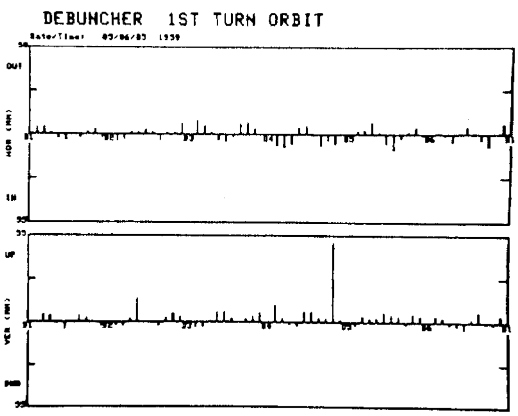

Figure 5. Debuncher BPM measurement of the first turn in the Debuncher; injection is in the vertical plane, just upstream of D5.

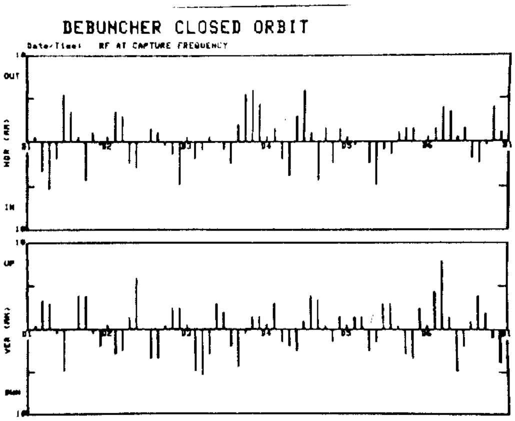

Figure 6. Debuncher closed orbit after RF capture by the h=4 system.

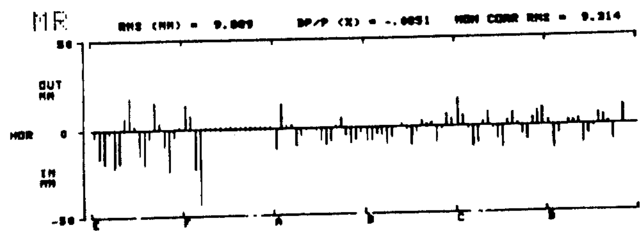

Figure 3. 120 GeV Main Ring horizontal BPM measurement of the last turn before extraction at F17. Kicker is at E17; orbit distortion between E12 and F14 limits excursions in this area.

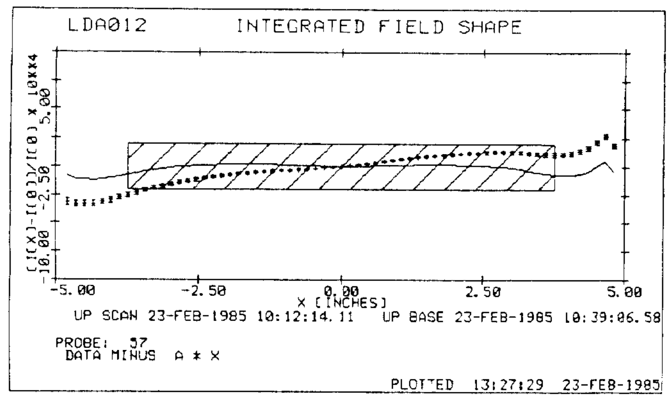

Figure 7. Field measurement of a typical Accumulator large dipole.

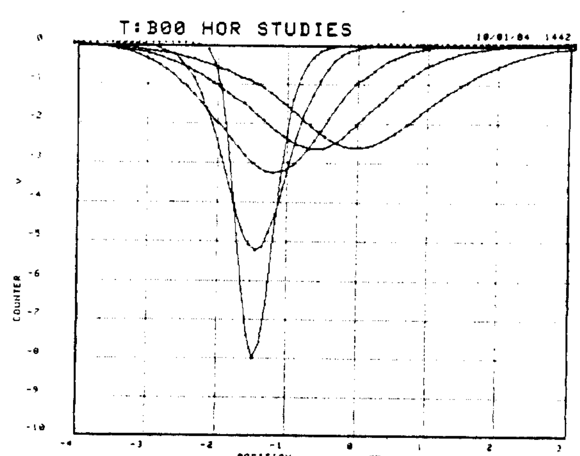

Figure 8. Flying wire scanner measurements of the horizontal profile at B0 at various points during the low beta squeeze. The centroid shifts are due to closed orbit changes caused by steering of the low beta quads.