THE FERMILAB $\bar{p}p$ COLLIDER

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Introduction

1983 saw the start of construction on the Fermilab $\bar{p}p$ collider, the Tevatron I project, as well as the commissioning of the new superconducting accelerator, the Tevatron, for high energy fixed target physics. The goal of the Tevatron I project is to achieve $\bar{p}p$ collisions in the centre-of-mass energy range up to 2 TeV with a luminosity of at least $10^{30}\text{cm}^{-2}\text{sec}^{-1}$. The project involves adapting the Tevatron to function as a storage ring and modifying the lattice to provide low-beta interaction points; changes to the Main Ring to allow $\bar{p}$ transfers and the installation of experimental equipment; and the construction of a $\bar{p}$ source. Major experimental areas will be located in the so-called B0 and D0 straight sections ~~(detailed descriptions of these areas are presented elsewhere in these proceedings)~~ together with smaller, more specialized experiments in several of the other interacting regions. (Orig./HSI)

The antiproton source consists of a targetting station and two separate rings (the Debuncher and the Accumulator) connected to the Main Ring, the Booster, and each other by various transfer lines (see Figure 1). The Debuncher ring provides a large acceptance for the $\bar{p}$'s produced on the target and precools the $\bar{p}$'s prior to injection into the Accumulator which stores and further cools the $\bar{p}$'s in a similar fashion to the AA ring at CERN. The use of two independent systems for capture and storage allows the design of each one to be optimized on the somewhat conflicting requirements which in turn produces a correspondingly high overall system performance.

In order to achieve a luminosity in the range of $10^{30}\text{cm}^{-2}\text{sec}^{-1}$ the antiproton source must be able to accumulate ~2×10^{11} $\bar{p}$'s within a time comparable to the luminosity lifetime. Head on collisions are obtained in all six straight sections by injecting three bunches of protons and three bunches of counter-rotating antiprotons into the Tevatron. We plan to maximize the luminosity lifetime by using bunches of the same transverse emittance for both protons and antiprotons (24 π mm-mrad invariant) as well as the same intensity to minimize the beam-beam tune shift for a fixed luminosity. With a β^* of 1 m at the interaction point the design luminosity is achieved under these conditions

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with a 6×10^{10} particles per bunch which leads to a linear beam-beam tune shift of 0.0017 per crossing.

It is difficult to make an accurate estimate of the luminosity lifetime which arises from residual beam-gas scattering, intrabeam effects, beam-beam interactions and overall machine stability. Based on operational experience in the SPS amongst other things we have chosen a design specification of 5 hours for the luminosity lifetime. The design of the antiproton source has a predicted accumulation rate of $\sim1\times10^{11}$ $\bar{p}$'s per hour which provides us with a safety margin of approximately 2.5 which hopefully will be sufficient to account for the inevitable operational inefficiencies in such a complex system.

The sequence of events leading to $\bar{p}p$ collisions involves several distinct operations. We shall describe each step in more detail.

Proton Targetting

The production of antiprotons for subsequent storage is accomplished by the acceleration and targetting of protons from the Main Ring. Data from nuclear targets when taken with the energy dependence of the Main Ring cycle time$^{1)}$ exhibit a broad maximum in $\bar{p}$ flux around an incident proton energy of 150 GeV. The desirability of locating the Antiproton Source near the Booster requires the protons to be extracted from the Main Ring at the F17 medium straight section (see Figure 1). This extraction location effectively limits the proton energy to 120 GeV but only reduces the $\bar{p}$ flux slightly. The Main Ring cycle time at 120 GeV is approximately 2 seconds.

Cooling the initial flux of $\bar{p}$'s is made easier if the phase space density at production is optimized. This is accomplished by minimizing the initial proton beam area and time spread. The proton beam area cannot be reduced arbitrarily since the temperature rise in the target is inversely proportional to the beam area for a fixed number of protons. The flux density which heats the target to the melting point defines the practical limit. Calculations show that a pulse of 2×10^{12} protons with an rms radius of 0.6 mm can be safely targetted on a 6 cm long tungsten-rehnium target every 2 seconds.

A single Booster cycle will suffice to produce a batch of 82 53 MHz bunches of protons with an intensity of 2×10^{12}. The normal time spread (several nsec) of the proton bunches will be reduced to 0.6 nsec by bunch rotation in the Main Ring just prior to extraction. This results in a momentum spread of 0.4% for the protons. The circulating beam is extracted in a single turn using a relatively slow rise time kicker magnet (~2 μsecs) located one sector upstream of the extraction channel in the E17 medium straight section.

Antiproton Production and Transport

The narrow bunches of protons produce equally narrow bunches of antiprotons We chose to collect these $\bar{p}$'s at 8.9 GeV/c as this is almost the optimum momentum and it corresponds to the standard Booster energy, which greatly simplifies the re-injection process *and also allows the Booster to be used as a direct* source of protons for reverse operation, for tune-up and commissioning purposes.

The yield of $\bar{p}$'s per incident proton is proportional to the product of the solid angle and the momentum spread accepted by the collection system, hence these quantities should be optimized in an efficient design. We plan to collect $\bar{p}$'s produced in a 60 mrad core using a pulsed lithium lens 2 cm in diameter and 15 cms long producing a peak field gradient of 1000 T/m. Under these conditions we expect to produce $\sim 7\times10^7$ $\bar{p}$pp transported to the Debuncher ring with a momentum spread of 3% and an invariant emittance of 20 π mm-mrad in each plane.

The Debuncher Ring

The primary purpose of the Debuncher is to reduce the large momentum spread of the 8-GeV $\bar{p}$ beam at production to 0.2% prior to injection into the Accumulator. This reduction is accomplished by RF bunch rotation and adiabatic debunching after the $\bar{p}$ beam is injected into stationary 53 MHz buckets. The debunching time is only slightly greater than 10 msec, the remainder of the *2 second cycle is used for betatron cooling* in each plane. The design calls for the reduction of transverse emittance from 20 π to 7 π mm-mrad prior to injection into the Accumulator.

The Debuncher lattice consists of 57 FODO cells with a $\sim 60°$ phase advance per cell, the regular quadrupole spacing is preserved throughout the 3 long straight sections where the RF, beam transfer and stochastic cooling systems are located. The maximum value of the beta function in either plane is ~20 m which keeps the beam size small enough to permit the stochastic cooling pickups and kickers to have a 30 mm aperture suitable for operation in the 2-4 GHz range. The Debuncher ring operates above the transition energy ($\gamma_T = 7.66$) with a natural chromaticity of ~ -10 in each plane. This choice of machine lattice requires an RF voltage of 5 MV for the bunch rotation and debunching. Table 1 lists the major machine parameters.

Table 1. Debuncher Lattice Parameters

Nominal tune $\nu_x = \nu_y$	9.75
γ_T	7.66
Transverse acceptance	20 π mm-mrad
Momentum acceptance	4%
Natural Chromaticity ξ_x, ξ_y	−10.4, −10.6
Maximum Amplitude function β_{max}	20 m

Table 1. (Cont.) Debuncher Lattice Parameters

Maximum Dispersion function η_{max}	2.1 m
R.F. Voltage	5 MV
Machine Circumference	505 m
Superperiodicity	3.

The horizontal and vertical betatron cooling systems consist of 4 modules of pickups and 4 modules of kickers. Each pickup module has 32 pairs of loop couplers with a maximum response at 3 GHz. The signals from each side are added in phase and subtracted from each other to give a final signal proportional to the beam position. Signals from 2 modules are added to each other amplified by 40 db and added to a similar signal generated 180° away in betatron phase. The resultant is further amplified by 40 db and then split and used to drive the 4 kicker modules arranged in a similar fashion to the pick-ups.

With the very low beam intensity in the Debuncher the pickup signal is dominated by thermal noise in the termination resistor and the preamplifier. To optimize the signal-to-noise ratio the pickups and the preamplifiers are cooled to liquid nitrogen temperatures. A schematic layout of the Debuncher and Accumulator cooling systems is shown in Figure 2.

After 2 seconds the beam is transferred from the Debuncher to the Accumulator by a fast kicker magnet and magnetic septa located in the #10 straight section. The injected orbit in the accumulator is displaced in momentum by ~0.9% from the central momentum of the stack core.

The Accumulator

The Accumulator is designed to cool and accumulate a flux of ~10^{11} $\bar{p}$'s per hour up to a maximum of 12 hours. To provide operational flexibility the accumulator should also be capable of storing cooled $\bar{p}$'s for much longer than the accumulation cycle.

The Accumulator possesses six independent cooling systems which provide horizontal and vertical betatron, and momentum cooling for both the newly injected batch of $\bar{p}$'s (the stack tail) and the circulating beam (the core). The momentum cooling systems require pick-ups in high dispersion regions and kickers in zero dispersion ones. The core betatron cooling takes place in zero dispersion areas, the stack tail betatron cooling in high dispersion ones. The physical layout of the cooling systems is shown in Figure 2. The lattice which accommodates this layout consists of 6 16 m straight sections which alternate between zero and high dispersion. The high dispersion (9 m) was achieved by concentrating the bending around the appropriate straight sections which gives the ring its' characteristic triangular shape. The beta functions throughout the straight sections are less than 16 m which allows an aperture of 30 mm to be used for both the pickups and the kickers.

The gain of the stack tail momentum system must be large in order to move the incoming $\bar{p}$'s from the stacking orbit to the tail of the core distribution before the next pulse of $\bar{p}$'s. This large gain will cause thermal noise in the bandwidth of the core unless the appropriate frequencies are strongly suppressed ($\gtrsim 40$ db). This is achieved by a system of notch and correlation filters which in turn provide practical limitations on the maximum bandwidth of the stack tail cooling system which was chosen to be 1-2 GHz. The requirement of non-overlapping Schottky bands in this frequency range together with the aforementioned aperture limitations defined the Accumulator acceptance for incoming $\bar{p}$'s to be $\lesssim 10\,\pi$ mm-mrad in both planes. The momentum spread of the incoming flux (0.2%) is limited primarily by the output power of the stack tail momentum system. The core momentum cooling system is similar but somewhat simpler than the stack tail and will operate in the 2-4 GHz region. In a similar fashion to the Debuncher ring thermal noise will be minimized in the pickups and preamplifiers by operating these devices at liquid nitrogen temperatures. To provide acceptable performance with regard to transmission losses and dispersion in the frequency ranges required the notch filters consist of a 1.6 mm, 50 Ω superconducting transmission line immersed in a liquid helium cryostat. Each notch filter is driven by a travelling wave tube amplifer rated at 200 W of saturated output power. The design output power for each element is ~40 W which is well beneath the quench level for the notch filter (~200 W).

The gain profile of the various cooling systems are adjusted by displacing the appropriate pickups by a different amount relative to the central orbit. There are 3 series of pickups (-25 MeV, -1 MeV, 16 MeV) appropriate combinations of each output can be made to maximize the required signal, for example by subtracting the -1 MeV signal from the 16 MeV one the amplifed Schottky signal from the core particles is essentially zero. The particle density with respect to energy is shown in Figure 3.

Antiproton-Proton Collisions

After cooling and accumulating $\sim 5\times 10^{11}$ $\bar{p}$'s the Accumulator will be ready to transfer beam for subsequent collisions. The transfer process starts by adiabatically capturing $\sim 8\times 10^{10}$ $\bar{p}$'s from the core using a single h = 2 bucket and slowly moving the beam to the extraction orbit. This beam is then extracted from the Accumulator in a single turn using a shuttered kicker magnet and transported towards the Main Ring via the same beam line used for proton targetting, bypassing the target and collection system. The $\bar{p}$ bunch is injected into a matched bucket in the Main Ring at h = 53 (~2.515 MHz). The normal Main Ring R.F. system is then slowly turned on and the beam rebunched into 13 53 MHz bunches and accelerated to 150 GeV. The 13 bunches are then coalesed into a single bunch prior to injection into the Tevatron, at this energy. The whole cycle is then repeated until 3 bunches of $\bar{p}$'s are circulating in the Tevatron along with three bunches of protons injected in the normal way prior to the $\bar{p}$'s.

The counter-rotating bunches are then accelerated up to the experimental energy. The final step in the collision process involves turning on the low-beta insertions in the experimental regions. The low-beta insertions are formed by replacing the normal 37" quadrupoles with stronger and separately powered quadrupoles and the addition of eight extra quadrupoles within the long straight section itself. During injection and acceleration these extra quadrupoles are turned off and the stronger elements at each end of the long straight are de-excited to provide the standard lattice configuration. After acceleration these elements are slowly adjusted until the final beta value of 1 m is reached. At this point the machine is in storage mode and the Main Ring can resume the 2 second cycle of $\bar{p}$ production.

Tevatron Operations

A major milestone on the way to colliding beams occurred in 1983 with the commissioning of the Tevatron as a fixed target machine and the subsequent first operational run which ended in February of this year. Machine commissioning started with the cooldown of the final sections of the machine which was accomplished at the beginning of May although prior beam tests had been made on the injection system and the first two sectors of the ring. Stable circulating beam was achieved seven weeks later after a shutdown to repair two magnets which were unable to carry sufficient current, and make small machine modifications to relieve aperture limitations. Beam was accelerated to an energy of 512 GeV at the beginning of August. A series of machine studies were then initiated which culminated with the resonant extraction of slow spill to the Switchyard dump. Operational high energy physics was started in October 83 with the machine running at 400 GeV with a 39 second time and a 15 second spill. The average beam intensity was slowly raised during the run up to 8×10^{12} ppp. The operational efficiency of the machine improved during the run with the final week showing beam delivered to the experimental areas for ~80% of the scheduled hours. It was encouraging to note that the downtime logged to the cryogenic systems remained a relatively constant 25-30% of the total.

The superconducting nature of the magnets places a stringent limit on the amount of beam loss which can be tolerated before the magnets will quench. Special designs were adopted in the areas of unavoidable beam loss (extraction, abort) to protect those superconducting elements immediately downstream of the known loss points. The beam abort is a single turn extraction system which takes the circulating beam out of the machine to an external beam dump within three turns (60 μsecs) of receiving an alarm. The decision to abort the beam is made primarily by information received by the loss monitor and position detector system. Individual thresholds can be set on each element in the ring which can be varied as a function of energy within the cycle. This system has proved very effective in reducing the number of beam induced quenches as operational experience revealed the appropriate threshold settings under various operational situations.

In spite of this quite sophisticated abort system, magnet quenches in a superconducting accelerator can be regarded as a fact of life. The problem then becomes to reduce the number of quenches per day to an acceptable level when taking into account the recovery time of the magnets. The amount of energy deposited in a magnet during a quench is the sum of the beam energy and the stored energy in the magnetic field, and consequently the magnet recovery time depends strongly on the machine energy at the time of the quench. We have found that this time varies between ~20 minutes at injection energy (150 GeV) up to ~1 hour at 800 GeV. Throughout the 400 GeV run the number of quenches was reduced from ~1 per 3 hours of HEP to ~1 per 15 hours of HEP. In the current 800 GeV run this number has been reduced further to approximately 1 per day. We believe that while a lot of work still needs to be done to increase the operational efficiency of the Tevatron, we have demonstrated that superconducting technology has come of age in particle accelerators and that large scale cryogenic systems can be made to operate reliably over long periods of time.

Initial Collider Studies

While the main thrust of machine development work to date has been concerned with fixed target machine operation a small amount of machine time has been made available for colliding beam work. The mechanics of beam storage were established over several study sessions and protons were successfully stored at 400 GeV for periods of up to 4 hours. Crude measurements indicate that the beam lifetime is consistent with that expected from the residual beam-gas scattering. The background rates in the collision region were also small (~30 kHz) measured with a 1 meter square scintillation counter horoscope. The transverse beam stability was good and we were unable to detect any signs of fifth order resonances. The sensitivity of the fixed target beam diagnostics to these effects is not high emphasizing that these results are encouraging rather than conclusive in any way. Longitudinal phase space dilution was observed during the stores with debunching times of the order of 1 hour. More effort will be needed to reduce the amount of noise present in the Tevatron low level R.F. system.

Modifications to the Tevatron lattice to allow the establishment of the low beta interaction region at B0 were made in February of this year. To date beta values at the interaction point have been reduced from the 'normal' 70 m to 2 m. Attempts to achieve the design value at $\beta^* = 1$ m have resulted in fast beam loss. Work is proceeding to understand and rectify this situation.

Schedule

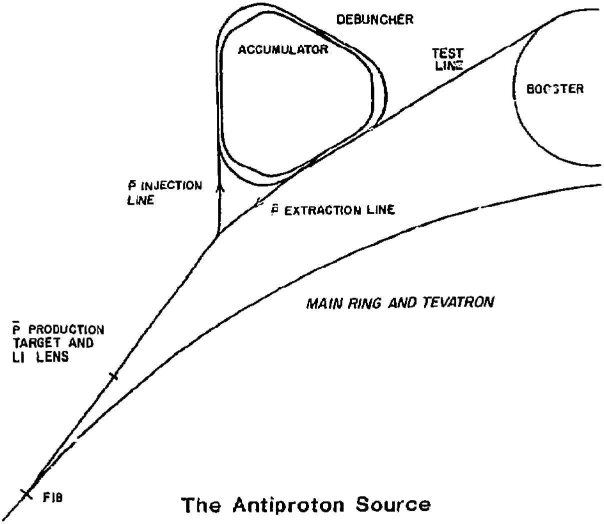
The civil construction for the antiproton source ring enclosures and targetting hall is well underway. Initial installation work of tunnel utilities will start in June 84 with the magnet and power supplies following immediately afterwards. The goal is to have both the Debuncher and Accumulator rings under vacuum by December 84. During the upcoming major summer shutdown (July - November 84) installation of the injection and extraction systems and the targetting station will take place in the main tunnel, as well as a test line from the Booster. Commissioning of the $\bar{p}$ rings with protons and targetting and production studies will start at the beginning of 1985. Initial attempts to obtain collisions in the Tevatron are scheduled for the Summer of 1985.

Conclusions

We are currently constructing an Antiproton Source that is capable of providing sufficient $\bar{p}$'s to achieve a luminosity of $\sim 10^{30}$ for collisions involving 3 bunches of protons and antiprotons. The Tevatron has been operational now for over six months in the fixed target mode with energies up to 800 GeV and intensities $\lesssim 10^{13}$ ppp. Machine studies associated with the collider mode of the superconducting ring are now underway.

Reference

1) Calculation of Antiproton Yields for the Fermilab Antiproton Source, Fermilab PUB 82/43, C. Hojvat and A. Van Ginneken.



The Antiproton Source

Fig. 1

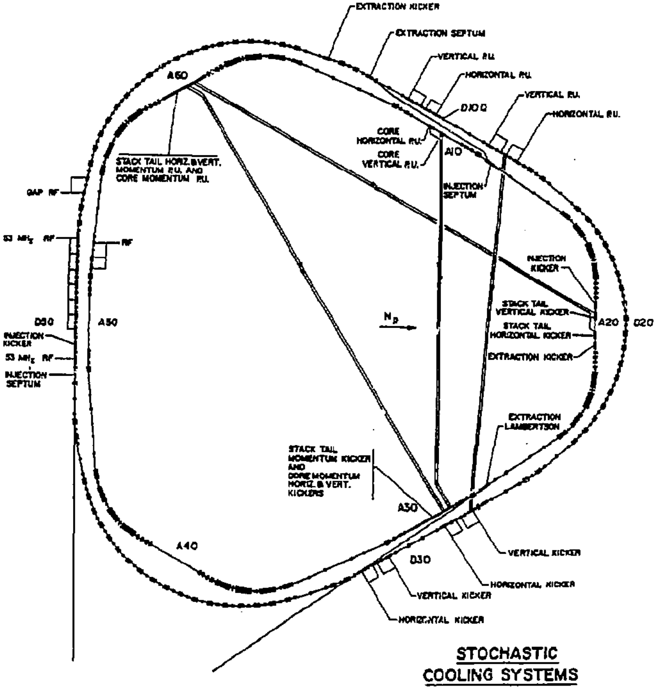

EXTRACTION KICKER
EXTRACTION SEPTUM
VERTICAL P.U.
HORIZONTAL P.U.
D10Q
VERTICAL P.U.
HORIZONTAL P.U.
A60
CORE HORIZONTAL P.U.
CORE VERTICAL P.U.
A10
STACK TAIL HORIZ.&VERT. MOMENTUM P.U. AND CORE MOMENTUM P.U.
INJECTION SEPTUM
GAP RF
53 MHz RF
RF
INJECTION KICKER
STACK TAIL VERTICAL KICKER
D50
A50
N_p
A20
D20
INJECTION KICKER
53 MHz RF
INJECTION SEPTUM
STACK TAIL HORIZONTAL KICKER
EXTRACTION KICKER
EXTRACTION LAMBERTSON
STACK TAIL MOMENTUM KICKER AND CORE MOMENTUM HORIZ.& VERT. KICKERS
A30
A40
D30
VERTICAL KICKER
HORIZONTAL KICKER
VERTICAL KICKER
HORIZONTAL KICKER
STOCHASTIC COOLING SYSTEMS

Fig. 2

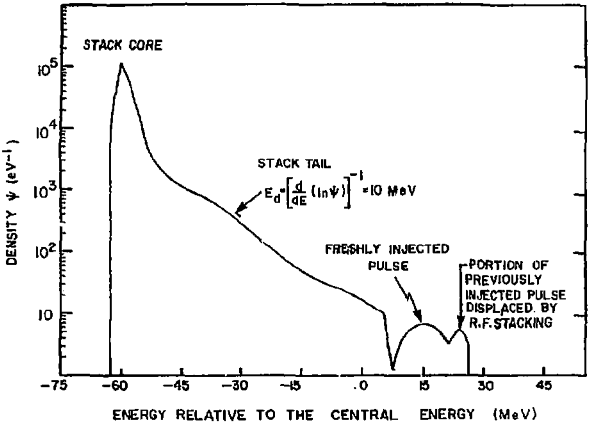

STACK CORE
STACK TAIL
$E_d = \left[\frac{d}{dE}(\ln \psi)\right]^{-1} = 10$ MeV
FRESHLY INJECTED PULSE
PORTION OF PREVIOUSLY INJECTED PULSE DISPLACED BY R.F. STACKING
DENSITY ψ (eV^{-1})
10^5
10^4
10^3
10^2
10
−75
−60
−45
−30
−15
0
15
30
45
ENERGY RELATIVE TO THE CENTRAL ENERGY (MeV)

Fig. 3