IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

THE FERMILAB PROTON-ANTIPROTON COLLIDER

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Summary

A 200-MeV proton storage ring has been constructed at Fermilab for studying techniques for increasing the phase-space density of the protons by using electron cooling or stochastic cooling. The experiments performed on these complementary types of cooling systems over the past year have reinforced the design of an antiproton collection system using both methods of cooling. Antiprotons from a target bombarded by 80-GeV protons are collected in a storage ring at 4.5 GeV and stochastically cooled in a stepwise deceleration scheme to achieve a momentum-spread reduction of a factor of about 250 in about 9 seconds. The antiprotons are then transferred to a lower-energy electron cooling ring for further cooling and accumulation. This system, using the virtues of both stochastic and electron cooling, will allow the accumulation of enough antiprotons in a few hours to give luminosities of 10^{30} cm^{-2} sec^{-1} for collisions between protons and antiprotons at about 2-TeV center-of-mass energy in the Fermilab Tevatron.

Introduction

Construction of a facility is underway at Fermilab that will have the capability of producing proton-antiproton collisions at about 2 TeV center of mass energy by 1984. The Tevatron will be used to accelerate the protons and antiprotons to approximately 1 TeV and to store the two beams, which then will be made to collide in two locations where experiments can be performed. The present scheme should enable a luminosity of 10^{30} cm^{-2} sec^{-1} to be achieved for the collisions. An essential element of the plan will be the construction of a source of antiprotons capable of producing and accumulating about 10^{11} antiprotons in a few hours. The antiprotons from a target bombarded by 80-GeV protons will be collected at 4.5 GeV in a storage ring, called a Precooler, where they will be stochastically cooled and decelerated for transfer to a second storage ring. In this second ring, successive pulses of antiprotons will be accumulated over several hours using electron cooling to achieve greater phase-space density of the accumulated beam. When a sufficient charge has been accumulated, the antiprotons will be extracted from this ring, reaccelerated in the Precooler to 8 GeV and ultimately injected into the Tevatron for acceleration to 1 TeV. The most critical elements in this scenario involve the processes of stochastic cooling, electron cooling, and the development of a bright source of antiprotons from a target capable of absorbing the instantaneous power of the 80-GeV proton beam. The stochastic and electron cooling have been experimentally studied in a 200-MeV proton storage ring[1] and the results are reported in these proceedings[2,3,4]. A 80-GeV target station is under construction to test the design and the preliminary design has been reported[5,6,7].

*The work reported is the result of the joint efforts of many people at Fermilab and a collaborative effort with Argonne National Laboratory, The Institute of Nuclear Physics at Novosibirsk, U.S.S.R., Lawrence Berkeley Laboratory and the University of Wisconsin.

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

Antiproton Source

The main features of the antiproton source are shown in Fig. 1. The Precooler, of the same average radius at the 8-GeV Fermilab Booster accelerator, will be located adjacent to the Main Ring and connected to the antiproton target station. A storage ring capable of operation up to 1 GeV will be used as an accumulator for the antiprotons and will be located adjacent to the Precooler. The use of these two rings in collecting antiprotons from the target can best be described by outlining sequentially the procedure for producing and accumulating antiprotons. The sequence

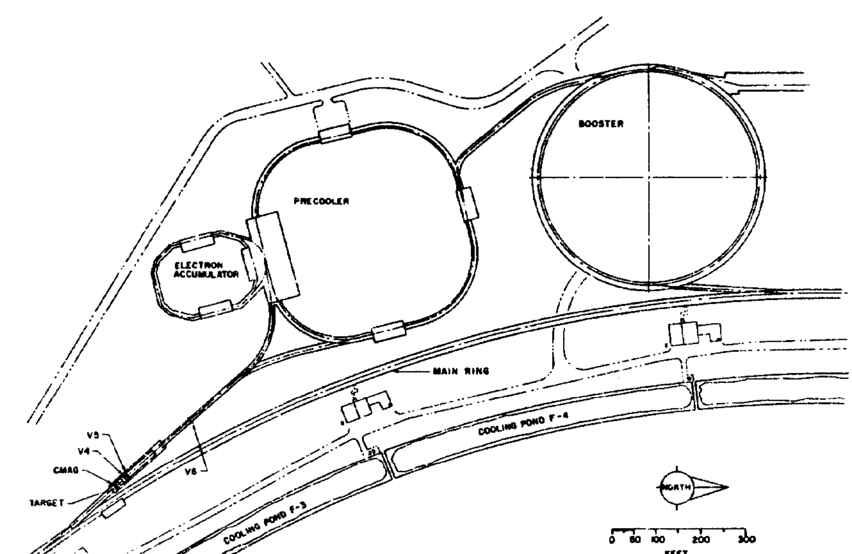

FIGURE 1
THE PRECOOLER LOCATION

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of steps to collect the required number of antiprotons is as follows (the numerical values are selected to produce a consistent set of values that might be possible in the early operation of the antiproton source and without a number of improvements that might be considered):

1. The Main Ring circumference is loaded with protons from the Booster in the conventional way, i.e., 13 batches of nearly Booster length are spaced around the circumference of the Main Ring with 2.0×10^{12} protons per batch. These protons are accelerated to 80 GeV. The Main Ring is then flat-topped for 2.4 sec.

2. The proton batches are extracted sequentially from the Main Ring at 200 msec intervals and targeted on the antiproton-production target. It has been calculated that for a spot diameter of 0.4 mm and a target length of 3 cm of tungsten, the target will not be depleted during the batch. If necessary, the beam can be swept across the target at a speed greater than the speed of the target shock wave. In this case, the $\bar{p}$ acceptance of the $\bar{p}$ channel will be swept synchronously with the proton beam. The $\bar{p}$ channel will contain a lithium lens as the first focusing element to increase the collection angle of the channel for $\bar{p}$'s. The $\bar{p}$ batches retain the rf structure of the Main Ring (53 MHz).

3. Antiprotons are injected into a large-acceptance Precooler ring at 4.5 GeV kinetic energy in a transverse emittance of 4.8 π mm-mrad in each plane and momentum spread of ± 0.5%. The bunches with the 53-MHz rf time structure are captured in existing 53 MHz stationary buckets. The bunches are then rotated 90° in longitudinal phase space to reduce the momentum spread. The 13 batches of antiprotons are rf stacked, resulting in a total momentum spread in the stack of 2%. Two full-aperture kickers are required to move the injection orbit past a septum magnet of conventional design, as well as to provide a local perturbation in the stacked beam.

4. After the 13 pulses have been stacked, the stacked beam is ready for stochastic cooling and deceleration. Cooling of the beam momentum spread takes place in three steps as shown in Fig. 3, followed by deceleration to reestablish phase mixing. The total cycle time in the Precooler to give a cooling factor of over 250, with the injection-rf stacking and deceleration-time included is about 11 seconds.

5. The cooled beam, now decelerated to 200 MeV, will be bunched on the first harmonic to reduce the bunch length to less than the circumference of the 200-MeV storage ring, then transferred to that ring. The injected beam is cooled by the electron cooling system in the storage ring and then momentum stacked onto the accumulated $\bar{p}$ beam. The accumulated beam is cooled in all three dimensions by the electron cooling system.

6. This process, steps 1 through 5, is repeated until approximately 10^{11} antiprotons have been collected, which is estimated to take 12 hours for a cycle time of 11 seconds.

After 10^{11} antiprotons have been accumulated in the storage ring, the following steps are taken to produce colliding beams in the Tevatron:

7. The antiprotons are bunched by a low-harmonic (h=6) rf system in the 200-MeV storage ring. Individual bunches are transferred to the Precooler ring, accelerated to 8 GeV, and injected into the Main Ring through the transport line used for antiproton injection. In the Main Ring, they are accelerated to 150 GeV and transferred into the Tevatron.

8. Protons are accelerated in the normal fashion to 150 GeV in the Main Ring. At this point, rf is used to rebunch the protons with 10^{11} protons per bunch. The appropriate bunches are then transferred to the Tevatron where both p aand $\bar{p}$ are accelerated to collision energy, about 1 TeV, using separate rf systems.

9. A low-beta insertion ($\beta^* = 2m$) is tuned to provide collisions with a luminosity of about 10^{30} cm^{-2} sec^{-1}.

10. The collision process continues until the antiprotons are depleted by collisions, at which time the Tevatron p and $\bar{p}$ beams are replenished.

The performance parameters for the system are summarized in Table I. In a collection time of approximately 12 hours, 10^{11} antiprotons will be collected. Six bunches of antiprotons (of approximately 1.7×10^{10} $\bar{p}$'s per bunch) in collision with bunches of 10^{11} protons in the low-beta collision region in the Tevatron will produce a luminosity of 10^{30} cm^{-2} sec^{-1}.

Table I

System Performance Parameters

Proton Energy for Production	80 GeV
Antiproton Energy (at collection)	4.5 GeV
Protons per MR cycle	2.7×10^{13}
Precooler cycle time	11.0 sec
$\bar{p}$ acceptance at 4.5 GeV, horizontal and vertical	$4.8\pi \times 10^{-6}$ m-rad
$\bar{p}$ momentum collection ($\Delta p/p$)	±0.5%
Invariant $\bar{p}$ cross section ($E\, d^3\sigma / dp^3$)	0.8 mb/GeV^2
Total absorption cross section (σ_a)	33 mb
Number of $\bar{p}$'s per proton ($N_{\bar{p}}/N_p$)	1.2×10^{-6}
Protons per sec. (N_p)	2.4×10^{12}
Antiprotons per sec. ($N_{\bar{p}}$)	2.9×10^{6}
$N_{\bar{p}}$/hr (with 80% efficiency factor)	8.4×10^{9}
Time to collect 10^{11} $\bar{p}$'s	12 hr

Antiproton Targeting and $\bar{p}$ Production

The overall goal in the production and collection of antiprotons from the target is to maximize the yield by appropriate design of the proton beam line, the production target, and the antiproton beam line. The principal difficulties in achieving this goal arise from the very small spot size (< 1mm diameter) that is needed to obtain high $\bar{p}$ source brightness and the resulting stringent conditions on beam optics and target heating, and from the necessity to produce an antiproton beam of length appropriate to fit in the Precooler. Designs have been considered in which the 80-GeV proton beam would be rebunched in the Main Ring to fit in a total length corresponding to the Precooler circumference[8], but when this beam is focused to a spot of 0.2 mm radius, the dE/dx energy loss results in an energy deposition great enough to create shock waves, resulting in target material depletion in the beam area[5]. Although there may be ways to solve this problem, a more conservative approach is to segment the beam in the Main Ring into Precooler-size pieces of an intensity that will not produce this disruptive shock wave. The present design has adopted this approach, although it will be possible to target the entire Main Ring beam if this problem can be solved. In this case, the $\bar{p}$ transport system from the target to the Precooler will be designed to accommodate a larger momentum bite (±2%) and a gain in $\bar{p}$ collection will result. In either case, the problem can be ameliorated by sweeping the proton beam across the face of the target at a rate greater than the propagation velocity of the shock wave (approximately 0.35 mm/μsec) so that no shock wave is formed[9]. In order to preserve the brightness of the antiproton source, the acceptance of the antiproton channel must be swept in a synchronized fashion.

The extracted proton beam from the Main Ring is focused on the target using a lithium lens[6] with a focal length of 50cm, as shown in Fig. 2. The diverging antiproton beam from the target is similarly focused with a lithium lens of focal length 20 cm. This is followed by a pulsed C-magnet to separate the antiprotons from the protons, with the protons directed toward a beam dump in the target vault. These three components have been designed and constructed by our collaborators at INP, Novosibirsk and will soon be under test at Fermilab. It is expected that experiments on the target station will begin in the fall of 1981.

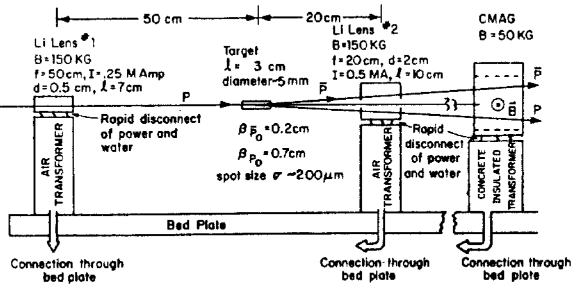

Figure 2 ANTIPROTON TARGET TRAIN DESIGN

Injection and RF Stacking in the Precooler

The antiprotons from the target are transported to the Precooler in a large momentum-acceptance, achromatic transport line capable of carrying the beam of 4.5-GeV antiprotons with a momentum spread of ±2% (only ±0.5% is required in this scenario) produced in the target up to an angle of 24 mrad[10]. The rf bunch structure of the antiprotons remains the same as that of the protons. These bunches are injected into the Precooler and captured into stationary rf buckets at 53 MHz with an rf voltage of 420 kV (bunch area 0.15 eV-sec). The bunches are then rotated in longitudinal phase space by 90°, i.e. one-fourth of a phase oscillation period (90 μsec), to reduce the momentum spread to ±0.115%. The rf voltage is then decreased until the bunch is just included in the bucket. Stacking of the bunches is then done by transforming adiabatically to a moving bucket (rf voltage = 32 kV) and decelerating by $\Delta p/p$=4%. The sweep time is 86.6 msec and the frequency swing is 41.6 kHz. The bunches are then adiabatically debunched at the stack to a momentum spread of ±0.07%. This process is repeated at 200-msec intervals until all 13 segments (batches) of protons have been extracted from the Main Ring and the 4.5-GeV antiprotons have been stacked in the Precooler. It is estimated that the stacking efficiency is 90%, so the total momentum spread of the 13 batches will be 2%. These rf capture, rotation, and stacking steps have been computer simulated and the beam loss estimated to be less than 3%.

Stochastic Cooling and Deceleration in the Precooler

The stacked unbunched antiprotons in the Precooler are cooled using stochastic momentum cooling with a notch filter using techniques similar to those used at CERN[11,12]. The cooling-deceleration sequence is shown in Fig. 3 and results in a $\Delta p/p$ reduction by a factor of about 250 in a cooling time of 7 sec with a cooling system power of 10 kW. After 4 sec of cooling at 4.5 GeV, the beam is bunched with an rf system at h=10. A modest 17.6-kV rf voltage is required. The beam is then decelerated to an energy where the Schottky frequency bands just touch and mixing has been reestablished, i.e., at an energy of 2.5 GeV. At this point, the beam is unbunched and stochastic cooling is re-applied with the same technique (but a slightly altered filter) to achieve a further reduction of $\Delta p/p$ by a factor of about 8 in 1.5 sec. After cooling, the process is repeated with the same rf system at a harmonic number of h=11 (V=18 kV) to an energy of 1.0 GeV. After the cooling is repeated at 1.0 GeV for the third time to achieve a momentum spread of $\Delta p/p$=±0.012, the antiprotons are decelerated to the energy of the accumulator ring (200 MeV). This cooling-deceleration sequence results in a total cycle time of 11 sec when the loading of the Precooler with antiprotons is added. This sequence has been optimized using computer simulation for a stochastic-cooling power of 10 kW. Greater stochastic power would reduce the cooling times in the cycle.

The same pickup, amplifier and kicker system can be used in all cooling steps, although either separate notch filters or a tunable system are required because of the velocity variation. The delay between pickups and kickers must also be adjusted. Relatively fast switches can connect the preamplifier stages to the several notch filters and delay lines.

Kinetic Energy (GeV)	Momentum Spread ($\Delta p/p$ ±%)	Cooling Time (Secs)
4.5	1	
(after 1st. Stoch.Cool)	0.176	4
2.5	0.289	
(after 2nd. Stoch.Cool)	0.0354	1.5
1.0	0.0684	
(after 3rd. Stoch.Cool)	0.0121	1.5
0.2	0.0318	

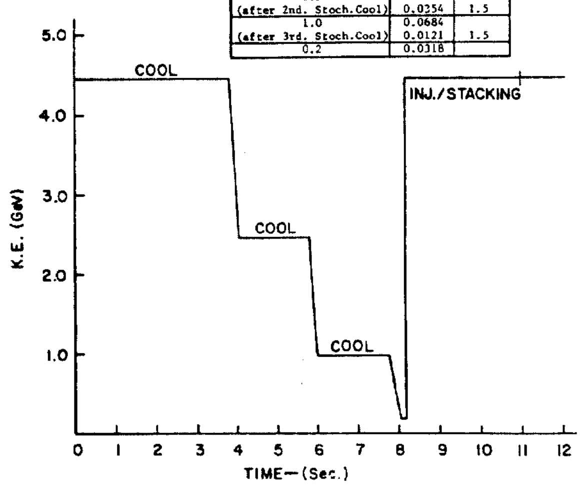

Fig.3 PRECOOLER CYCLE TIME

Precooler Ring Design

The requirements placed on the Precooler design by the antiproton collection scheme can be summarized as follows:

(i)	Average radius	75m
(ii)	Momentum dispersion function (at 4.5 GeV)	0.02
(iii)	Momentum acceptance	±2%
(iv)	Transverse acceptance at 200 MeV	$40\pi \times 10^{-6}$ m-mrad
(v)	Dispersion-free straight section length	~20m
(vi)	Peak operating energy	8.0 GeV
(vii)	Transition energy	>8 GeV
(viii)	Highest practical superperiodicity	
(ix)	Deceleration from 4.5 GeV to 200 MeV	
(x)	Acceleration from 200 MeV to 8 GeV	
(xi)	Room in the lattice for rf (3 systems), correction magnets, and injection-extraction devices (>4 systems)	

These specifications have been met in a strong-focusing FODO design of periodicity two, with two long straight sections with zero dispersion for the stochastic-cooling pickups and kickers, and the other two long straight sections with dispersion for injection-extraction. The parameters of this lattice are shown in Table II. The horizontal magnet aperture is determined by the momentum spread at 4.5 GeV and the vertical aperture is set by the transverse emittance at 200 MeV.

Table II

Precooler Parameters

Superperiodicity	2
Long straight sections, dispersion-free	
length	20m
number	2
Long straight sections, dispersion matching	
length	20m
number	2
Average radius	75.47m
Betatron tunes	
ν_x	11.02
ν_y	11.21
Transition γ	10.1
Revolution period (at 4.5 GeV)	1.6 μs
Dispersion $\eta=(\Delta t/t)/(\Delta p/p)$ @ 4.5 GeV	0.02
$\hat{\beta}x$	55.9m
$\hat{\beta}_y$	61.2m
$\hat{x}p$	-2.5m
Lattice components	
Bending magnet:	
field at 8 GeV	11.1kG
length	1.52m
gap height	6.4cm
gap width between coils	18cm
number used	112
Normal quadrupoles:	
gradient at 8 GeV	<160kG/m
length	0.55m
pole-tip radius	4.8cm
pole-tip field	<7.8kG
number used	48
Special quadrupoles:	
gradient	<137kG/m
length	0.91m
pole-tip radius	10cm
number used	16

Accumulator Ring (Electron-Cooling Storage Ring)

The accumulation of the antiprotons after collection, stochastic cooling and deceleration will be carried out in a separate storage ring. It is planned to use electron cooling to cool the antiprotons as they are stacked in the ring. Electron cooling is most effective on small dense beams and can cool all dimensions of the beam simultaneously.

Following the experience gained on the 200-MeV storage ring[2] constructed at Fermilab for studying electron and stochastic cooling, the accumulator ring will use magnets of similar design placed in a larger average-diameter ring. In this configuration, it will be capable of operating at energies up to about 1 GeV. This will allow the ring to operate at 200 MeV using an electron-cooling system of 110 kV similar to the one presently being tested in the 200 MeV cooling-ring experiment at Fermilab. It is also possible with a new electron-gun design and other relatively minor modifications to raise the voltage to 200 kV. In this case, the proton energy of the accumulator ring could be raised to 367 MeV. This would allow an increase in the number of antiprotons collected per unit time because of the larger acceptance of the ring at this energy. Similarly, an even greater development in the electron-system technology to allow operation at even higher voltages could be accommodated in this ring to increase the collection rate of antiprotons. The electron-cooling accumulator parameters are given in Table 3.

Table III

Electron-Cooling Accumulator Parameters

Energy	200 to 1000 MeV
Bend Field	0.66 T (at 1 GeV)
Radius	32.96 m
Superperiodicity	2
Nominal Tune (stacked orbit)	ν_h=4.194
	ν_v=5.533
Number of Dipoles	44
Length of Dipoles	1.219 m
Effective Dipole Length	1.309 m
Number of Quadrupoles	32
Length of Quadrupoles	0.6096 m
Number of Sextupoles	16
Length of Straight Sections (half)	
Short Straight (2 each)	2.297 m
Long Straight (2 each)	10.668 m
Total Length of Orbit	207.13 m
Vacuum-Chamber Aperture	±76mm x ±25mm
Acceptances	ϵ_h=40π x 10^{-6} m-mrad
	ϵ_v=20π x 10^{-6} m-mrad
	$\Delta p/p$=±1.5 x 10^{-3}

Conclusion

The Fermilab Proton-Antiproton Collider is part of a larger plan, the Tevatron Project, which is centered on the superconducting accelerator ring now being constructed. For proton-antiproton collisions in the Tevatron, a source of antiprotons is under design and construction, with the expectation of having antiprotons available in 1984. The collector scheme has been designed to allow future improvements to be incorporated to increase the antiproton collection rate. For example, if improvements can be made in the targetry, a larger momentum bite would allow a greater number of antiprotons to the collected in the Precooler. Likewise, if improvements in the stochastic or electron cooling of the antiprotons can be made, these can also be accommodated. It is entirely possible to operate the Precooler ring as an accumulator of antiprotons to allow some early, lower-luminosity experiments to be undertaken while the remainder of the system is being developed. The Precooler ring has been designed to accommodate all these possible cooling scenarios.

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