The Fermilab Antiproton Source : Prospects for $p\bar{p}$ Experiments

Petros A. Rapidis
Fermi National Accelerator Laboratory, Batavia, Illinois

Talk presented at the Workshop on Antimatter Physics at Low Energies, held at the Fermi National Accelerator Laboratory, April 10-12, 1986.

The Fermilab Antiproton Source has been described in previous publications[1]. The purpose of this short contribution will therefore be limited to a quick overview of the salient features of the Source. In contrast I will concentrate on some of the questions that arise if one contemplates using the source as a low energy proton-antiproton scattering facility. In particular, I will discuss the changes in operation needed to accomodate the recently aproved experiment[2] (E760) that will use an internal gas jet target in the Accumulator storage ring of the Source.

The Fermilab Antiproton Source is a complex accelerator complex whose ultimate function is the production, accumulation, and cooling of antiprotons to be used for high energy proton antiproton interactions. The primary users of these antiprotons will be the experiments situated arround the Tevatron, i.e. Fermilab's superconducting high energy accelerator, that will serve for part of the time as a colliding beam machine. It should be emphasized that this function of the antiproton source should not be compromised. Alternative uses for the Source, e.g. as a low energy proton-antiproton facility, may be acceptable only if they do not significantly impact upon the normal operation of the machine.

In order to appreciate how such a *non-interference* requirement may be satisfied one should go through the scenario of antiproton production and accumulation. The overall layout of the source is shown in Figure 1. To produce antiprotons, once every 2 seconds 2×10^{12} protons at 8 GeV† are transfered from the Booster to the Main Ring. They are accelerated to 120 GeV in the Main Ring, extracted at the F17 medium straight section, transported to the Antiroton Source target and focused to a σ=0.4 mm spot on a production target. The extracted Main Ring beam consists of 82 53 MHz bunches, each of whose time spread has been narrowed to 0.7 nsec by RF manipulations in the Main Ring. A transport system following the target selects 8.9 GeV/c negatively charged secondaries for injection to the Debuncher, the first of a pair of storage rings. This transport system, which includes a lithium lens immediately downstream of the production target, allows for a secondary beam that contains 7×10^7 antiprotons with a momentum spread of 3% and a transverse emittance‡ of 20π mm-mrad to be injected into the Debuncher. In this ring, the beam is debunched, exchanging the narrow time spread of the injected antiprotons for a reduced momentum spread (.2%); it is also stochastically cooled for 2 seconds to a transverse emittance of 7π mm-mrad. After 2 seconds the beam is transfered to the second storage ring, the Accumulator, and the next antiproton pulse enters the Debuncher. The Accumulator, like the Debuncher, is an 8 GeV storage ring with a 474 m circumference. 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 decrease to 2π mm-mrad, over a period of 4 hours. During this time, 4.3×10^{11} antiprotons are accumulated in a dense beam 'core'.

For colliding beam operations, $.6 \times 10^{11}$ antiprotons are displaced by an RF system from the core to an exraction orbit, bunched, and extracted from the Accu-

† In accordance with common usage the energy of a machine is the kinetic energy. On the other hand beam energy will always refer to the total energy of the particles.

‡ For transverse emittances the quoted values contain 95% of the beam.

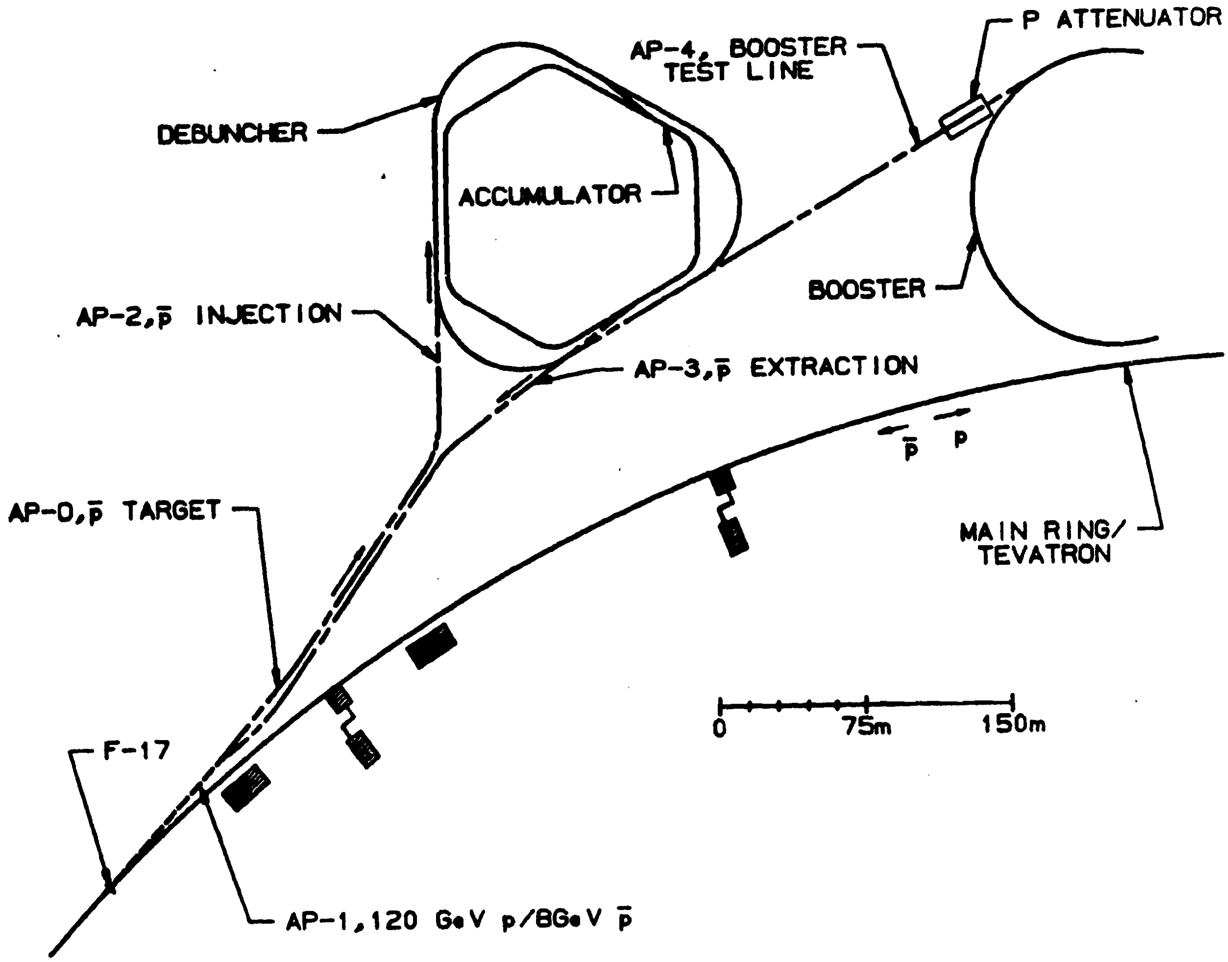

Figure 1 : Schematic of the antiproton source and the related accelerators and beam transport lines used for $\bar{p}$ production and source commissioning.

mulator. This beam is transported back to the Main Ring for acceleration to 150 GeV. The 150 GeV antiprotons are coalleseced into a single 53 MHz bunch and injected in to the Tevatron. In the Tevatron three proton bunches have been previously injected and are circulating in the opposite direction. This process is repeated two more times, resulting in a total of 1.8×10^{11} antiprotons in 3 equally spaced bunches circulating in the Tevatron, as well as 3 bunches of protons. A rather elaborate synchronization and RF manipulation scheme assures that the bunches are equally spaced and that the proton-antiproton bunches cross each other at the desired interaction areas. The 6 bunches get accelerated to 1 TeV, the low beta quadrupoles of the Tevatron are energized to reduce beta to 1 m at the intersection region, and colliding beam experiments can begin. For the next 4 hours the experiments will accumulate data; meanwhile the Main Ring keeps on cycling, accelerating protons to 120 GeV which are used to produce antiprotons for injection in the Tevatron 4 hours later...

It is obvious that during colliding beam operation the Source is fully occupied with supplying antiprotons to the Tevatron and any other use is excluded. Nevertheless, one should be aware of the fact that the Tevatron will be used as a colliding beam facility for only half of the time. The schedule of operations of Fermilab envisions five month long colliding beam runs followed by five month long runs for fixed target experiments, i.e. running during which protons from the Tevatron are extracted and used as the primary particles of high energy scattering experiments. It is during these periods that the Source is available for other uses (including machine studies).

In order to appreciate the compatibility of running the Antiproton Source and the Tevatron simultaneously during the fixed target period one needs to examine the operation of the Fermilab accelerator complex during fixed target running. 8 GeV protons from the Booster are injected in the Main Ring and are accelerated to 150 GeV in 2 seconds. At that point they are transfered to the Tevatron and accelerated to 800 GeV. The superconducting magnets of the Tevatron cannot be made to increase their magnetic guide field at a high rate since this will drive the superconductor normal. Thus the acceleration time is 22 seconds long. The flat top period, i.e. the time following this ramping up of the magnets and during which protons are kept at an energy of 800 GeV while they are gradually extracted, is usually 23 seconds. This is an arbitrary time determined by the demands of the various experiments, but a flat top period much longer or shorter than 23 seconds is unlikely. Finally, 20 seconds are needed to reduce and stabilize the Tevatron guide field to the 150 GeV injection level.

From the above one sees that during fixed target running, the Main Ring is needed as an injector for the Tevatron for a grand total of 2 out of 65 seconds. During the remaining time one can use the Main Ring to accelerate protons to 120 GeV, and then extract at F17, transport these protons to the antiproton target etc. , i.e. one can operate the Source and accumulate antiprotons in the Accumulator. It should be noted that other demands on the Main Ring, namely for machine studies, as well as interference with portions of the Tevatron ramping, limit the availability of the Main Ring as a 120 GeV proton accelerator to less than 63 of the 65 seconds of each Tevatron cycle. Nevertheless, at the least, one can expect that the Main Ring can be used for antiproton production with a duty factor of 50%. As a matter of fact, a mode of operation almost identical to the one outlined (the major difference being that instead of the 120 GeV Main Ring cycles repeating at the maximum rate of one every 2 seconds they repeated only every 4 seconds) was used during the summer of 1985 when the Source was being commissioned. A diagram showing the Tevatron and Main Ring ramps from that run is shown in Figure 2.

It was the recognition of this compatible mode of operating the Tevatron and the Source, that lead a group of physicists to propose E760, an experiment to investigate the formation of charmonium states using the Antiproton Accumulator Ring. The impetus for this experiment came from the ISR experiment[3] R704 that pioneered the use of proton-antiproton collisions for producing charmonium states. In E760 the antiprotons stored in the Accumulator are brought to collide with (almost)

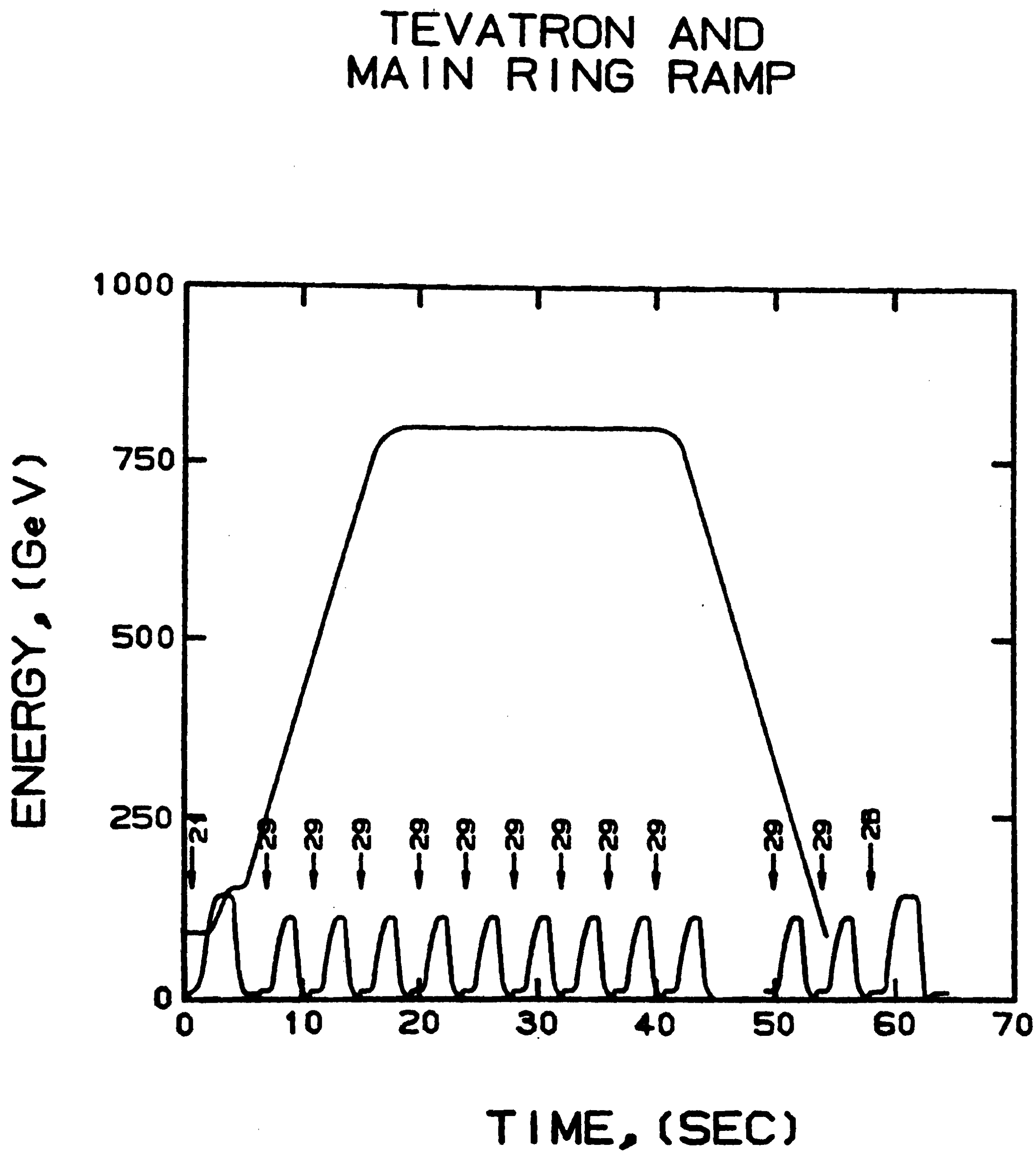

Figure 2 : The Tevatron and Main Ring ramps during the fixed target run of the summer of 1985 when the Antiproton Source was being commissioned. The Main Ring cycle marked '21' is the 150 GeV proton pulse injected to the Tevatron. The '29' cycles are the 120 GeV proton pulses used for antiproton production. The '2B' cycle was used for Main Ring studies.

stationary protons in the form of an internal gas jet target. Details of E760 can be found in the contribution of E. Menichetti to this workshop. The required energy range of the antiprotons neccessary to cover the masses of the various charmonium states (E_{beam}= 3.8 GeV to 6.3 GeV) led us to an investigation of the possibility of varying the energy of the antiprotons in the Accumulator.

The first constraint is imposed by the Debuncher, in the sense that it fixes the accumulation energy of antiprotons to be 8 GeV. This requirement arises from the fact that the RF systems used for debunching have to operate at the radiofrequency of the injected antiproton beam which has to be a harmonic of the revolution frequency for this ring. The narrow tuning range of the RF cavities used dissallows the use of any other harmonic but the 90th one, thus in effect fixing the antiproton energy to 8 GeV. The same reason makes it impractical to use this RF system for deceleration. Thus the scheme to be adopted involves accumulation at 8 GeV. Only after an adequate number of antiprotons have been stored in the Accumulator we will decelerate them to the desired energy. It is expected that the accumulation time will be 4 hours, while the deceleration time will be only a few minutes.

In E760 one studies charmonium by forming a resonant state, e.g.

$$p\,\bar{p} \rightarrow \psi \rightarrow e^+e^-$$

which may be detected amidst the ferocious hadronic background thanks to its characteristic decay. The resolution in the center of mass energy, i.e. in the mass of the resonance, is related to the energy spread of the beam by :

$$\delta m_\psi = \frac{m_p}{m_\psi}\delta E_{beam}$$

The major task that we face in running such an experiment is keeping the energy spread of the beam as small as possible. The difficulty of this task is compounded by two facts : the variable energy of the beam and the presence of mechanism that causes beam heating, viz. the target gas jet itself. Other requirements are the control of the energy of the beam to 1 part in 10^4 and the deceleration from a beam energy at accumulation of 8.94 GeV to an energy in the range 3.8-6.3 GeV; we expect to satisfy these last two requirements by meticulous control of the accelerator parameters and through the use of a newly installed RF system with a wide frequency range, respectively. The control of the energy spread of the beam, and of the beam emittance in general, deserve a lengthier discussion since they point to the essential limitations on the Accumulator performance.

As one changes the energy of the Accumulator the momentum compaction factor $\eta = -(df/f)/(dp/p)$, i.e. the ratio of the fractional change of the revolution frequency in the Accumulator to the fractional change in the beam momentum,also changes. The equilibrium emittance of the beam, both transversely and longitudinally, is inversely proportional to $|\eta|$. Another expression for η is ${\gamma_T}^{-2} - \gamma^{-2}$, where γ is the usual relativistic factor. The $1/\gamma^2$ term expresses the increase in revolution frequency as a particle's velocity increases. γ_T is the transition energy gamma and the $1/{\gamma_T}^2$ term expresses the decrease in revolution frequency due to the increase in path length for higher momenta. If this factor $|\eta|$ is not large enough, all the particles in the machine are esentially isochronous and the major condition for stochastic cooling is not satisfied, i.e. that one has 'mixing' of particles with different momenta. The design Accumulator lattice has γ_T=5.4, and the values of η are shown in Table I.

Table I

Mass, beam energy, and η for the Charmonium states

State	Mass (MeV/c^2)	$\bar{p}$ Beam Energy (MeV)	γ	η
ψ'	3685	6297	6.714	.0121
${\eta_c}'$	3595	5950	6.341	.0094
χ_2	3555	5797	6.179	.0081
χ_1	3510	5628	5.998	.0065
χ_0	3415	5277	5.625	.0027
ψ	3097	4173	4.448	-.0162
η_c	2984	3807	4.058	-.0264

For the χ_0, using the design lattice for the Accumulator, we have a value of $|\eta|$ less than .005, .005 being the minimum value for which the stochastic cooling system is effective. In order to be able to run at such an energy we will have to use a different lattice. There are two ways to solve this problem. After one has accumulated enough antiprotons one may slowly change the currents in the Accumulator magnets, in order to realize a different γ_T while trying to keep the vertical and horizontal tunes constant. Such a scheme was suggested[4] in the E760 proposal and will involve a change in the dispersion of the Accumulator, a change that is not very detrimental since this lattice modification will take place with a cooled beam of antiprotons of a low energy spread. An alternative that is being explored[5] now, as part of a general program of upgrading the Source performance, would involve running the Accumulator as an antiproton accumulator with a lattice having γ_T=7.1, Q_x=6.67, and Q_y=7.51 (vs. Q_x=6.61, and Q_y=8.64 of the original design). With either one of these solutions running at the χ_0 and having a cooling system that will be capable to overcome the heating effects due to multiple scattering in the hydrogen gas jet and keep the antiproton emittance small becomes a viable situation.

Calculations[6] indicate that with a minor modification to the existing stochastic cooling system, that is the addition of a set of pickups at the center of the high dispersion regions of the Accumulator, we expect to have an antiproton beam with a transverse emittance of 5π mm-mrad and an r.m.s. beam energy spread of .5 MeV (which implies a mass r.m.s. resolution of approximately 200 KeV/c^2 !). These conditions are for a circulating beam of 1.5×10^{11} antiprotons, a gas jet target with 10^{14} hydrogen atoms per cm^2; these correspond to a luminosity of 10^{31} $cm^{-2}sec^{-1}$. Given that β=7.5m at the gas jet, the transverse beam size at that point will be $\pm$1.1 cm (for 95% beam containment).

Another effect that complicates operations is the deterioration of the field quality in the Accumulator magnets at the extremes of the apperture for energies lower than 8 GeV. The magnets in the accumulator operate in a partially saturated state at the design energy of the ring (e.g. B=17KGauss for the dipoles). As a result the field shape, epecially near the apperture limits, changes significantly as the field in the magnets is lowered and the steel at the edges of the magnet comes out of saturation. This effect is one of the reasons that accumulation and extraction have to happen at a ring energy of 8 Gev, since the full apperture is neccessary for these processes. Beam storage at lower energies is possible as long as the beam is stored at the central momentum (and orbit) of the machine and has a low enough emittance. A beam with a transverse emittance of 5π mm-mrad fulfills these requirements. In all of the previous discussion we had implicitly assumed that after accumulation the antiprotons are moved to the central orbit and then they are decelerated to the desired energy.

In summary, the Accumulator can be coaxed to perform in a manner that will allow us to carry out E760, i.e. charmonium production. This will neccessitate the building of new RF systems, and a modification in the stochastic cooling system. It will also involve a lot of experimentation with the machine parameters. We expect to carry out a machine study program before or during 1987, and run E760 in 1988. We will also study the possibility of lowering the value of β at the interaction region by retuning the existing quadrupole triplets flanking the interaction region. Finally, we hope to be able to lower the beam energy to 1.64 GeV and reach a mass of 2.2 GeV/c^2, a region where the $\xi(2230)$ was observed[7]. This last step involves a large momentum excursion and may be a rather delicate operation.

The obvious question, following the above discussion, is what other feats can one perform with the Accumulator? Could one use it as a LEAR? The answer is no. The Accumulator magnet lattice, dictated by the requirements of the stochastic cooling systems, is too constraining and will not allow for any elaborate extraction scheme (e.g. slow extraction). The Accumulator will be able to accumulate 10^{11} $\overline{p}$/hour (according to the design goals) to 4×10^{11} $\overline{p}$/hour (according to the goals of the upgrade being contemplated). These antiprotons may be extracted using the present fast extraction system at a beam energy of 8.9 GeV (and perhups lower energies if the behaviour of the magnetic field quality at lower energies is understood). At that point they may be transferred to another 'LEAR'-like storage ring. In short, besides the possibility of running experiments utilizing an internal gas jet target (as in E760), the Accumulator can only serve as an injector of antiprotons for another machine. Finally, some members of the Antiproton Source group at Fermilab have looked[7] at the possibility of using the Accumulator as a low energy $p\bar{p}$ collider; the expected luminosity is too low to justify much more work along these lines, we refer the reader to the contribution[9] of D.Möhl at the Tignes workshop for a discussion of such a collider.

References

1 Design Report, Tevatron I Project, Sept. 1984, Fermilab.
G. Dugan, *IEEE Transactions on Nuclear Science*, **NS-32**, 1583 (1985).

2 Fermilab Proposal P760, Fermilab - Ferrara - Genova - Irvine - Northwestern - Penn State - Torino Collaboration, *A Proposal to Investigate the Formation of Charmonium States Using the $\bar{p}$ Accumulator Ring*, March 1985, (aproved Dec. 1985).

3 See the contribution of E. Menichetti to this workshop and the references contained therein.

4 S. Holmes, private communication, see also Ref. 2.

5 G. Dugan, private communication.

6 J. Peoples, contribution to the Antimatter Facility Workshop held at Madison, Wisconsin, September 1985, to be published.
J. Marriner, E760 Internal Memorandum, January 1986, unpublished.

7 R.M. Baltrusaitis *et al.* , *Phys. Rev. Lett.*, **56**, 97 (1986).

8 J. Peoples, private communication.

9 D. Möhl in *Proceedings of the Third LEAR Workshop: Physics with Antiprotons at LEAR in the ACOL Era*, Tignes, France, 1985, ed. by U. Gastaldi *et al.* , Éditions Frontières, p. 65.