Low and Medium Energy Antiproton Facilities in the U.S.

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Abstract

The use of the Fermilab Antiproton Source for charmonium physics, and the possibilities for further experiments there are described. Future low and medium energy antiproton studies at Fermilab as discussed in the Workshop on Physics at Fermilab in the 1990's are presented. Finally, the possibility for a low energy antiproton program at Brookhaven National Laboratory is described.

1 Introduction

The physics with antiprotons at low and medium energies has until recently been the exclusive province of CERN, either at the ISR with experiment[1] R704 or at the many LEAR experiments. This situation has changed with the recent run of experiment E760 at the Fermilab Antiproton Source. I will review the use of the Fermilab Antiproton Source for charmonium physics, and the possibilities for further experiments there. In the Workshop on Physics at Fermilab in the 1990's held last August a group of physicists considered a rather extensive list of future experiments with low and medium energy antiprotons at Fermilab. The outcome of these considerations will also be presented. Finally, the proposal for a low energy antiproton program at Brookhaven National Laboratory will be discussed.

2 The Fermilab Antiproton Source and E760

The Fermilab Antiproton Source has been described in previous publications[2]. The discussion will therefore be limited to a quick overview of its salient features[3]. The

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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 are the experiments situated around the Tevatron, i.e. Fermilab's superconducting high energy accelerator, that serves 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, are 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 2.6 seconds protons at 8 GeV/c are transferred from the Booster to the Main Ring. They are accelerated to 120 GeV/c in the Main Ring, extracted at the F17/F18 medium straight section, and are focussed on the antiproton production target. 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. In this ring, the beam is debunched, exchanging the narrow time spread of the injected antiprotons for a reduced momentum spread; it is also stochastically cooled in the transverse planes. After 2.6 seconds the beam, which is now composed of antiprotons since all the other particle species have decayed, is transferred to the second storage ring, the Accumulator, and the next antiproton pulse enters the Debuncher. The Accumulator, like the Debuncher, is an 8.9 GeV/c 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 more than two orders of magnitude, and the transverse emittance to decrease to 2π mm-mrad. A dense 'core' of antiprotons is accumulated at a rate of 2.2×10^{10} antiprotons per hour.

For colliding beam operations antiprotons are extracted at 8.9 GeV/c from the Accumulator to the Main Ring, accelerated to 150 GeV/c, and then they are transferred to the Tevatron. In the Tevatron they are accelerated to 800 GeV/c and made to collide with counter rotating protons. 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 year long colliding beam runs followed by year 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 exam-

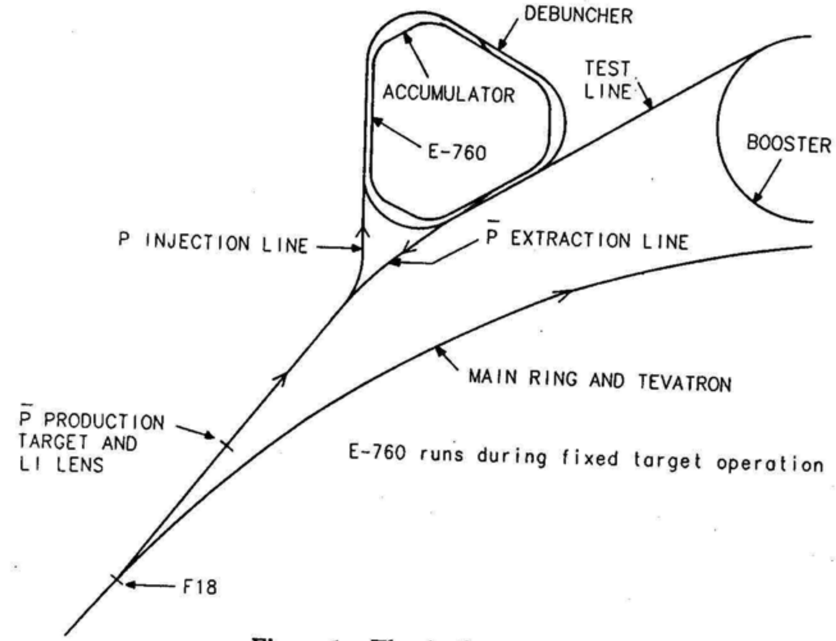

Figure 1: The Antiproton Source

ine the operation of the Fermilab accelerator complex during fixed target running. 8.9 GeV/c protons from the Booster are injected in the Main Ring and are accelerated to 150 GeV/c in 3.2 seconds. At that point they are transferred to the Tevatron and accelerated to 800 GeV/c. 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/c 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/c 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 3.2 out of 65 seconds. During the remaining time one can use the Main Ring to accelerate protons to 120 GeV/c, and then extract at F17/F18, 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/c proton accelerator to less than 62 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%.

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[4]. The impetus for this experiment came from the ISR experiment[1] 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) stationary protons in the form of an internal hydrogen gas jet target. Details of E760 can be found in the contribution of R. Cester to this conference[5]. The required energy range of the antiprotons necessary to cover the masses of the various charmonium states (p_{beam}= 3.6 to 6.3 GeV/c) led us to an investigation of the possibility of varying the energy of the antiprotons in the Accumulator.

The design of the source requires antiprotons to be accumulated at 8.9 GeV/c. Only after an adequate number of antiprotons have been stored in the Accumulator (15 to 20 $\times 10^{10}$) we decelerate them to the desired energy. During the recent E760 run (July and August 1990) we usually accumulated antiprotons for 24 hours at a maximum rate of 1.1 $\times 10^{10}$ per hour. This accumulation rate is compatible with the 2.2×10^{10} per hour achieved during colliding beam running if one takes into account the duty factor (72%), and a deliberate decrease of the secondary beam intensity (66%) that was imposed in order to minimize the radiation dose on the E760 lead glass calorimeter. This was followed by a period of one to two hours during which the beam was cooled, decelerated to the desired energy, and the gas jet was turned on. A data taking period of roughly 48 hours followed. This rather wasteful mode of running was forced upon us by the short beam lifetime ($\approx$30 hours) which was caused by a pesky vacuum problem. The vacuum leak has been fixed and the lifetime is expected to double; this alone will lead to a 40% increase in the integrated luminosity.

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

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

which may be detected amidst the ferocious hadronic background thanks to its electromagnetic decay. The resolution in the center of mass energy is given 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 momentum at accumulation of 8.9 GeV/c to one in the range 3.7 to 6.2 GeV/c.

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 essentially 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/c²)	$\bar{p}$ Beam Energy (MeV)	γ	η
ψ'	3685	6297	6.714	.0121
η_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
J/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 have to use a different lattice. After enough antiprotons have been accumulated the currents in the Accumulator magnets are slowly changed, in order to realize a different γ_T while the vertical and horizontal tunes are kept constant. Such a scheme was suggested in the E760 proposal[4] and involves a change in the dispersion of the Accumulator, a change that is not very detrimental since this lattice modification takes place with a cooled beam of antiprotons of a low energy spread.

The deceleration procedure has been developed during the last three years. Up to 20×10^{10} $\bar{p}$'s have been decelerated down to 5600 MeV/c. In order to decelerate to energies corresponding to masses equal or lower than the χ_0 mass the transition energy must be crossed and at this point the beam is inherently unstable. 10×10^{10} $\bar{p}$'s have been decelerated to 3800 MeV/c with 90% efficiency, the intensity being limited by beam losses due to longitudinal instabilities induced by the RF cavities of the Accumulator. A shorting device is now being installed in these cavities now in order to eliminate these problems. During the last two months of running a maximum luminosity of $8 \times 10^{30} cm^{-2}s^{-1}$ was achieved, and an integrated luminosity of $\approx 200 nb^{-1}$ per day.

The energy of the beam is calculated[6] from the velocity of the circulating beam. The velocity is given by $L \times f$, where L is the orbit length and f is the beam revolution frequency. The position of the beam orbit is fixed by the position of the pickup electrodes of the 4-8 GHz momentum stochastic cooling system. (This newly commissioned system with moveable pickups in a high dispersion area of the Accumulator has been instrumental in achieving a high degree of beam energy reproducibility and small beam energy spread.) The length for a reference orbit was measured at the J/ψ, which is our energy calibration point. The reference orbit is 474.065 m long, and an orbit's length can be measured with respect to this reference with an accuracy of 1.6 mm.

The accuracy of our orbit length measurement is limited by the reproducibility and resolution of the beam position measurement system; we have achieved a c. of m. energy reproducibility of $\approx 70 MeV/c^2$ at the J/ψ and $\approx 210 MeV/c^2$ at the ψ'. The center of mass width due to the momentum spread of the beam has been measured in two ways: using the double scan technique described in Ref. 5, and by measuring the frequency spread of the Schottky noise of the circulating beam[7] and the η of the machine. The value of the parameter η is deduced from synchrotron frequency measurements on bunched beam. Both techniques give consistent results; we have an RMS spread in the c. of m. energy of 160 keV/c^2 at the J/ψ and 230 keV/c^2 at the ψ'. This good performance of the machine may allow for a direct measurement of the J/ψ width, a better measurement of the mass and width of the ψ', as well as the masses and widths of the other charmonium states.

3 Future Plans at Fermilab

Fermilab has embarked on an ambitious program[8] of increasing the luminosity of the Tevatron Collider. The instantaneous luminosity achieved in 1989 was $\mathcal{L} \approx 2 \times 10^{30} cm^{-2}s^{-1}$, and the objective for 1995 is $50 \times 10^{30} cm^{-2}s^{-1}$. This increase in luminosity will be achieved at first mostly by improving in the intensity and emmitance of the booster beam, and in a later phase by the construction of the Main Injector - a new accelerator with a maximum energy of 150 GeV, a repetition rate of 1.5 s at 120 GeV, an admittance of 4π mm $mrad$, an an intensity of 3×10^{13} protons per pulse. This machine will replace the present Main Ring, will be 3.3 km long, and will be housed in its own tunnel, to be located to the west of the present Main Ring and Antiproton Source. Without going into details, the first phase of the Fermilab upgrade, which includes a new 400 MeV Linac as well as various improvements in the Antiproton Source and its target, will allow for an antiproton accumulation rate of 7.6×10^{10} per hour ($vs.$ 2.2×10^{10} presently) by 1993. The second phase, with the Main Injector, will allow for an antiproton accumulation rate of 16.8×10^{10} per hour by 1995.

The Main Injector with its very high intensity will allow Fermilab to operate in three different modes : as a Collider, as a 1TeV fixed target machine, and as a high intensity 150 GeV fixed target machine. The two fixed target programs can be pursued simultaneously, while the Collider running, with its requirement for intense antiproton bunches, is not compatible with the 150 GeV fixed target program. A vigorous program of research with the intense secondary neutrino and kaon beams from the Main Injector is envisioned[8,9,10]. In addition with a small reduction in the protons available to the 150 GeV program (of the order of 25%) an antiproton program can also be pursued. As a matter of fact, it may be the case that enough antiprotons will be produced during the Collider running, so that if there exists a low energy antiproton facility (similar to LEAR), such a facility could run concurrently with the Collider with only a small impact on the overall luminosity of the Collider.

The short term implications of the upgrade will be a doubling of the E760 average luminosity. The E760 collaboration intends to pursue the program of charmonium physics during the 1991 and the 1993 fixed target runs. The collaboration has also indicated its intent to the study of the reaction

$$p\bar{p} \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$$

as well as charmonium production with nuclear targets (*i.e.* heavier gas jet).

For the longer term, after the objectives of the upgrade have been met, the building of a low or medium energy antiproton facility has been contemplated. In the Breckenridge Workshop a subgroup of physicists considered the possibilities of experiments with low energy antiprotons at Fermilab[10]. The following areas of interesting experiments were identified : search for CP violation in the reaction $p\bar{p} \rightarrow \Lambda_c\bar{\Lambda}_c$, precision measurements in antihydrogen that will test CPT, and tests of the gravitational weak equivalence principle with antihydrogen[11].

It was assumed that the current setup in the Accumulator will allow E760 or its successors to essentially complete the study of charmonium and related topics. In addition the symmetric production of charmed hyperon-antihyperon pairs in $p\bar{p}$ collisions was considered. For the heaviest charmed baryons a beam momentum of ~ 25 GeV/c is needed. A place for such experiments is the Main Injector itself, either as a storage ring with a gas jet target, or with an extracted antiproton beam. It was felt that such a program would require too large a fraction of the Main Injector's availability.

The most important outcome of the discussions was that both the $\Lambda_c\bar{\Lambda}_c$ and the low energy experiments have very severe requirements on beam quality and the deceleration system that will not be easily met without building *ad hoc* facilities. Thus two facilities were discussed :

3.1 Dedicated Decelerator Ring

The DDR will have a circumference of 60 m and will decelerate 10^{10} antiprotons from 1 GeV/c to 60 MeV/c (i.e. 2 MeV kinetic energy). The antiprotons will then be further decelerated in an RFQ to 5-10 keV, and then be captured in a Penning or Paul trap, which in turn will supply the various low energy experiments. The upgraded Booster injection momentum will be about 1 GeV/c. Thus we will be able to supply the DDR by extracting in the standard way from the Accumulator, sending the 8 GeV beam backward through the Main Ring or Main Injector into the Booster, decelerating to 1 GeV/c, extracting the bunches, and transporting them to the DDR. Here they must be cooled and decelerated to 2 MeV.

Cooling is needed at several stages: after injection, during deceleration, and at 60 MeV/c. At injection, stochastic cooling of 1-2 GHz bandwidth will provide a cooling time of 1-2 minutes. At low energy, electron cooling will be more favorable. For cooling times of 100 sec, beams of $10^{10}\,\overline{p}$ with emittance 30π mm mrad and $\Delta p/p = \pm 2 \times 10^{-3}$ can be maintained at 60 MeV/c against intrabeam scattering.

3.2 $\Lambda,\overline{\Lambda}$, Ring

The preferred momentum for this ring is 1.65 GeV/c, just below the threshold for competing hyperon-antihyperon production channels. To get sufficient data (5×10^9 events) in, say one year, a luminosity of about 5×10^{31} cm^{-2} sec^{-1} is needed. With a gas jet target whose density is 10^{14} cm^{-3} with an effective target length of 1 cm, and for a revolution frequency of 4 MHz, 10^{11} antiprotons are needed in the ring. In order to utilize a large fraction of the events, the beam pipe must have a diameter of 1 cm or less for 40 cm from the target.

The envisioned ring will have two 13 m straight sections with dispersion suppressors and low β sections, one for the experiment and the other for injection, RF, and diagnostics. A stochastic cooling system is needed to obtain adequate luminosity lifetime ($\approx$ 10 hours).

Since the antiproton beam needs to be cooled prior to injection at 1.65 GeV/c, a likely way is to decelerate the beam in the Accumulator and cool prior to extraction. The circumference of the ring is about 70 m, so the beam in the Accumulator will have to be extracted in seven pieces, injected and RF stacked in the $\Lambda,\overline{\Lambda}$, ring. Alternatively, if the DDR exists, the ring can be charged from it at 1 GeV/c. This avoids the RF stacking, but requires acceleration in the $\Lambda,\overline{\Lambda}$, ring.

Operation of this ring will require a significant fraction of the Main Injector's time ($\approx$ 40-50%) and, in contrast to the low energy program of the DDR, is probably not compatible with Collider running.

4 Low Energy Antiproton Possibilities at Brookhaven

A new Booster ring is nearing completion at the AGS at Brookhaven National Laboratory. This new Booster will normally accelerate protons to 1.5 GeV for injection into the AGS, but due to the requirements of the heavy ion program at the BNL RHIC it will be capable of running at a maximum momentum of 5.2 GeV/c. The Booster will have a momentum aperture of $\pm 1\%$ and an acceptance of 50π mm mrad. It will be 1/4 as long as the AGS, thus four Booster cycles each having 3 bunches of 5×10^{12} protons for a total of 6×10^{13} protons will be injected every 2 seconds into the AGS.

Since this filling of the AGS will only take .5 seconds, the Booster will idle for 1.5 seconds. It was this observation that led to the recognition[12] that an opportunity for producing antiprotons existed. It was suggested that one of the four Booster turns (i.e. 1/4 of the AGS intensity) be fast extracted from the AGS at 28 GeV, and be transported onto an antiproton production target. A lithium lens and transport system will bring 4 GeV/c antiprotons back to the Booster. Meanwhile, the Booster will have been ramped up to 4 GeV/c and will accept these antiprotons. They then may be decelerated to any energy between 4 GeV/c and 200 MeV, while the remaining 3/4 of the AGS protons are slowly extracted for the AGS fixed target program. The 200 MeV antiprotons can be further decelerated in the AGS linac, and then in an RFQ, in a manner similar to the one described for the Fermilab DDR. The layout of the proposed antiproton source, and the described sequence are shown in Figures 2 and 3.

With an expected production rate of 4×10^{-6} $\bar{p}$ per proton incident upon the target, one can produce up to 1×10^{11} antiprotons per hour. This rate will be severely limited by the limited admittance of the Booster and the linac at low energies. Without any stochastic cooling systems only 7×10^{4} antiprotons will survive to 750 keV. With cooling the transfer efficiency could, theoretically, be up to 50%.

The same sort of experiments considered in the Breckenridge workshop[10] have been suggested for Brookhaven. In addition, the prospects of AGS II, an AGS proposed upgrade that includes a Stretcher, a Post-Booster, and a Collector rings, allow for more ambitious proposals[13] similar to SuperLEAR.

5 Conclusions

All the proposed facilities, with the exception of the use of the Fermilab Accumulator for E760, are not part of any laboratory's long term plan at this time. They share the feature of being quasi parasitic programs, either on the Main Injector or the upgraded AGS. As such, whether such facilities will be built, will in all likelihood be decided based on the open physics issues, if any, remaining at the time the primary projects are completed.

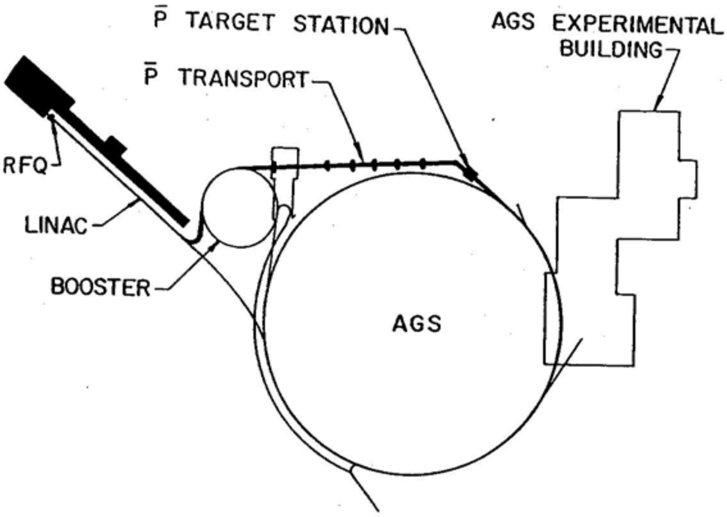

Figure 2: AGS Accelerator Complex

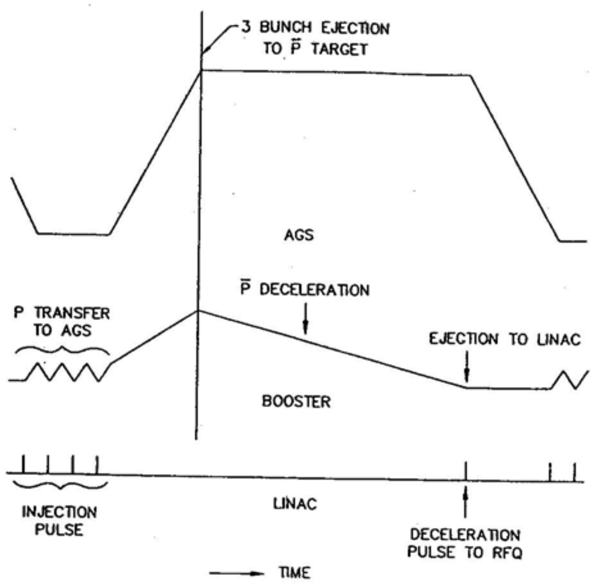

Figure 3: BNL Booster and AGS Magnetic Cycle

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