An intense source of antiprotons for antimatter research at FNAL

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There is considerable interest in low energy antiprotons for atomic, nuclear, and particle physics. The LEAR facility at CERN is currently the only source of antiprotons with low enough energy to be stored and accumulated in a Penning trap. With only minimal hardware modifications, the Fermilab Linac and Booster synchrotron can be used to decelerate an initial ensemble of 10^{11} antiprotons with an efficiency of approximately 0.5%. Subsequent improvements will be able to increase this efficiency to near 100% transmission of 10^{12} antiprotons. These transfers could take place as often as two or three times a day with only a marginal decrease in Tevatron Collider luminosity.

1. Motivation

Low energy antiprotons are in demand to perform experiments in atomic, nuclear, and particle physics [2]. By adding low energy positrons, the antimatter version of the hydrogen atom "antihydrogen" can be synthesized. Trapping the antiprotons or antihydrogen in a Penning trap would make the above experiments possible [3].

An experiment with important implications in particle physics and cosmology is the measurement of the gravitational acceleration of antimatter. While the standard model predicts the same sign and magnitude of the gravitational force as matter, some theories predict either the opposite sign or a larger same sign force for antimatter. Another use for antihydrogen is to compare the wavelengths of spectral lines with hydrogen. Differences may be signs of CPT invariance breaking. In addition, the wavelength difference may be a measure of anomalous gravitational effects.

One of the fascinating implications of some theories in nuclear physics is the possibility of heavy hadronic molecule production. The presently observed hadronic states are color singlet $Q\overline{Q}$ mesons and 3 quark QQQ baryons. New heavy states such as $QQ\overline{QQ}$, $QQQQ\overline{Q}$, and $QQQ\overline{QQQ}$ may be synthesized. There is already evidence that the 0^+ mesons $a_0(980)$ and $f_0(975)$ are $K\overline{K}$ bound states. Given sufficient physics motivation, it may be possible using low energy antiproton collisions and positron

bombardment to create antihelium. Antiproton and positron bombardment of the antihelium nuclei could create antilithium, and so on up the antimatter periodic table.

At higher energies, it may be possible to observe $\Delta S = 2$ CP violation effects in the hyperon decays $\Lambda \rightarrow p\pi^-$ and $\Lambda \rightarrow \bar{p}\pi^+$. The observation of CP violation in this system, outside of neutral kaon decays, would rule out theories like the "superweak" theory. To perform these measurements, 5×10^9 events are required in proton–antiproton collisions at beam kinetic energies of 960 MeV.

2. Antiproton production

Antiprotons are created by accelerating protons to high energy and directing them into a target. Since the injector chain used to produce these protons is also the means by which the antiprotons are decelerated, an overview of Fermilab [1] operations is required.

The protons at Fermilab start as negatively charged hydrogen ions H^- (a proton orbited by two electrons) which exit the Cockroft–Walton electrostatic generator at a kinetic energy of 750 keV. The Linac accelerates the negative hydrogen ions to a kinetic energy of 400 MeV. The Linac RF system has a base frequency of 201 MHz, which is the bunch spacing within the beam. The charge density of this beam is not sufficiently high to support the high energy physics program. Therefore, at injection into the Booster a charge reversal method is used to multiply this density by up to an order of magnitude.

Assume a pulse of Linac beam which has a length equal to an integer times the time-of-flight around the Booster ring. A dipole magnet is used to merge the injected negatively charge H^- beam with the positively charged proton beam circulating in the Booster. A thin foil is used to strip the unwanted electrons away.

Because the RF frequency at injection in the Booster of 38 MHz is not phase locked to the 201 MHz Linac system, the Linac beam is debunched and then adiabatically captured into the Booster RF buckets. At this point 84 bunches are accelerated up to a kinetic energy of 8 GeV. The Booster magnet system resonates at 15 Hz, so the time to accomplish the Booster acceleration cycle is 33 ms. Because of the change in velocity of the proton beam as it becomes more relativistic during the acceleration cycle, the Booster RF system has a frequency of 53 MHz at extraction.

At present the 8 GeV protons are injected into the Main Ring, a 6 km circumference synchrotron which has an RF system also operated at 53 MHz. After 1998 the Main Injector [4] will take over the responsibilities of the Main Ring. During antiproton production the Main Ring accelerates the protons to an energy of 120 GeV. After RF manipulations used to shorten the bunches, the protons are extracted and focussed onto the antiproton production target. Antiprotons with a mean kinetic energy of 8 GeV and an energy spread of $\pm 2\%$ are then captured, cooled, and stacked (stored) in the Antiproton Source facility [5]. At present the antiproton stacking rate is approximately 5×10^{10}/h. After completion of the Main Injector a stacking rate of 15×10^{10}/h is

anticipated. In addition, there are plans [6] to increase this rate to 1×10^{12}/h early in the next century.

The transfer lines between the Main Ring and the Antiproton Source allow injection of the 8 GeV antiprotons into the Main Ring, where they circulate in the opposite direction as the protons. This operation typically takes place during injection into the Tevatron Collider, where the counter-rotating antiprotons are required for collisions in the high energy physics detectors. This Antiproton Source to Main Ring antiproton transfer capability serves as the starting point for the deceleration of an antiproton beam.

3. Antiproton deceleration

The transverse 95% normalized emittance of the antiprotons in the Main Ring is approximately 6π mm mr. The total longitudinal emittance of a pulse of 10^{11} antiprotons from the Antiproton Source is approximately 1 eV s, where this emittance is distributed over a user-specified number of bunches. The maximum number of bunches is 84. Table 1 contains some antiproton beam parameter values which will be used in deceleration efficiency calculations below.

Once the antiprotons are circulating in the Main Ring, the fact that they are circulating in the opposite direction of the protons means that the 8 GeV transfer line which links the Booster to the Main Ring can be used without modification to inject the antiprotons into the Booster synchrotron. By timing this transfer to coincide with the peak of the Booster sinusoidal magnet cycle, the antiprotons can be decelerated to a kinetic energy of 400 MeV.

The efficiency of this deceleration, which quantifies the fraction of the antiprotons which survives, depends on the transverse aperture, longitudinal aperture, and vacuum lifetime of the Booster. Assuming a Gaussian bunch charge distributions in the transverse plane, the rms beam size $\sigma_\perp$ is related to the 95% normalized transverse emittance ε_n by the equation

$$\sigma_\perp = \sqrt{\beta_\perp \varepsilon_n / (6\beta_r\gamma_r)}, \tag{1}$$

Table 1
Parameter values for the antiproton beam injected into the Main Ring.

Main Ring Antiproton Beam parameter	Value
Total Number of Antiprotons	1×10^{11}
Total Normalized Longitudinal Emittance (eV s)	1
Number of Bunches per Pulse	20
Pulse Length (ns)	380
Number of Antiprotons per Bunch	5×10^{9}
Invariant Longitudinal Emittance per Bunch (eV s)	0.05
95% Normalized Transverse Emittance (π mm mr)	6

where $\beta_\perp$ is the value of the Booster magnet lattice beta function and the relativistic momentum $\beta_r\gamma_r$ is the product of relativistic velocity β_r and the relativistic energy γ_r of the antiprotons. Assuming that the longitudinal charge distribution is also Gaussian, the relationship between the invariant 95% longitudinal emittance A of a bunch is related to the rms bunch length σ_τ and energy spread σ_E is

$$A = 6\pi\sigma_\tau\sigma_E. \tag{2}$$

Table 2 shows the results of applying these equations to the antiproton beam in the Booster at 400 MeV. The transverse beam size of 5 mm is small enough to avoid scraping on the vacuum chamber walls. The minimum energy spread is important since the beam must be debunched so that after extraction into the Linac it can be rebunched at 201 MHz. The momentum aperture of the Booster is sufficiently large to efficiently transmit a beam of this emittance. Based on the performance of low intensity proton acceleration, the combination of vacuum lifetime and transition crossing losses should be approximately 80%. In fact, proton deceleration down to the original minimum kinetic energy of the Booster of 200 MeV was already once accomplished [7]. Extraction from the Booster requires a kicker magnet upstream of the location of the stripping foil (around which the beam is directed so as to avoid emittance growth caused by multiple scattering). Just after

Table 2
Parameter values for the antiproton beam at 400 MeV in the Booster.

400 MeV Booster Antiproton Beam parameter	Value
Relativistic Momentum	1.02
Beta Function (m)	25
95% Normalized Transverse Emittance (π mm mr)	6
RMS Beam Size (mm)	5
Invariant Longitudinal Emittance (eV s)	0.05
RF Bucket Length (ns)	26
Maximum RMS Bunch Length (ns)	4
Minimum RMS Energy Spread (keV)	660
Deceleration Efficiency (%)	80
Number of Antiprotons per Bunch	4×10^5

Table 3
Parameter values for the antiproton beam at 400 MeV in the Linac.

400 MeV Linac Antiproton Beam parameter	Value
Pulse Length (ns)	530
Number of Bunches	106
Extraction and RF Capture Efficiency (%)	75
Number of Antiprotons per Bunch	566×10^6
Invariant Longitudinal Emittance per Bunch (eV s)	0.01
Average Beam Current during Pulse (mA)	18

capture into the Linac 201 MHz RF system, the longitudinal emittance and intensity per bunch are reduced because the number of bunches in increased. See table 3 for expected beam parameter values. One of the interesting features of this calculation is the fact that the average beam current during the antiproton pulse is 18 mA, which is about half of the average H^- current. The transfer and capture efficiency of 75% is an estimate again based on H^- transfer from the end of the Linac down to the Booster and extrapolating kicker based extraction efficiency from other accelerators.

Deceleration of the antiprotons traveling up the Linac is the first time the transverse aperture of the vacuum vessel (either beam pipe or RF cavity) is guaranteed to scrape away particles and reduce the deceleration efficiency. For an aperture restriction which is comparable or longer than a betatron oscillation, the reduction in beam intensity of a Gaussian profile beam from the half aperture Δ is

$$\frac{N}{N_0} = 1 - \exp\left[-\frac{\Delta^2}{2\sigma_\perp^2}\right]. \tag{3}$$

Because of the energy dependence of the beam size indicated in eq. (1), the worst case aperture occurs at the very upstream end of the Linac when the beam has a kinetic energy of 750 keV. Table 4 contains a summary of the beam size and deceleration efficiency calculation results at the upstream end of the Linac.

Table 4
Parameter values for the antiproton beam at 750 keV in the Linac.

400 MeV Linac Antiproton Beam parameter	Value
Relativistic Momentum	0.04
Beta Function (m)	9
95% Normalized Transverse Emittance (π mm mr)	6
RMS Beam Size (mm)	15
Transvsere Aperture Radius (mm)	30
Antiprotons Inside Transverse Aperture (%)	85
Minimum RMS Energy Spread (keV)	660
Energy Aperture (keV)	100
Antiprotons Inside Longitudinal Aperture (%)	1
Total Number of Surviving Antiprotons	0.6×10^9

Table 5
Parameter values for antiproton capture in a magnetic trap.

Antiproton Trap parameter	Value
Maximum Relativistic Velocity at 200 keV	0.02
Maximum Velocity at 200 keV (m/s)	6.2×10^6
Antiproton Pulse Length (ns)	530
Required Trap Length (m)	1.64

Therefore, approximately 0.5% of the beam survives to the end of the Linac. The transverse beam profile is a slightly clipped Gaussian of full width 60 mm. After using the 201 MHz bunching cavity at the end of the Linac as a debuncher, the longitudinal beam phase space distribution is rectangular with a full pulse length of 530 ns and a full energy spread of 200 keV. The magnetic trap used to capture these antiprotons must be able to accept a beam with these characteristics.

One possible scenario would be to electrostatically decelerate solenoidally focused antiprotons by 650 keV so that some antiprotons are just stopping while others are reduced to a kinetic energy of 200 keV. Using a linear trap where the magnetic confinement fields on one end can be opened to inject beam and then closed again to trap the beam, the required length of the trap is determined by the 200 keV antiproton time-of-flight. In table 5 the beam parameters above are summarized along with the calculation result that the minimum length of the trap is 1.64 m.

4. Positron production

Many of the applications for low energy antiprotons call for the production of antihydrogen. Therefore, positrons must be injected into the trap. At present there is no explicit source of positrons at Fermilab.

Using as much of the existing accelerator hardware as possible, one scenario is to direct the 400 MeV kinetic energy H^- beam at the exit of the Linac into a target. With the addition of focusing and steering optics, the result would be a useable positron beam. Within the energy bandwidth of 10 MeV to 20 MeV the expected H^- to positron production efficiency is expected to be approximately 10^{-5} [8]. For a typical H^- current of 30 mA, the average positron current would be 300 nA. Because a 10 MeV positron has a relativistic velocity of unity, the maximum pulse length injected into the 1.64 m trap is 11 ns. At a bunch spacing of 201 MHz, it corresponds to a practical limit of a H^- single bunch. The number of H^- atoms per bunch is 1×10^9, which means that the number of positron per pulse would be roughly 10 000. These values are summarized in table 6. This form of positron production could be carried

Table 6
Parameter values for the positron capture in the trap.

Antiproton Trap parameter	Value
Maximum Momentum Aperture (MeV/c)	19.4
Maximum Relativistic Positron Momentum Aperture	38
Maximum Relativistic Positron Velocity	1
Available Positron Kinetic Energy Aperture (MeV)	38
H^- Atoms per Bunch at 30 mA	1×10^9
Positrons Production Efficiency	1×10^{-5}
Positrons per Bunch	1×10^4

out during normal beam operations parasitically without requiring additional Linac pulses.

If the trap could cool the positrons in 3 s, which is the average Linac pulse rate, targeting one bunch each pulse would allow stacking positrons at a rate of 12×10^6/h. Assuming the transfer cycle of antiprotons into the trap is twice per day, this means a dedicated positron stacking trap could make 1×10^8 positrons available for the creation of antihydrogen.

5. Required hardware modifications

Even though the vast majority of work required to accomplish antiproton deceleration and trapping is in control software, a modest hardware modification effort cannot be avoided. The following changes are listed in the order of descending antiproton energy.

The low level control circuits for the Booster RF system were designed on the assumption that the entire ring is filled uniformly with beam. In the case of antiproton production, only part of the Booster azimuth is filled. Therefore, sample and hold electronics are needed to mimic the signal from a full ring. Electronic hardware for this purpose already exists in the Main Ring, and could be quickly reproduced for the Booster.

Once the beam is decelerated to a kinetic energy of 400 MeV it must be extracted from the Booster. It may be possible to use the already existing Booster extraction kicker magnets to perform this operation. A detailed study of this question is required. The worst case conclusion would be the need for installing existing spare kicker and septum magnets from another Fermilab accelerator.

Unlike the case of the Booster and the Main Ring, where the combination of opposite proton to antiproton charge and direction conspire to allow the same sign magnetic bend and focusing magnetic fields, the 400 MeV transfer line magnets between the Booster and Linac would have to have reversible fields. In addition, in order to avoid reversing the sign of all Linac magnets, 400 MeV transfer line quadrupoles strengths would be modified via computer to match into the reversed Linac magnetic lattice the antiprotons would encounter.

At the upstream end of the Linac there exists a 201 MHz RF cavity with a 2π mm mr transverse aperture. Without replacing this cavity with a wider aperture version, the net deceleration efficiency would decrease by an additional factor of 0.2. Since this is a simple single cell cavity, the effort to replace it should be minor. If the replacement RF system is designed for a peak gradient of 650 keV, it could be phased for deceleration to accomplish the required energy distribution for entry into the Penning trap.

The bending magnet needed to send the antiproton beam into an enclosure suitable for the magnetic trap already exists. All that is needed is to provide the vacuum chamber and the 650 keV of electrostatic deceleration (if needed). The electrostatic deceleration voltage may be generated by a low current power supply, since the total

charge decelerated is sufficiently small to eliminate the need for high power devices such as Pelletrons [9]. The design of this line should be closely coupled to the design of the antiproton trap.

In order to capture the positrons in the magnetic trap, a 180° bend magnet, a return line, and 10 MeV of 201 MHz RF are required. The 180° bend magnet directs the positrons back toward the upstream end of the Linac. The 201 MHz RF system decelerates the antiprotons to the energy range 0–10 MeV such that they can be injected into the trap.

6. Possible future upgrades

The 0.5% deceleration efficiency and antihydrogen production rate in the minimal low energy antiproton facility outlined above can be greatly enhanced with additional hardware. The three upgrades outlined here improve the number of antiprotons captured, the number of positrons produced, and additional physics which could be performed.

As seen above, the dominant reason for low deceleration efficiency of antiprotons is energy spread. If a 400 MeV stochastic [10] or electron cooling [11] ring were built in the Booster tunnel, the longitudinal and transverse emittances could be reduced by at least an order of magnitude. In addition, this ring could act as a storage ring, allowing a more controlled transfer of beam to the trap at intervals and with pulse lengths tailored to the trap and the antihydrogen experiments. For cost and reliability reasons, the ring would probably be fabricated using permanent magnets [12].

The positron flux could be improved dramatically by building a 400 MeV electron linac. An RF photocathode electron gun project is already underway at Fermilab [13]. This beam concentrates 1×10^{10} electrons into a single bunch. In addition, the positron to electron production efficiency is 10–100%, much higher than the case of the H^- beam. Therefore, this positron facility would be 1×10^5 times more intense.

One physics goal of the low energy antiproton facility is to perform Hyperon colliding beam experiments with a 1 GeV proton–antiproton storage ring. In order to attain the highest possible luminosity, this ring would use the cooled antiprotons (and probably protons also) from the 400 MeV cooling ring and accelerate them back up to a kinetic energy of 1 GeV. This ring would probably also be placed in the present Booster tunnel.

7. Conclusions

A facility for producing low energy antiprotons and positrons at intensities much higher than presently available was described. An initial stage requiring minimal hardware modifications which could be commissioned in a short period of time with a small amount of manpower and financial resources was proposed. As physics results

demonstrate the need for a higher antihydrogen flux, upgrades are described which could trap higher intensity antiproton and positron ensembles.

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