Efficient transfer of positrons from a buffer-gas-cooled accumulator into an orthogonally oriented superconducting solenoid for antihydrogen studies

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Abstract. Positrons accumulated in a room-temperature buffer-gas-cooled positron accumulator are efficiently transferred into a superconducting solenoid which houses the ATRAP cryogenic Penning trap used in antihydrogen research. The positrons are guided along a 9 m long magnetic guide that connects the central field lines of the 0.15 T field in the positron accumulator to the central magnetic field lines of the superconducting solenoid. Seventy independently controllable electromagnets are required to overcome the fringing field of the large-bore superconducting solenoid. The guide includes both a 15° upward bend and a 105° downward bend to account for the orthogonal orientation of the positron accumulator with respect to the cryogenic Penning trap. Low-energy positrons ejected from the accumulator follow the magnetic field lines within the guide and are transferred into the superconducting solenoid with nearly

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100% efficiency. A 7 m long 5 cm diameter stainless-steel tube and a 20 mm long, 1.5 mm diameter cryogenic pumping restriction ensure that the 10^{-2} mbar pressure in the accumulator is isolated well from the extreme vacuum required in the Penning trap to allow for long antimatter storage times.

Contents

1. Introduction

Large numbers of trapped antiprotons ($\overline{p}$) and positrons (e$^+$) are required for precision antihydrogen ($\overline{H}$) studies. The goals of such studies are to test CPT invariance [1] and to measure the gravitational force [2] on antimatter.

Over the last 25 years, much effort has gone into capturing $\overline{p}$ into an environment suitable for long-term storage and manipulation and for the production and study of $\overline{H}$. During these years, $\overline{p}$ were slowed to 5 MeV at CERN, first by the LEAR (Low-Energy Antiproton Ring) and then by the AD (Antiproton Decelerator), and were further slowed in a beryllium degrader. In 1986, $\overline{p}$ were first captured in a Penning trap [3], housed in a superconducting (SC) solenoid and then cooled to meV energies [4] by thermalizing with a plasma of electrons. Antiproton storage times of up to 1 month [5] indicated a pressure inside the 4.2 K vacuum enclosure of less than 7×10^{-17} mbar. Larger Penning trap electrodes allow for a loading rate of over 10^5 $\overline{p}$ per 90 s cycle of the AD [7]. Stacking of $\overline{p}$ from subsequent cycles of the AD traps a greater number (up to 10^7) of $\overline{p}$ [8]. A pumped helium system allows for $\overline{p}$ within a 1.2 K Penning trap [9]. Antiproton plasmas have been further cooled by evaporative cooling [10] or, more recently, by adiabatic cooling [7]. The latter allows for cooling of the $\overline{p}$ without any $\overline{p}$ losses.

The availability of radioactive isotopes that produce e$^+$ through β^+ decay makes e$^+$ considerably easier to obtain than $\overline{p}$. However, trapping e$^+$ in the same Penning trap apparatus as $\overline{p}$ is a considerable challenge. e$^+$ loading is restricted by the limited access and large fringing magnetic fields of the SC solenoid, and it is essential that the cold temperature of the Penning trap and of the $\overline{p}$ be maintained, as must the extreme vacuum needed for long-term storage of antimatter. These challenges were first overcome [11] by lowering a ^{22}Na radioactive source to a position just above the Penning trap (inside of the high magnetic field of the SC solenoid), which allowed high-energy e$^+$ to pass through a thin titanium foil into the Penning trap vacuum system, where they were moderated by single-crystal tungsten to produce e$^+$ of about 1 eV. At the exit of the moderator, some of the slow e$^+$ bind with an electron to form a highly excited state of positronium, which is Stark ionized inside of the Penning trap, allowing the e$^+$ to be captured in the trap [12]. An advantage of this loading technique is that extremely low vacuum

pressures can still be achieved since an isolated sealed cryogenic vacuum system is maintained. This method allows for loading rates of up to 4×10^4 e$^+$ h^{-1} per mCi of ^{22}Na [13].

An alternative method for obtaining e$^+$ for $\overline{\text{H}}$ studies [14] uses a buffer-gas-cooled e$^+$ accumulator [15], in which e$^+$ from a ^{22}Na source are moderated in a cryogenic neon solid [16] to produce an intense beam of slow e$^+$. These slow e$^+$ are magnetically guided into a room-temperature Penning trap where inelastic collisions with nitrogen molecules in the buffer gas reduce the e$^+$ kinetic energy, causing them to be axially trapped in the electric potential wells of the Penning trap. Radial confinement is provided by an axial magnetic field, and a rotating transverse electric field compresses the trapped e$^+$ plasma to within a small radius near the axis of the accumulator [17]. Such an e$^+$ accumulator can collect e$^+$ at much higher rates than the positronium method described above, but has the disadvantage of requiring approximately 10^{-2} mbar of buffer gas.

The magnetic guide described in this work is used to transport e$^+$ from the higher pressures of the buffer-gas-cooled e$^+$ accumulator to the extremely low pressures of the cryogenic ATRAP Penning trap used for $\overline{\text{H}}$ studies. The e$^+$ accumulator is located 6 m from the cryogenic Penning trap. The magnetic field of this accumulator is horizontally oriented, whereas the magnetic field of the cryogenic Penning trap is oriented vertically. This paper describes the techniques and challenges of efficiently transporting large numbers of e$^+$ from the accumulator to the cryogenic Penning trap while maintaining a vacuum suitable for antimatter confinement.

2. The ATRAP apparatus

The ATRAP cryogenic Penning trap has a vertical magnetic field (of 1–3 T) provided by a 152 cm high, 62 cm diameter SC solenoid. There are distinct advantages of orienting the cryogenic Penning trap vertically. A vertical orientation simplifies the cryogenic system design required to maintain a temperature of 4.2 K for the SC solenoid and a temperature of 1.2 K for the Penning trap electrodes [9]. Long thermally insulating supports suspend the Penning trap electrode stack from only a few points at the top of the trap, whereas a far larger number of shorter supports would be required along the length of the cryogenic Penning trap if it were oriented in the horizontal direction, resulting in much poorer thermal isolation. With the vertical design, the ATRAP cryogenic Penning trap can maintain its operating temperature for more than 30 h between liquid-helium refills of the 60 liter dewar. The vertical orientation will also facilitate higher-precision tests of gravitational forces on antimatter, since it allows far more distance for the neutral $\overline{\text{H}}$ to accelerate under gravity before annihilating on the walls of the apparatus.

The simplest experimental setup for introducing e$^+$ into the $\overline{\text{p}}$ Penning trap would be to have the e$^+$ accumulator and the cryogenic Penning trap aligned coaxially as in [14]. In such a configuration, the magnetic field lines originating from the central axis of the e$^+$ accumulator would continue into the field lines on the central axis of the SC solenoid, and these field lines would guide the e$^+$ along this axis. The challenge that ATRAP faced in implementing a buffer-gas-cooled e$^+$ accumulator is that the vertical space above the cryogenic Penning trap is restricted by clearance for a bridge crane used inside the AD hall, making such a coaxial alignment impossible. Instead, the e$^+$ accumulator was oriented horizontally and was placed at the nearest location available in the AD hall (approximately 6 m away from the SC solenoid), and a magnetic guide that has two bends (15° and -105°) was implemented, as shown in figure 1.
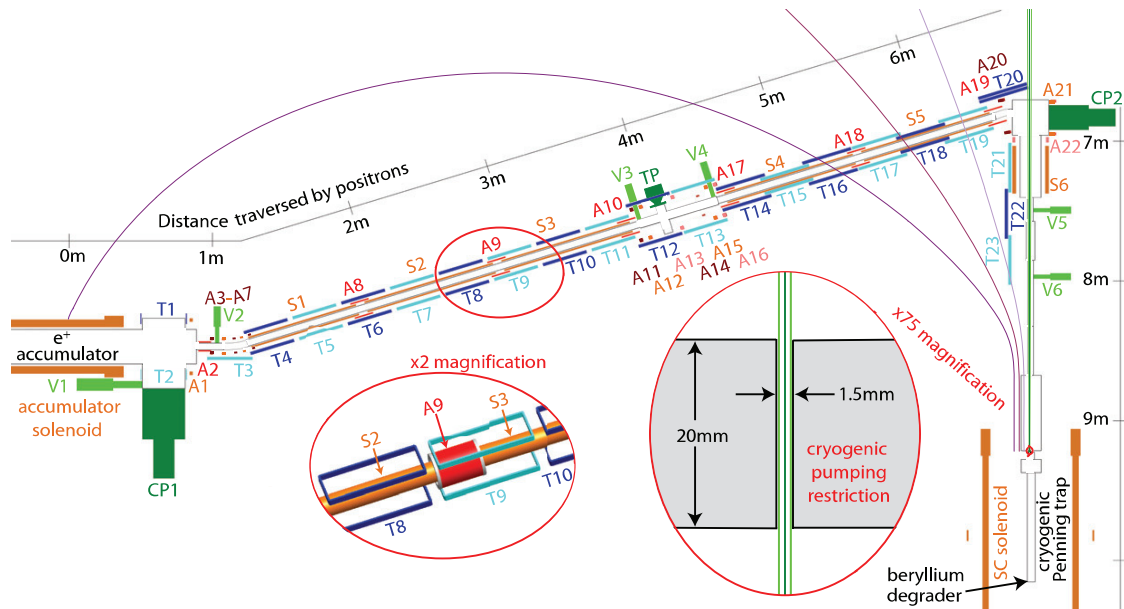
Figure 1. Magnetic guide for e$^+$. Axial magnetic fields used to guide the e$^+$ are provided by solenoids S1–S6 and supplementary circular electromagnets A1–A22, along with the fringing fields of the 0.15 T accumulator solenoid and the 1–3 T SC solenoid. The fringing field of the SC solenoid (purple field lines) and other external fields need to be canceled by a set of rectangular electromagnets T1–T23 (a three-dimensional view of some of these electromagnets is shown in the inset). A similar set of rectangular electromagnets (not shown) cancel smaller external fields in the other transverse direction (perpendicular to the plane of the figure). The SC solenoid field lines shown (both near the axis of the solenoid (in green) and far off of the axis (in purple)) do not include the effect of any of the other electromagnets.

3. The positron magnetic guide

To ensure that $\overline{p}$ and $\overline{H}$ do not annihilate quickly with residual gas in the cryogenic Penning trap located inside of the SC solenoid, an extremely low vacuum pressure is required. With this in mind, the e$^+$ magnetic guide is designed to act as a pumping restriction that isolates the buffer-gas-cooled e$^+$ accumulator, which has pressures of 10^{-2} mbar, from the cryogenic Penning trap, which was shown to have a vacuum pressure of less than 7×10^{-17} mbar in an earlier, closed apparatus [5]. To maintain a low pressure in the e$^+$ magnetic guide, a 3600 liter s^{-1} cryopump (CP1 at 0.7 m in figure 1) ensures that very little of the buffer gas enters the magnetic guide. An 80 liter s^{-1} turbo pump (TP at 4 m in figure 1) and a 1500 liter s^{-1} cryopump (CP2 at the 7 m in figure 1) provide successively lower pressures along the magnetic guide. The pressure in the vacuum space near CP2 is 10^{-8} mbar. A 1.5 mm diameter, 20 mm long hole maintained at 4.2 K, and located inside of the SC solenoid (as shown in figure 1) provides a final pumping restriction while allowing e$^+$ to enter the cryogenic Penning trap. Background gas atoms and molecules incident on this pumping restriction freeze onto its cryogenic surfaces, with only the

small fraction with straight-line ballistic trajectories that do not hit these surfaces entering the cryogenic Penning trap.

With this system in place, an exceedingly good vacuum is maintained in the cryogenic Penning trap. An experiment where a calibrated number of $\bar{p}$ were held for 15 h in the Penning trap and then released and counted indicated a $\bar{p}$ loss rate consistent with zero, and set a minimum $\bar{p}$ annihilation lifetime of over 200 h. This lifetime is sufficient for precision $\bar{H}$ studies, and confirms that we have been successful in preserving the exceptional vacuum in our system despite the open connection to the 10^{-2} mbar e^+ accumulator system.

The e^+ must pass through the 1.5 mm cryogenic pumping restriction to enter the cryogenic Penning trap. Figure 1 shows some fringing field lines of the SC solenoid. One possibility for guiding e^+ from the accumulator to the SC solenoid would be to follow one of these fringing field lines (such as the purple line shown which intersects the e^+ accumulator). However, e^+ loaded along this field line would be 11 cm from the axis of the SC solenoid, well outside of the 1.5 mm pumping restriction and outside of the cryogenic Penning trap. In order to load e^+ near the axis, they must follow the field lines shown in green. The dark green field line goes through the center of the 1.5 mm pumping restriction, and the light green lines pass near the edges of the restriction. The main function of the magnetic guide is to direct the e^+ onto these central (green) field lines.

A series of electromagnets produce magnetic fields along the axis of the magnetic guide. Electromagnets A1 and A2 (of figure 1, where a cross-sectional view of the circular electromagnets is shown) continue the fringing field of the 0.15 T accumulator solenoid, and electromagnets A3–A7 bend these field lines by $15°$. Solenoids S1–S5 are wound directly on the outside of the 5 cm diameter stainless-steel vacuum tubes and provide an axial field of 0.02 T along the straight-line path to a point that is 3.5 m above the center of the SC solenoid. Electromagnets A8–A20 produce additional axial fields in locations where vacuum pumps, valves and flanges do not allow for a continuation of the main (S1–S5) solenoids. A particularly challenging region between S3 and S4 results from a pump and two valves (TP, V3 and V4 in figure 1), which are necessary so that the right-hand portion of the magnetic guide (from V4 to V5) can be removed (with breaking vacuum only between V3 and V4 and between V5 and V6) when access is needed for repairs and upgrades of the cryogenic Penning trap apparatus.

If it were not for the fringing field of the large-bore SC solenoid (and the earth's field of 5×10^{-5} T and fields produced by other electromagnets within the AD hall), the axial electromagnets would be sufficient to guide the e^+ along the $15°$ inclined straight-line path. The fringing field, however, is large (up to 0.015 T) at positions along the guide, and, as can be seen from the purple field lines in figure 1, is mostly perpendicular to the guide. To cancel these position-dependent fields, a series of individually controllable 30 cm long rectangular windings are placed in pairs above and below the magnetic guide (T3–T20 of figure 1). A similar set of rectangular electromagnets (not shown in figure 1) cancel smaller horizontal magnetic fields. Additional transverse electromagnets (T1, T2) ensure that the e^+ are guided into the center of the magnetic guide.

At the end of the 6 m long inclined section of the guide, electromagnets A21, A22, S6, T21, T22 and T23 cause the field line at the center of the guide to join the green field lines of figure 1 that go through the 1.5 mm cryogenic pumping restriction.

The e^+ are transferred adiabatically through the magnetic guide at low energies (10–100 eV). At these energies, the e^+ are expected to almost exactly follow the magnetic field lines, and this has been confirmed by numerical calculations of the trajectories. More precisely,
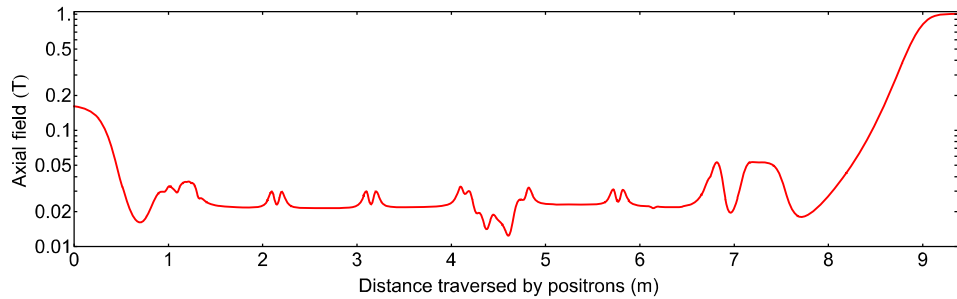
Figure 2. Axial field along the magnetic guide. The distance scale refers to the scale shown in figure 1. The axial field is 0.15 T in the accumulator (at 0 m) and remains at values of at least 0.012 T along the entire path to the SC solenoid (which has a 1 T field in this example).
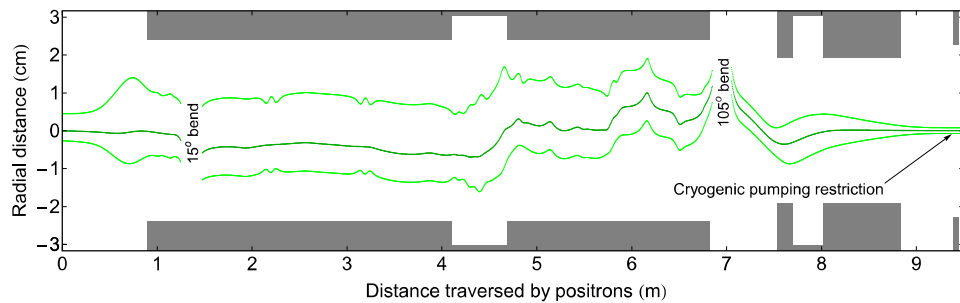

Figure 3. Field lines along the magnetic guide. The distance scale is that of figure 1, and the positions of the bends in the magnetic guide are noted on the plot. The scale of the y-axis of this plot shows the position of the field lines relative to an axis through the center of the guide and is expanded relative to the x-axis by a factor of 300 to allow a clear view of the field lines that go through the center (dark green) and edges (light green) of the 1.5 mm cryogenic pumping restriction. In this figure the SC solenoid has a field of 1 T. The field lines do not intersect the gray areas in the figure, which show the locations of the walls of the magnetic guide.

the e^+ execute cyclotron motion (with cyclotron radii much less than 1 mm) around the field lines leading to helical trajectories that remain centered near the field lines.

Figure 2 shows the magnitude of the axial magnetic field along the length of the guide. The field for most of the length of the guide is 0.02 T, with smaller axial fields (as low as 0.012 T) in the regions before S1, between S3 and S4 and after S5 of figure 1. The field lines are shown in figure 3. The field lines shown are the ones that go through the 1.5 mm pumping restriction (the same green field lines as those of figure 1, but now with the inclusion of the magnetic fields due to the 70 magnetic-guide electromagnets and the accumulator solenoid, and now traced back to the e^+ accumulator). The field-line spacing (the top to bottom line in the figure) is 7.5 mm within the e^+ accumulator, expands to 20 mm through most of the magnetic guide, where the field is 0.02 T, becomes as large as 28 mm at the lowest field points and finally reduces to 1.5 mm inside a 1 T field for the SC solenoid, as shown in figure 3. The wiggles in the field lines show that
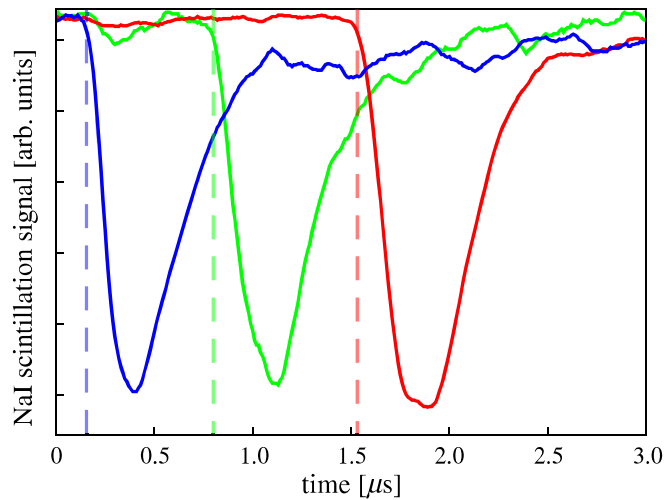
Figure 4. Signal seen on a NaI scintillating crystal for e^+ that are intentionally made to annihilate at V2 at 1 m in figure 1 (blue), at a retractable Faraday cup below TP at 4.1 m in figure 1 (green) and at a second retractable Faraday cup halfway between V5 and V6 at 7.8 m in figure 1 (red).

the transverse magnetic field (mostly due to the fringing field of the SC solenoid) cannot be canceled perfectly using the series of finite-length rectangular electromagnets, but it can also be seen that the field lines stay safely away from the stainless-steel walls of the magnetic guide. The wiggles become more pronounced when the SC solenoid is energized to its maximum field of 3 T.

Initially, it was a significant challenge to find the current settings for the 70 electromagnets that would connect the central field lines of the accumulator to the central field lines of the SC solenoid. It is necessary to have the field lines not intersecting the 5 cm diameter stainless-steel vacuum tube, since otherwise the e^+ would annihilate. These annihilations produce 511 keV gamma rays, which are detected with NaI scintillating crystals and photomultiplier tubes. For a plasma of e^+ launched in a short time window from the e^+ accumulator (with a kinetic energy set by the electrostatic potential from which they are released—typically 10–100 eV), the timing of the annihilation signals depends on the distance the e^+ travel before annihilating on the surfaces. Figure 4 shows signals from a NaI detector located 11 m away from the magnetic guide, at a position where the detector has a relatively unobstructed view of the entire magnetic guide. From the launch energy for the e^+ and the delay time to the NaI signal, it is possible to determine the approximate position of the annihilations and therefore to determine which electromagnet should have its current adjusted to better center the field lines through the 6 m long, 5 cm diameter tube and into the SC solenoid. After adjustment of the currents, there are no longer any visible signals on the NaI detectors, indicating that a negligible fraction of the e^+ hit the walls of the guide.

The 70 electromagnets of the e^+ magnetic guide are energized by independent programmable power supplies operating in constant-current mode. The voltages across shunt resistors in series with each electromagnet are monitored and recorded every few minutes as a means of precisely monitoring the current in the electromagnet. In addition, the voltage

across each electromagnet is monitored and recorded to identify possible shorts or elevated temperatures in the windings of the electromagnets. The active monitoring provides an immediate warning if any of the voltages or currents have fallen out of their typical operating range.

A series of Faraday cups provides an additional diagnostic tool for monitoring the transport of e^+ through the magnetic guide. Faraday cups that can be moved into (or out of) the e^+ path are located at 0.7, 4.1 and 7.8 m in figure 1. An additional Faraday cup that could be inserted into the center of S5, and that could be moved along the length of S5, was critical for tuning the magnetic field through this region where the fringing field of the SC solenoid and its gradient are particularly large. Just above the cryogenic pumping restriction (shown in the inset of figure 1), a Faraday cup segmented into four quadrants detects the charged particles that make it through the entire magnetic guide, but are not aimed through the 1.5 mm hole. By monitoring the charges on these four quadrants, the e^+ can be guided onto the central axis of the cryogenic Penning trap. When the electromagnets are tuned to guide the e^+ onto the central axis, no e^+ are found to hit any of the four quadrants. Finally, the beryllium degrader at the bottom of the cryogenic Penning trap of figure 1 (used to slow the $\bar{p}$ which enter from below) also acts as a Faraday cup to monitor the charged particles that make it through the pumping restriction. A movable electron gun can be inserted just before the accumulator solenoid to provide an intense continuous beam of electrons that can be monitored on each Faraday cup to aid in optimizing the currents for the 70 electromagnets of the magnetic guide. e^+ could also be detected on each Faraday cup by measuring the integrated current with a charge amplifier when an accumulated plasma of e^+ are launched from the e^+ accumulator.

4. Performance of the e^+ magnetic guide

The e^+ magnetic guide has performed with high reliability during its five years of operation. Typically, 10^7 e^+ are launched into the magnetic guide. The fact that no e^+ annihilations are seen on the NaI scintillating detectors during the $3\,\mu$s period (see figure 4) that it takes for the e^+ to traverse the magnetic guide indicates that no e^+ are lost as they travel between the accumulator and the SC solenoid. Charge measurements on a Faraday cup inside the SC solenoid confirm that all e^+ successfully enter the large magnetic field of the SC solenoid. The fact that no e^+ hit the four quadrants of the Faraday cup surrounding the 1.5 mm cryogenic pumping restriction indicates that the e^+ are tightly focused to less than this 1.5 mm diameter within the field of the SC solenoid.

When e^+ are launched from the accumulator into the magnetic guide, the details of the spatial and velocity distributions of the e^+ before launch, and of the space charges and applied potentials during launch, can affect the distribution of kinetic energies for the released e^+. The launch leads to most of the e^+ kinetic energy being due to the axial motion along the magnetic guide (along the direction of the field lines), but some of the kinetic energy is also due to transverse motion (which leads to cyclotron orbits around the field lines). As the e^+ enter the larger field of the SC solenoid, the angular momentum due to this cyclotron motion is conserved (since there is no torque), but due to the smaller cyclotron orbits in the larger field, the transverse velocity must be increased to maintain the angular momentum. The result is that the axial kinetic energy is reduced. The effect slows the e^+ and leads to a larger axial energy distribution for the e^+. This axial energy distribution is measured by applying a series of increasing potentials in an attempt to block the e^+ from reaching the beryllium degrader, as shown in figure 5. The
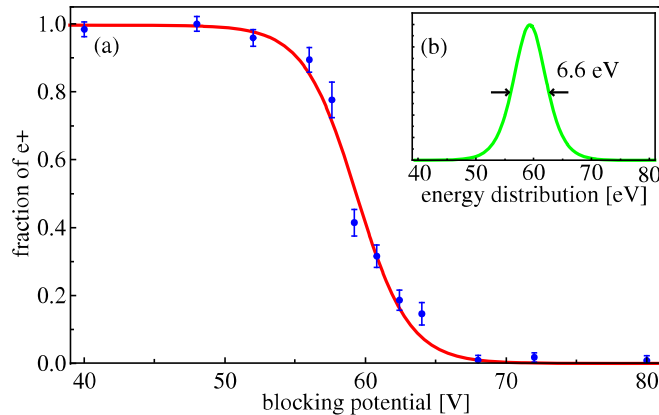
Figure 5. The energy distribution of the e⁺ as they enter the 1 T field of the superconducting solenoid. The fraction of e⁺ that pass by a blocking potential barrier is shown in (a). The energy distribution of the e⁺ entering the cryogenic Penning trap (b) is obtained from the derivative of the red curve.
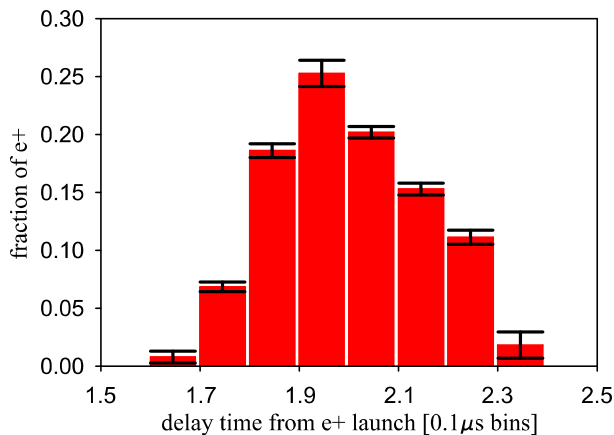

Figure 6. Temporal spread of the e⁺ as they enter the SC solenoid.

figure demonstrates that the width of the e⁺ axial energy distribution within the SC solenoid is 7 eV, or ±6% of the average value. The lowest observed energy is 50 eV, indicating that this slowing effect is not large enough to cause so-called magnetic mirroring, in which the e⁺ lose all of their axial kinetic energy, and are reflected back out of the higher field. As expected, no annihilations are seen with the NaI detectors at delayed times due to magnetic mirroring of e⁺.

The same factors that affect the energy distribution can also affect the arrival time of the e⁺ into the SC solenoid. Figure 6 shows the distribution of arrival times, as measured using a large blocking potential that was pulsed off at a series of times. The figure shows that almost all e⁺ arrive in a time interval of less than 600 ns.

The combination of a small range of energies (figure 5) and a small range of arrival times (figure 6) makes it possible to capture most of the e⁺ in the cryogenic Penning trap.

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5. Conclusions

We have demonstrated that the large numbers of e^+ available from a buffer-gas-cooled e^+ accumulator can be transferred from this accumulator into a perpendicularly oriented SC solenoid containing a cryogenic Penning trap used for $\overline{\text{H}}$ studies. The e^+ are transferred along a magnetic guide with near unity efficiency. The time and energy distributions of the e^+ as they enter the SC solenoid are sufficiently small to allow for efficient capture of the e^+ in the cryogenic Penning trap. Most importantly, the vacuum of this cryogenic Penning trap is demonstrated to still be sufficient to allow for long storage times of $\overline{p}$, despite the open connection between this vacuum system and the 10^{-2} mbar of pressure in the e^+ accumulator, thus allowing for the possibility of precision $\overline{\text{H}}$ studies.

Acknowledgments

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