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Electron-cooled accumulation of 4×10^9 positrons for production and storage of antihydrogen atoms

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Abstract

Four billion positrons (e^+) are accumulated in a Penning–Ioffe trap apparatus at 1.2 K and $<6 \times 10^{-17}$ Torr. This is the largest number of positrons ever held in a Penning trap. The e^+ are cooled by collisions with trapped electrons (e^-) in this first demonstration of using e^- for efficient loading of e^+ into a Penning trap. The combined low temperature and vacuum pressure provide an environment suitable for antihydrogen ($\overline{H}$) production, and long antimatter storage times, sufficient for high-precision tests of antimatter gravity and of CPT.

Keywords: positrons, antihydrogen, Penning trap

(Some figures may appear in colour only in the online journal)

1. Introduction

Cold antiprotons ($\overline{p}$) and cold positrons (e^+) are required to achieve the substantial number of trapped antihydrogen ($\overline{H}$) atoms desirable for precise tests of CPT [1] and of antimatter gravity [2]. CERN's antiproton decelerator provides 5 MeV $\overline{p}$, which are slowed in a Be degrader, captured [3] in a 1.2 K [4] extremely high-vacuum Penning trap, cooled to meV energies by collisions with trapped electrons (e^-) [5], and further cooled by adiabatic cooling [6]. Each 100 s, 10^5 $\overline{p}$ are captured, and a total of 10^7 have been accumulated [6].

Larger loading rates and accumulations are possible for e^+ since they are available from β^+ decay of radioactive nuclei. However, e^+ for $\overline{H}$ production requires extremely high vacuum (to allow $\overline{H}$ storage for a long time), cryogenic temperatures and a 1 T magnetic field (lower than usual to allow for a magnetic minimum within a Ioffe trap). Each of these requirements provides a challenge for efficient accumulation of e^+.

This paper describes how these challenges are overcome and describes the accumulation of up to 4×10^9 e^+ into the 1.2 K extremely high-vacuum trap (which simultaneously traps $\overline{p}$) using e^- cooling of the e^+. The e^+ are accumulated at a rate of 2.4×10^4 e^+/s per mCi. This work represents the first demonstration of efficient capture of e^+ into a Penning trap using e^- to cool the e^+. The accumulated number is more than 3 times larger than that achieved in any other e^+ trap [7].

Cryopumping and differential pumping keeps the background gas in the 1.2 K trap at a number density of less than 500 cm^{-3}, despite being continuously open to a room-temperature e^+ system that uses a buffer gas to capture and slow e^+. The trap temperature and pressure are more than 8 and 900 times lower than used by others [8, 9]. The lower

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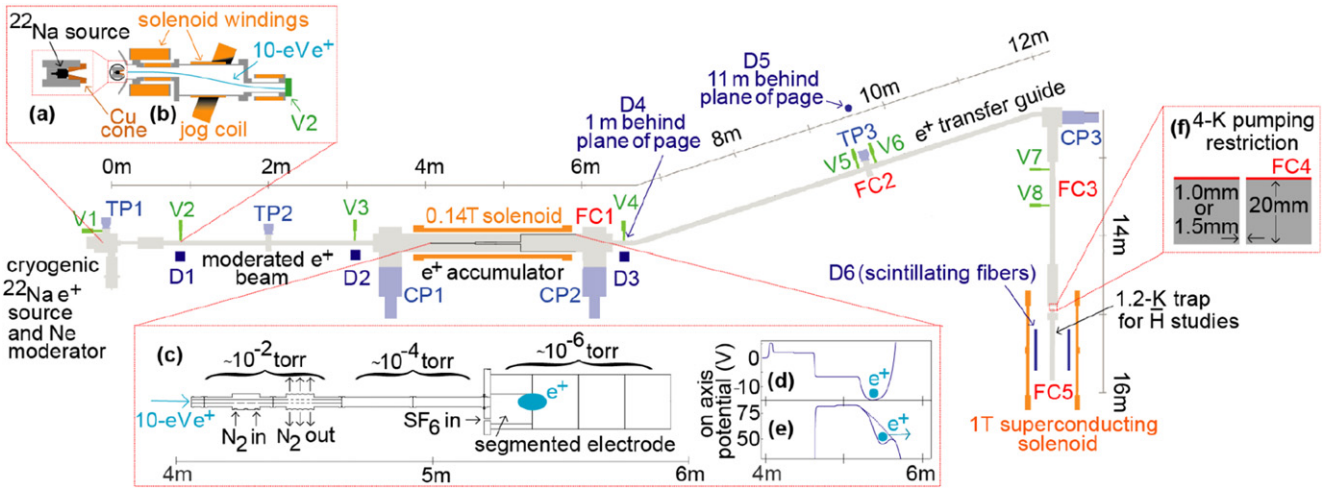

Figure 1. An overview of the 16 m long apparatus used to moderate e^+, capture them via N_2 collisions into a 0.14 T room-temperature accumulator, and transfer them into a 1 T trap, with expanded views of the ^{22}Na source and Ne moderator (a), the jog to separate out low-energy e^+ (b), electrodes and N_2 pressure in the accumulator (c), along with the potentials at the center axis of these electrodes for accumulation (d) and ejection (e) of e^+, and the 4 K pumping restriction, through which the e^+ enter the 1.2 K trap (f). Also shown on the figure are Faraday cups (FC), detectors (D) for gammas produced from e^+ annihilation, turbo pumps (TP), cryopumps (CP), and vacuum gate valves (V).

temperature is achieved by a pumped liquid-helium system [4]. Cryopumping by the 1.2 K electrodes and the surrounding 4 K vacuum enclosure provides the primary pumping for the trap. The 1.2 K trap is isolated from the much-higher-pressure room-temperature e^+ system by a very narrow 4 K tube through which the e^+ enter the trap. The lower temperature and pressure dramatically decrease collision rates [10] between low-energy $\overline{H}$ atoms and background gas and allow for long hold times for trapped $\overline{H}$ spectroscopy.

Already with the smaller number of e^+ available prior to this work, it was possible to create $\overline{H}$, both by three-body collisions [11, 12] and by laser-controlled charge exchange [13, 14]. It has now been demonstrated that $\overline{H}$ creation is still possible when the Penning trap is combined with a Ioffe trap [15], and this has allowed for the trapping of small numbers of ground-state $\overline{H}$ atoms [8, 9, 16]. Larger number of e^+ are now available, as described in this work, which may allow for enhanced $\overline{H}$ production. In particular, for the laser-controlled charge-exchange method, the $\overline{H}$ production rate is expected to grow linearly with e^+ number.

Other e^+ physics [17], including studies of surfaces and solids [18–22], and of positronium atoms (See, e.g., [23, 24]) and molecules [25], also require large numbers of e^+. These studies may also benefit from the efficient loading techniques and large e^+ numbers reported here.

Several steps are required to achieve the record number of trapped e^+ reported here, namely, (1) moderation of high-energy e^+ from a radioactive source to obtain low-energy e^+, (2) capture of these e^+ into an initial Penning trap using collisions with a gas, (3) transfer of these e^+ to the 1.2 K trap and (4) capture and cooling in this trap (using e^-). These steps are accomplished using the apparatus shown in figure 1 and are described below.

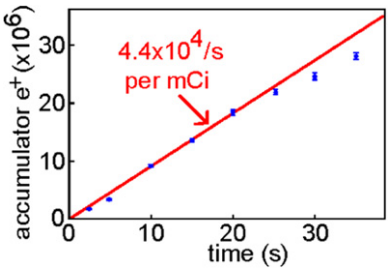

Figure 2. The number of e^+ captured in the room-temperature 0.14 T trap versus accumulation time.

2. Moderation and buffer gas accumulation

The e^+ are obtained from β^+ decay from a sealed ^{22}Na source [26] (50 mCi, 2.6 y half-life), with approximately 9×10^6 e^+/s per mCi emerging through the 5 μm thick Ti foil window at the front of the source capsule. Solid neon (at cryogenic temperatures) has been shown to be the most efficient moderator for e^+ obtained from β^+ decay [27–32], and thus we freeze a layer of Ne onto the Ti window of the ^{22}Na source and the Cu surfaces shown in figure 1(a). Up to $2.6 \pm 0.3 \times 10^5$ e^+/s per mCi are moderated in the Ne and emerge with a few eV of energy.

Moderated e^+, accelerated to approximately 10 eV of kinetic energy by a potential applied to the ^{22}Na source and moderator, are separated from the high-energy unmoderated e^+ by magnetically guiding them through the jog of figure 1(b). The 10 eV e^+ are captured into a 0.14 T, room-temperature Penning trap via three inelastic collisions with an N_2 buffer gas (as in [33]). Figures 1(c) and (d) show the electrodes, approximate pressures and on-axis potentials within the three stages of this trap. Figure 2 shows that 4.4×10^4 e^+/s per mCi accumulate in the third stage, at an N_2 pressure of approximately 10^{-6} Torr. This figure shows

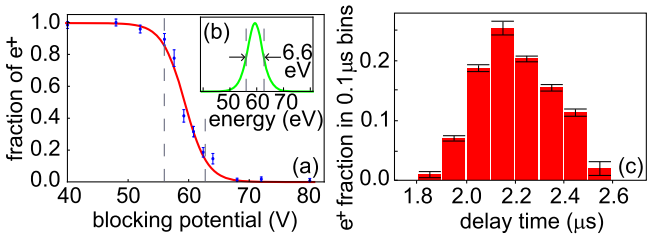

Figure 3. Blocking the e^+ entering the 1 T trap with a potential (a) determines the axial kinetic energy distribution (b). The timing of the e^+ entering the trap is shown in (c).

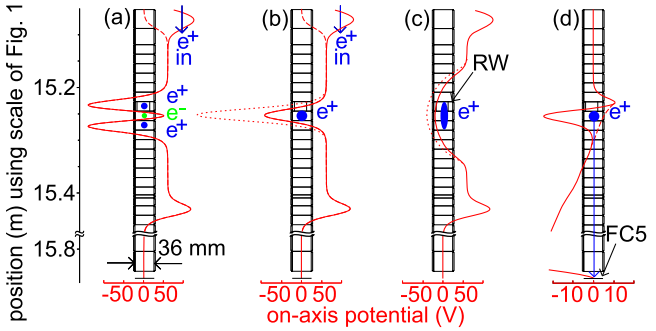

Figure 4. The hollow cylindrical electrodes of the 1 T trap, along with the on-axis potentials used (a) to capture e^+ and cool them with e^-, (b) for e^+ cooling after e^- are ejected, (c) to radially compress the e^+ using a rotating wall in an extended well, (d) to send the e^+ to FC5 for charge counting. The solid lines in (b) and (c) give the initial wells, and the dotted lines indicate how these wells are deepened after one billion e^+ are accumulated. To count the accumulated e^+ on FC5, they are suddenly ejected (dashed line in (d)).

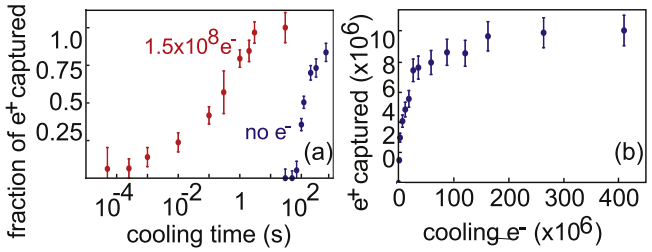

Figure 5. The time required for the e^+ to cool is substantially reduced (a) with 150 million e^- compared to no e^- cooling. The dependence of the cooling efficiency on the number of cooling e^- is shown in (b).

that the number of e^+ accumulated is approximately proportional to time (to within 10% for times of less than 30 s), which indicates that annihilation losses are less than 10% for the 30 s accumulation time used. Time-varying potentials are applied on the azimuthally segmented electrode of figure 1(c) to produce a rotating electric field (often referred to as a rotating wall [34]). The rotating wall counteracts outward migration of e^+ resulting from trap asymmetries and non-harmonicities, and reduces the radius of the e^+ plasma to 3 mm. Collisions with the N_2 and 3×10^{-8} Torr of SF_6 cool the e^+.

3. Positron transfer into 1.2 K trap

After 30 s of accumulation, the e^+ well is elevated to +50 V (solid line in figure 1(e)), and the e^+ are suddenly ejected (dashed line in figure 1(e)). A 0.02 T field in the magnetic guide connects central field lines of the 0.14 T accumulator to central field lines of the 1 T trap, with 70 independently controlled sets of magnet windings used to overcome the fringing field of the 1 T solenoid. The e^+ are magnetically guided [35] along a 10 m path into the 1 T superconducting solenoid. The guide is nearly 100% efficient, having no detectable loss when transferring e^+ into the 1 T field despite the 15° upward bend and 105° downward bend of figure 1 to account for the orthogonal orientation of the 0.14 and 1 T fields. The 30 s cycle time is chosen to maximize the number of e^+ transferred and allows for 3 e^+ transfers within the 100 s $\bar{p}$ cycle of the CERN antiproton decelerator when simultaneously loading e^+ and $\bar{p}$.

Approximately 60% of the e^+ make it through the 1.5 mm diameter cryogenic pumping restriction (figure 1(f)). They enter the 1 T trap with a 6.6 eV energy width (figure 3(b)), 1.8–2.6 μs after they are ejected from the e^+ accumulator (figure 3(c)). The spread in time and energy is partially due to conversion of axial energy into cyclotron energy, as required to conserve angular momentum, when the e^+ enter the 1 T field. To capture the e^+, a 40 cm long potential well (see, for example, figure 4(b)) is momentarily opened (dashed line) to allow e^+ to enter, and closed before the e^+ travel the 80 cm return trip. The well is offset from zero potential to slow the e^+ during this return trip. The long well and the slow speed allow more than 85% of the e^+ that enter to be captured, despite the energy and temporal distributions of figure 3.

Since the 40 cm long well is reopened every 30 s (for the next e^+ accumulation), it is necessary that the e^+ quickly cool into the deep well of figure 4(b). The cyclotron motion cools by synchrotron radiation, which has a time constant of $\tau_c = 3c/(4r_0\omega_c^2) = 2.7$ s. (Here r_0 is the classical radius of the electron, ω_c is the cyclotron frequency for the e^+ in the 1 T field, and c is the speed of light.) To cool the axial motion (the vertical oscillations in the long well of figure 4(b)) it is necessary to transfer axial energy into cyclotron energy via e^+–e^+ collisions. With 10^7 e^+ present in the 40 cm well, these collisions happen at a slow rate, and the e^+ take more than 10^2 s to cool into the deeper well (as shown in figure 5(a)). This rate is too slow given that the well needs to be reopened every 30 s to receive the next accumulation of e^+. To resolve this problem, we have implemented a new e^- cooling technique. Compressing the accumulated e^+ with a rotating wall could also reduce the cooling time with no e^- present, and might be an alternative method to increase the rate of e^+ cooling.

4. Electron cooling of positrons

Before transferring the first e^+, 1.5×10^8 photoelectrons obtained using a UV laser [36] are loaded into the center of the nested well at 15.25 m in figure 4(a). These e^- form a

plasma with a measured radius of approximately 1 cm and a density of approximately 10^8 cm^{-3}. As in figure 4(b), the e^+ are captured by momentarily opening the 40 cm well (dashed line) and the captured e^+ pass through the space charge of the e^- plasma with a kinetic energy of approximately 35 eV. The e^+ lose energy by collisions with the e^-, and the time constant for capture into one of the two e^+ wells on either side of the e^- well is 1 s (as shown in figure 5(a)). This time agrees with the predicted cooling time constant of 0.1 s for 35 eV e^+ in an e^- plasma [37] of this density, when one considers that the e^+ spend only approximately 1% of their time in the e^- plasma and that they only need to lose 10% of their kinetic energy to be captured into one of the e^+ wells.

Once captured, the e^+ continue to cool to the bottom of one or the other of the e^+ wells. Using methods similar to those in [6], where the temperature distribution of a $\overline{p}$ plasma is measured by counting the number of $\overline{p}$ that escape over a potential barrier of known height, the e^+ temperature is confirmed to be less than 100 K. This upper bound ensures that the e^+ can be used for production of $\overline{H}$ by either of the demonstrated production methods [11, 12, 14]. The e^+ temperature is likely to be similar to the inferred e^- temperature of 17 K [6], and should thermalize to the 1.2 K temperature of the electrodes in the absence of electrical noise.

This work represents the first demonstration of efficient e^- cooling of low-energy e^+ into a Penning trap. The entire process works well, with $\geqslant$85% of the e^+ entering the 1 T trap being captured, cooled and accumulated. This efficiency is almost two orders of magnitude higher than that obtained from slowing [38] of a dc beam of moderated e^+ by dense e^- and ion clouds. The efficiency is similar to that obtained with neutral gas cooling, but such a cooling technique is inconsistent with our need for an extremely low vacuum pressure. The effectiveness of the capture versus the number of e^- used is shown in figure 5(b).

This new method of cooling e^+ using e^- has similarities to the method of cooling trapped $\overline{p}$ by e^- [5], but differs due to the opposite charges of e^+ and e^- and because of the possibility of e^+–e^- annihilation. The e^+–e^- annihilation rate is predicted to be many orders of magnitude smaller than the rate for cooling collisions [39]. The opposite charges require the nested well of figure 4(a), which is inherently less efficient for cooling due to limited spatial overlap between the e^+ and e^-. The opposite charges also allow for the possibility of forming bound-state positronium (Ps), but the rates for this formation are predicted to be many orders of magnitude lower than the rates for collisional cooling of the particles [39]. Even if Ps would be formed, the three-body formation is predicted to give very weakly bound states [40] which would Stark ionize in the electric fields seen by the Ps before exiting the nested well.

The e^- cooling is important for accumulating the first 1.5×10^8 e^+. However, once 1.5×10^8 e^+ are accumulated, the e^- are ejected, as this number of trapped e^+ provide approximately the same cooling as was obtained from the 1.5×10^8 e^-. The simpler well structure for this cooling is shown in figure 4(b). In this well, the plasma of 1.5×10^8 e^+ has a radius of approximately 0.6 cm and a density of approximately 1.4×10^8 cm^{-3}. The number of e^+ accumulated in the 1 T trap increases proportionally with time (figure 6), with the rate of accumulation unaffected by the ejection of e^-, showing that cooling using e^- or cooling using e^+ is equally efficient, and, as expected, that Ps formation and e^+–e^- annihilation are not significant for our method of cooling e^+ using e^-.

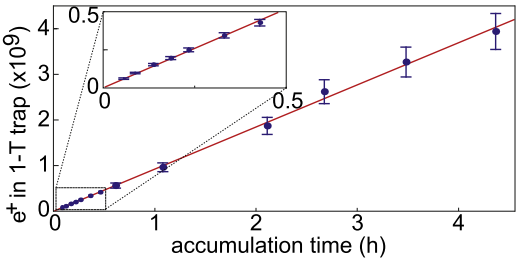

Figure 6. The number of e^+ accumulated in the 1 T trap versus time. Four billion e^+ are trapped in 4.5 h.

5. Accumulation of 4 billion positrons

As the number of e^+ in the 1 T trap increases, radial expansion of the e^+ plasma becomes a concern. To avoid radial expansion, every 1800 s the e^+ well is extended (figure 4(c)) and a rotating wall (with frequency 5 MHz and rms voltage of approximately 2 V) is applied for 150 s to the four-segment electrode marked RW in the figure. After the 150 s, the well reverts to the well structure of figure 4(b), but is deepened (as indicated, e.g., by the dotted line) to accommodate the larger charge. Each rotating wall application occurs in successively deeper wells, as indicated, e.g., by the dotted line in figure 4(c).

As shown in figure 6, 4×10^9 e^+ are accumulated after 4.5 h of accumulation. This is the largest number of e^+ that has ever been trapped in a Penning trap. In order to trap more than 1.2×10^9 e^+ (the previous record number of e^+ trapped [7]), both the rotating wall procedure and the process of deepening the wells were necessary. The excellent vacuum allowed for almost no annihilation of e^+ during the 4.5 h accumulation time. The linear trend in figure 6 suggests that it would be possible for more e^+ to be trapped using these techniques.

In order to trap $4 \times 10^9 e^+$, the potential of the trap is increased to an applied voltage of 1000 V (which leads to a 530 V deep potential well on axis in figure 4(b)), and the potential well of figure 4(c) used for the rotating wall is increased to 120 V. The current trap does not allow for the application of voltages larger than 1000 V.

Counting techniques based on Faraday-cup detection of e^+ charge (FC1–5 of figure 1) and on detection of e^+ annihilation gammas (with NaI(Tl) crystals D1–5 and scintillating fibers D6 of figure 1) have been used to determine the number of moderated and accumulated e^+. Faraday cups FC1–5 are connected to calibrated charge-sensitive amplifiers, with the

first four being retractable to allow the e^+ to pass by when these are not in use. Ejection of secondary e^- from the Faraday cups overestimates the count rate unless each Faraday cup is biased by $>+15$ V relative to its surroundings, as shown, e.g., in figure 4(d). Comparison of Faraday-cup counts obtained from e^- plasmas with counts from identical e^+ plasmas (created using a calibrated potential-well depth and measured using mode frequencies [41]) confirms that neither reflection of e^+ from the biased Faraday cup, nor annihilation gammas affect the charge measurement. D1–6 are also used for counting, and are calibrated with respect to the counts on the Faraday cups. FC1 through FC4 give consistent counts. No annihilation gammas are observed on D1–4 during the transfer, and 60% of the e^+ pass through the pumping restriction of figure 1(f) and are counted on FC5. A larger aperture in this pumping restriction would increase this percentage, but at the expense of a possible increase in vacuum pressure.

6. Extremely high vacuum for e^+, $\overline{p}$ and $\overline{H}$ storage

A 7 m long, 5 cm diameter, room-temperature, stainless-steel tube, and a 20 mm long, 1.0 or 1.5 mm diameter 4 K pumping restriction (figure 1(f)), along with a series of vacuum pumps (figure 1), isolate the extremely high-vacuum 1.2 K trap from the Ne, N_2 and SF_6 in the accumulator and from outgassing from room-temperature walls, despite vacuum valves V2–8 of figure 1 being always open to allow continued simultaneous accumulation of e^+ and $\overline{p}$. To measure the pressure in the 1.2 K trap, a calibrated number of $\overline{p}$ is held for 15.3 h with no observable loss ($<3\%$), implying a $\overline{p}$ hold time of more than 500 h and a background gas number density of $<50\,\mathrm{cm}^{-3}$. This represents the best measured evacuation for any vacuum system which includes room-temperature components. At 1.2 K, this number density corresponds to a pressure of $<6\times10^{-17}$ Torr, comparable to the record-low-pressure measurement of $<5\times10^{-17}$ Torr (obtained in an all-cryogenic system [42] previously used to hold $\overline{p}$).

A vacuum pressure of $<6\times10^{-17}$ Torr, along with a temperature of 1.2 K, implies a $\overline{H}$ collision rate of 0.3 per year [10], with direct annihilation collisions dominating over elastic collisions at this temperature. Here the background gas is assumed to be He since this is the only gas with a significant vapor pressure at 1.2 K (although similar collision rates would be expected from other gases). Room-temperature gas molecules that originate near the top of the e^+ transfer guide have a small probability of taking a straight-line path through the pumping restriction of figure 1(f) and into the 1.2 K trap, but are only a small contribution to the background gas. The low collision rate will allow for storage of trapped $\overline{H}$ for time scales of longer than one year, much longer than the estimated 300–10^5 s of another $\overline{H}$ trap [8, 9], and much greater than demonstrated hold times of approximately 1000 s [8, 9, 16].

7. Conclusions

In summary, we have developed methods for efficient e^- cooling of e^+ and for accumulating very large numbers of e^+ in a Penning trap. This work uses an extremely high-vacuum trap appropriate for Ps and $\overline{H}$ studies, but the results might also be applicable to other e^+ studies. Accumulations of up to 4×10^9 e^+ in a single Penning trap have been demonstrated. The trap simultaneously traps cold $\overline{p}$ for >500 h. The expected $\overline{H}$ hold time of >1 y will facilitate high-precision spectroscopy of $\overline{H}$, with the long hold time partially compensating for the much smaller number of $\overline{H}$ available than can be used for precision H spectroscopy. The large number of e^+ and the long hold time are significant steps towards furthering the study of $\overline{H}$ atoms.

Acknowledgments

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