Laser-cooled positron source ☆

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We examine, theoretically, the feasibility of producing a sample of cold ($\leqslant 4$ K), high-density ($\approx 10^{10}/\mathrm{cm}^3$) positrons in a Penning trap. We assume $^9Be^+$ ions are first loaded into the trap and laser-cooled to approximately 10 mK where they form a uniform density column centered on the trap axis. Positrons from a moderator are then injected into the trap along the direction of the magnetic field through an aperture in one endcap of the trap so that they intersect the $^9Be^+$ column. Positron/$^9Be^+$ Coulomb collisions extract axial energy from the positrons and prevent them from escaping back out the entrance aperture. Cooling provided by cyclotron radiation and sympathetic cooling with the laser-cooled $^9Be^+$ ions causes the positrons to eventually coalesce into a cold column along the trap axis. We present estimates of the efficiency for capture of the positrons and estimates of densities and temperatures of the resulting positron column. Positrons trapped in this way may be interesting as a source for antihydrogen production, as an example of a quantum plasma, and as a possible means to produce a bright beam of positrons by leaking them out along the axis of the trap.

1. Introduction

1.1. MOTIVATION AND BACKGROUND

For over a decade, slow positron beams using moderators [1–3] have found use in diverse areas such as the formation of positronium, measurement of atomic scattering cross sections, and surface studies. In addition to the importance of slow positron beams, it would be useful to have an accumulator and reservoir of cold positrons for various experiments. An important application of such a reservoir might be for forming antihydrogen by passing cold antiprotons through the positron reservoir and relying on three-body recombination [4]. Since the recombination rate is expected to scale as $n^2 T^{-9/2}$, where n and T are the positron density and temperature [4,5], it is important to achieve as high a density and as low a temperature as possible in the reservoir.

A cold positron reservoir has other potential applications. Surko et al. [6] point out possible applications such as the study of electron/positron recombination, the

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study of resonances in electron/positron scattering [6,7], a positron source for accelerators, a diagnostic for fusion plasmas, and studies of basic plasma physics. With the techniques described here, the resulting positron plasma may reach the conditions for a quantum plasma [8] in the sense that $\hbar\omega_p > k_B T$ where ω_p is the plasma frequency and k_B is the Boltzmann constant. The techniques described here may also be useful for providing a reservoir of cold high-Z ions or other ions which are difficult to cool by other means.

If cold positrons are extracted from the reservoir, a beam source with high brightness might be obtained. Such a source might be useful in atomic scattering experiments which seek to observe positron/atom scattering resonances, diffraction from atoms, and high angular resolution [3].

Several other groups have already investigated and demonstrated trapping of positrons in Penning traps. Schwinberg, Van Dyck, and Dehmelt have captured small numbers of positrons in a Penning trap by injecting positrons from a ^{22}Na source through an aperture in one endcap of the trap and extracting the axial energy by resistive damping of the currents induced in the electrodes [9]. Gabrielse and Brown have discussed a similar idea with potential increased loading efficiency by use of a moderated positron source [10]. Surko et al. have achieved a nonneutral positron plasma stored in a Penning trap [6]. In this work, positrons from a moderator are injected into the trap and their energy reduced by collisions with background gas. Conti, Ghaffari, and Steiger have trapped positrons in a Penning trap by injecting positrons from a moderator through one endcap while ramping the voltage of the trap [11]. Mills has discussed a scheme for positron accumulation in a magnetic bottle [12].

In this paper, we investigate the feasibility of making a positron accumulator and reservoir by injecting positrons from a moderator through an aperture in one endcap of a Penning trap and extracting axial energy from them through collisions with a simultaneously trapped laser-cooled ion plasma.

1.2. BASIC IDEA

The basic idea of the scheme is illustrated in fig. 1. We assume that ^{9}Be$^+$ ions are first loaded into a Penning trap and laser-cooled by established techniques [13]. With only ^{9}Be$^+$ ions in the trap, the ions form a uniform density nonneutral ion plasma (temperature $T(^9\mathrm{Be}^+) \approx 10$ mK) which rotates about the trap axis at frequency ω. We will assume the Debye length of the plasma is small compared to its dimensions. Therefore, the potential inside the plasma is independent of the axial coordinate. We assume that positrons from a moderator are injected through an off-axis aperture in one endcap (endcap 1) with just enough energy to pass through the center of the aperture. The potential at the center of the aperture is less than the potential V_1 of endcap 1 because of the proximity of the tube (held at potential $V_T < V_1$) between the moderator and endcap 1. The diameter of the ^{9}Be$^+$ plasma is assumed to be large enough that the incoming positrons pass through the ^{9}Be$^+$

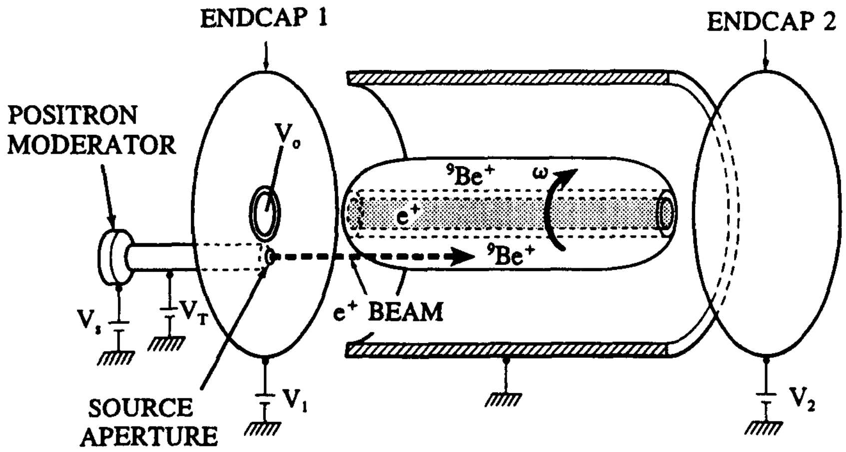

Fig. 1. Schematic diagram of a possible Penning trap apparatus for capturing and cooling positrons injected into the trap from a moderator. The trap magnetic field (not shown) is assumed parallel to the axis of the electrodes. The $^9Be^+$ ions damp the motion of the positrons along the B field direction causing them to be trapped. As the positrons are cooled, they are forced inside the $^9Be^+$ ions where they eventually form a cold column centered on the trap axis.

ion plasma. The other trap endcap (endcap 2) is biased at a potential V_2 which is sufficient to reflect the positrons back through the $^9Be^+$ plasma. Positrons inside the $^9Be^+$ plasma also rotate about the trap axis at approximately frequency ω. If ω is large enough and/or the $^9Be^+$ plasma is sufficiently long, the positrons will have been displaced azimuthually when they approach endcap 1 from inside the trap and are reflected by the potential V_1 back through the $^9Be^+$ plasma. As the positrons pass through the $^9Be^+$ ions they undergo Coulomb collisions which extract axial energy from them. At the low energies we consider, positron annihilation by collisions with the $^9Be^+$ ions is suppressed by Coulomb repulsion. Initially, the positrons' axial energy is primarily transferred into their cyclotron motion energy since the recoil energy of the $^9Be^+$ ions is small. If these collisions extract enough axial energy before the positrons encounter the entrance aperture again, they will be trapped. If the entrance aperture is mounted off axis, the positrons can make many oscillations along the trap axis (and through the $^9Be^+$ ions) before encountering the entrance aperture again. This is the same idea proposed by Dehmelt et al. [14] and used successfully by Schwinberg et al. [9] except we assume the axial energy is extracted by $e^+/^9Be^+$ collisions rather than resistive damping.

Once trapped, the positrons cool by cyclotron radiation and sympathetic cooling with the cold $^9Be^+$ ions. When sufficiently cooled, the positrons coalesce to a uniform density plasma column along the trap axis which co-rotates with the $^9Be^+$ plasma (both at frequency ω) as shown in fig. 1 [8,15,16]. At low temperatures, the

$^9Be^+$ plasma separates from the positron plasma forming an annular region outside the positron plasma [8,15,16]. Qualitatively, the separation occurs because of the larger outward centrifugal force on the $^9Be^+$ ions. The positron cyclotron motion is strongly coupled to the ambient temperature T_0 (4 K assumed here) by cyclotron radiation. At temperatures below about 10 K, the positron axial motion decouples from the cyclotron motion [17] and we expect the positron axial or "parallel" motion temperature $T_{\parallel}$ to be reduced to less than T_0 by the Coulomb interaction with the cold $^9Be^+$ ions. Therefore we expect the parallel temperature $T_{\parallel}$ to be lower than the cyclotron or "perpendicular" temperature $T_{\perp}$. For $\omega < \Omega/2$, the positron and $^9Be^+$ plasma densities will be approximately equal [8] and limited by the maximum attainable $^9Be^+$ plasma density (Brillouin density). Here we will make the approximation $n(e^+) \approx n(^9Be^+) \equiv n$. Since the Brillouin density for an ion species of mass M scales as B^2/M, where B is the magnitude of the Penning trap magnetic field, we want B as large as possible and M as small as possible. This is the reason for choosing $^9Be^+$ ions; other ions would work in the scheme described here, but $^9Be^+$ has the smallest mass of any of the positive ions which can be easily laser cooled therefore giving the highest density ($n \approx 10^{10}$ cm^{-3} for $B = 6$ T).

1.3. USEFUL FEATURES OF A LASER-COOLED POSITRON SOURCE

If this reservoir of cold positrons can be achieved, it should have some interesting features compared to those of other schemes. (1) Under the assumptions described below, the efficiency of capturing moderated positrons can be very high, approaching unity. (2) Relatively direct visual information is available on the positron plasma. By use of imaging techniques, the $^9Be^+$ plasma can be observed in real time [13,18]. The positron plasma is then observed by the "hole" it creates in the image of the $^9Be^+$ plasma. In this way we obtain fairly direct information on the size and shape of the positron plasma. (3) If there is sufficient Coulomb coupling between the positrons and $^9Be^+$ ions, the density and temperature of both species can be determined by spectroscopic techniques [13,18]. (4) The density of both plasmas can be varied by controlling the angular momentum imparted to the $^9Be^+$ plasma by the laser [13,18]. (5) The apparatus can be operated at high vacuum, thereby reducing positron loss due to annihilation or positron formation with neutral background gas.

1.4. APPROXIMATIONS

The calculations contained here are, admittedly, based on approximations. In addition, the availability of a moderated source with certain characteristics (in particular a small energy spread, $\Delta E_i = 0.1$ eV) is freely assumed. The purpose of these notes is to give an estimate of what might be achievable with the proposed technique.

2. Positron capture

2.1. POSITRON INJECTION

We assume positrons are emitted from a moderator (fig. 1) with axial energy spread and cyclotron energy spread both equal to ΔE_i. They enter the Penning trap along magnetic field lines through a tube held at potential V_T. We assume they enter the trap through a circular aperture in endcap 1 which is offset from the trap axis by distance R_A. Near the center of the aperture the potential is between V_1 and V_T; we consider an area A_1 ($= \pi r_A^2$) centered on the aperture which is smaller than the geometrical area of the aperture. The area A_1 is such that V_1 minus the potential within A_1 is larger than ΔE_i. We make the approximation that over A_1 the potential is constant and equal to V_A, where $V_1 > V_A > V_T$ and $V_1 - V_A > \Delta E_i$. Outside A_1, we assume the potential is equal to V_1. We assume the potential V_s is adjusted so that the positrons have just enough axial energy to spill over the potential V_A and enter the trap. The positrons then are accelerated to an energy E_i by the potential difference between V_A and the $^9Be^+$ plasma potential $\phi_p(R_A)$ at radius R_A; we have $E_i = q(V_A - \phi_p(R_A)) + E_o$, where q is the positron charge and E_o ($\approx \Delta E_i$) is the mean axial kinetic energy of the positrons at the aperture. When the positrons enter the plasma they drift through it with a velocity $(2E_i/m)^{1/2}$, where m is the positron mass. Positrons exit the far side of the plasma and are then reflected back by endcap 2. They then traverse the plasma in the opposite direction and approach endcap 1. If the length of the plasma is long compared to the spacings between the plasma and the endcaps, the positrons spend most of their time in the plasma. Therefore, upon returning to endcap 1 for the first time, they rotate an azimuthal angle

$$\Delta\theta \approx 2\omega h(2E_i/m)^{-1/2} = 0.18(\omega/(\Omega/2))hBE_i^{-1/2}, \tag{1}$$

where $\Delta\theta$ is in radians, ω is the plasma rotation frequency, and in the last expression the plasma length h is expressed in cm, B in T, E_i in eV and Ω is the $^9Be^+$ cyclotron frequency. We have $\Omega/2\pi = 1.70 \times B[T]$ MHz when B is expressed in T. If $\Delta\theta$ is larger than the angle subtended by the effective entrance aperture $\theta_A(\approx 2r_A/R_A)$, then positrons are again reflected back into the plasma where they have a greater chance to lose axial energy [14]. As long as $\Delta\theta > \theta_A$, the positrons typically take $2(2\pi/\theta_A)$ passes through the $^9Be^+$ plasma before encountering the entrance aperture again. If $\Delta\theta < \theta_A$, only a fraction of the positrons which enter the trap make multiple bounces [19]. In order to have all of the positrons enter the trap we want $E_i > \Delta E_i$. We would like E_i to be as small as possible to satisfy the condition $\Delta\theta > \theta_A$ and to make the positrons scatter through the largest angles.

If the length of the positron/$^9Be^+$ plasma is much longer than its diameter, the potential inside the plasma as a function of radius is approximately equal to that of an infinitely long uniformly charged cylinder inside of a concentric grounded cylinder. Therefore the potential at radius r inside the plasma is approximately equal to

$$\phi_p(r) \approx \pi q n r_p^2 [2 \ln(r_w/r_p) + 1 - (r/r_p)^2], \tag{2}$$

where r_p is the plasma radius, and r_w is the radius of the grounded outer cylindrical "wall" electrode. Since the potential inside the plasma is independent of the axial coordinate, to keep the plasma confined along the axis, we require V_o, $V_2 > \phi_p(0)$, where V_o is the potential on the central portion of endcap 1 as shown in fig. 1. We adjust V_o and V_1 (and V_T and V_s) so that E_i is kept small. This implies $V_o > V_1$ and that the end of the plasma bulges out towards endcap 1 at the radius R_A. The $^9Be^+$ plasma density n is related to the rotation frequency ω by [20]

$$n = \frac{M\omega(\Omega - \omega)}{2\pi q^2} = 2.95 \times 10^8 B^2 \left(\frac{\omega}{\Omega/2}\right)\left(2 - \frac{\omega}{\Omega/2}\right), \tag{3}$$

where M is the $^9Be^+$ mass and in the last expression B is expressed in T. The maximum density, called the Brillouin density, is obtained when $\omega = \Omega/2$.

2.2. POSITRON DAMPING

We assume that the positrons initially lose axial kinetic energy by Coulomb scattering off the $^9Be^+$ ions. This transfers some of the initial positron axial kinetic energy E_i into cyclotron motion energy. We assume that the cyclotron motion energy is predominantly extracted by cyclotron radiation in the first stages of cooling. In the first stages of the cooling, a good approximation is to assume that the $^9Be^+$ ions are stationary and infinitely heavy; cooling of the positrons by the recoil of the $^9Be^+$ ions is negligible. We assume that the positrons scatter through a net angle θ_s (relative to the magnetic field direction) before encountering the entrance aperture from inside the plasma. The scattering angle θ_s results primarily from multiple small angle scattering of the positrons in the $^9Be^+$ plasma. The mean scattering angle $\langle\theta_s\rangle = 0$. The mean-squared scattering angle is nonzero and given by [21]

$$(\Delta\theta_s)^2 \equiv \langle\theta_s^2\rangle = \frac{2\pi n L q^4}{E_i^2} \ln(b_{max}/b_{min}), \tag{4}$$

where L is the effective length of the plasma. When $\Delta\theta > \theta_A$, L is equal to $2h(2\pi/\theta_A)$. For a weakly magnetized plasma b_{max}/b_{min} is given by r_c/b, where r_c is the positron cyclotron radius and b is the distance of closest approach ($b = q^2/k_B T$) [22]. For the plasma to be weakly magnetized, we require $r_c/b \gg 1$. We assume that $\frac{1}{2} m \Omega_p^2 r_c^2 \approx \Delta E_i$, where Ω_p is the positron cyclotron frequency. Therefore, we can write

$$r_c/b = 2320 \frac{E_i \Delta E_i^{1/2}}{B}, \tag{5}$$

where the energies are expressed in eV and the field in T. Therefore, when $\Delta\theta > \theta_A$, we can write eq. (4) in the form

$$\Delta\theta_s = 1.28 \times 10^{-6}[\ln(r_c/b)nh/\theta_A]^{1/2}/E_i, \tag{6}$$

where the angles are expressed in radians, h in cm, n in cm^{-3}, and E_i in eV.

From simple geometric considerations, the axial energy lost before re-encountering the entrance aperture (assuming the initial cyclotron energy is much less than E_i) is

$$\Delta E_s = E_i \sin^2\theta_s. \tag{7}$$

We will make the approximation that the positrons are captured if $\Delta E_s > \Delta E_i$. Therefore from eq. (7), positrons are captured if they scatter through angles greater than θ_c where

$$\theta_c = \sin^{-1}(\Delta E_i/E_i)^{1/2}. \tag{8}$$

If we assume that the distribution of angles θ_s is Gaussian, the fraction of positrons which enter the trap and are captured is given by

$$\eta_c = 1 - \mathrm{erf}(\theta_c/(2^{1/2}\Delta\theta_s)). \tag{9}$$

In table 1, we list values of η_c for various positron and $^9Be^+$ plasma parameters.

3. Beam source

In addition to using this configuration as a cold positron reservoir, it might also be possible to use it as a positron beam source by leaking positrons out a hole in endcap 2, which is centered on the trap axis. If the positrons are injected into the trap at an arbitrarily slow rate, they can be extracted as a beam with an internal temperature governed by the final equilibrium conditions achieved for the reservoir discussed in the previous section. For a beam source we would like as high a throughput as possible. Therefore it is useful to estimate the temperature of the ex-

Table 1
Calculated values of $\Omega/2\pi$, θ_A, $\Delta\theta$, n, $\theta_p(0)$, r_c/b, η_c, and $T - T_o$ for various values of input parameters. We assume h = 10 cm and ΔE_i = 0.1 eV for all entries. The last column for $(T - T_o)$ applies only for the positron beam source described in the text (for all rows we assume $dN/dt = 10^7$ s^{-1}). The first row gives a high value of η_c but requires a very high trap potential ($> \phi_p(0)$). The last two rows assume the entrance aperture for positrons is centered on the trap axis.

B (T)	E_i (eV)	r_A (cm)	R_A (cm)	r_p (cm)	r_w (cm)	$2\omega/\Omega$	$\Omega/2\pi$ (MHz)	θ_A (rad)	$\Delta\theta$ (rad)	n (10^{10} cm^{-3})	$\phi_p(0)$ (V)	r_c/b	η_c	$(T - T_o)$ (K)
10	1	0.05	0.5	0.7	2.0	0.5	17	0.2	9.0	2.2	15200	73	0.91	0.013
5	1	0.05	0.25	0.4	2.0	0.1	8.5	0.4	0.9	0.14	427	147	0.55	2.52
5	10	0.025	0.25	0.3	1.0	0.1	8.5	0.2	0.28	0.14	194	1470	0.27	44.8
10	10	–	–	0.1	1.0	0.5	17	2π	–	2.2	560	734	0.11	6.38
10	10	–	–	0.1	0.5	0.1	17	2π	–	0.56	107	734	0.001	25.2

tracted beam versus throughput. As a conservative estimate we will assume that the positron energy is extracted only by cyclotron radiation. In steady state, energy balance is therefore described by the expression $(\mathrm{d}E/\mathrm{d}t)_{\mathrm{in}} \simeq (\mathrm{d}E/\mathrm{d}t)_{\mathrm{c}} + (\mathrm{d}E/\mathrm{d}t)_{\mathrm{b}}$, where $(\mathrm{d}E/\mathrm{d}t)_{\mathrm{in}}$ is the energy input from the incoming positron beam, $(\mathrm{d}E/\mathrm{d}t)_{\mathrm{c}}$ is the energy extracted by cyclotron radiation, and $(\mathrm{d}E/\mathrm{d}t)_{\mathrm{b}}$ is the energy removed by the extracted beam. The cyclotron energy decays at the rate $\gamma_{\mathrm{c}} \simeq 0.39B^2[\mathrm{T}]\ \mathrm{s}^{-1}$. This rate is lower than the equilibration rate between $T_{\parallel}$ and $T_{\perp}$ for temperatures down to about 10 K (for $n \approx 10^9$, $B \approx 6$ T, see fig. 3 of ref. [23]), therefore above this temperature $T_{\parallel} = T_{\perp} \equiv T$. In this case, the expression for energy balance can be written

$$(\mathrm{d}N/\mathrm{d}t)E_{\mathrm{i}} = \tfrac{2}{3}\gamma_{\mathrm{c}} N k_{\mathrm{B}}(T - T_{\mathrm{o}}) + \tfrac{3}{2}k_{\mathrm{B}}T(\mathrm{d}N/\mathrm{d}t), \tag{10}$$

where $(\mathrm{d}N/\mathrm{d}t)$ is the positron flux, N is the total number of trapped positrons, and T_{o} is the ambient temperature. This equation yields the solution

$$T - T_{\mathrm{o}} \approx 4.43 \times 10^4 \frac{(\mathrm{d}N/\mathrm{d}t)E_{\mathrm{i}}}{NB^2}, \tag{11}$$

where E_{i} is given in eV and B in T. Examples are included in table 1. Similar considerations must be addressed to ensure that the laser beams can remove the (canonical) angular momentum and energy input to the $^9\mathrm{Be}^+$ ions due to the incoming positrons. With care these requirements can be satisfied. For small values of $\mathrm{d}N/\mathrm{d}t$, the parallel and perpendicular motions become decoupled [22] and we expect $T_{\parallel} \ll T_{\perp} \simeq 4$ K. In this case the positron plasma is expected to be strongly coupled. Under these conditions, it may be possible to extract a "string" of positrons which is located on the axis of the trap [18]. For these positrons, the angular momentum is zero, so when the positrons are extracted from the B field, the transverse energy can be quite small. In the extraction to zero magnetic field, the cyclotron energy is converted to axial energy spread. At $B \approx 6$ T and $T_{\perp} \simeq 4$ K, the cyclotron energy is concentrated in the $n = 0$ and 1 quantum levels, so the axial energy of the extracted positrons is concentrated in two energy peaks.

4. Experiments

Cooling positrons with $^9\mathrm{Be}^+$ ions has not been tried yet. However, some important aspects of the scheme have been demonstrated by using one laser-cooled ion species to sympathetically cool another ion species. In fig. 2 we show an image taken by viewing along the z axis of a Penning trap [13,18]. In this (UV) photograph, a column of $^9\mathrm{Be}^+$ ions, centered on the trap axis, is sympathetically cooled by laser-cooled Mg^+ ions at a magnetic field $B \approx 0.82$ T [24]. We have also demonstrated the use of laser torque to control the shape and density of a $^9\mathrm{Be}^+$ ion plasma, reaching densities very near the Brillouin density ($n \approx 10^{10}\ \mathrm{cm}^{-3}$ for $B \approx 6$ T) [13].

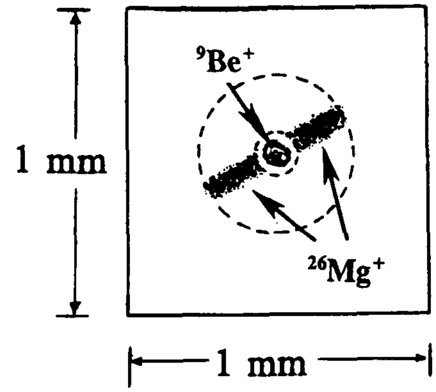

Fig. 2. Ultraviolet photograph showing the light scattered from laser beams which intersect a $^{9}Be^{+}/^{26}Mg^{+}$ plasma confined in a Penning trap ($B = 0.82$ T). The view is along the direction of the trap axis (and B field) as described in refs. [13,18]. The laser beam for the Mg^{+} ions intersects only a portion of the Mg^{+} plasma whose boundary is indicated by the dashed lines. The separation of the species is probably exaggerated because the photograph required a double exposure. The optics were refocused between the 313 nm ($^{9}Be^{+}$) and 280 nm (Mg^{+}) images. This probably resulted in different magnifications of the two wavelengths. The separation between plasmas is expected to be approximately equal to the interparticle spacing for low rotation frequencies ($\omega \ll \Omega/2$) [15,16].

5. Discussion

If the configuration above can be achieved, antihydrogen formation from three-body recombination with cold antiprotons passed through the positron plasma should be very efficient. If the positron plasma is strongly magnetized, the recombination rate should depend on $T_{\parallel}$ as $n^2 T_{\parallel}^{-9/2}$. In this case the probability of antihydrogen formation might be unity for one pass of cold antiprotons through the positron plasma [4,5]. Similarly, for the positron plasma to be quantized we require $\hbar\omega_p > k_B T_{\parallel}$.

On the theoretical side, more exact calculations are required to achieve better estimates of η_c and other parameters. We have omitted any details of the positron cooling for $T < 10$ K. For example, for $\omega \ll \Omega$, the separation between plasmas is approximately the interparticle spacing. As ω approaches Ω, the separation becomes large compared to the interparticle spacing and the Debye length [8,15]. In this case, we expect the thermal coupling between the positron axial motion and the $^{9}Be^{+}$ ions to become weak. If the coupling between the positron axial motion and the $^{9}Be^{+}$ ions remains relatively weak compared to the coupling between parallel and perpendicular positron motions for $T \approx 4$ K, then $T_{\parallel}$ will not be significantly below $T_{\perp}$. In principle, we could decouple the positrons' cyclotron motion from the ambient temperature by avoiding the resonances of the cavity formed by the trap electrodes [25]. However, this decoupling will be more difficult to achieve for plasmas whose dimensions are large compared to the cyclotron wavelength.

On the experimental side, we have assumed narrow energy distributions ΔE_i from the moderator, which we have implicitly assumed is in the trap magnetic field. These values of ΔE_i must be demonstrated experimentally. Use of a transmission moderator would be desirable; the high energy particles from the moderator could perhaps be rejected with an $\boldsymbol{E} \times \boldsymbol{B}$ filter.

The long $^9Be^+$ plasmas assumed here ($h = 10$ cm) have not been demonstrated yet. This is an important question which must be resolved experimentally; in general, longer plasmas are more prone to mode excitation from static field azimuthal asymmetry which limits their density [13]. Currently we are assembling a new apparatus which should allow us to investigate the storage of large plasmas. If the desired long plasmas are difficult to achieve, it should be possible to stack shorter plasmas with traps stacked along the axis of the system. This configuration may also have the advantage that between the trap sections, $\boldsymbol{E} \times \boldsymbol{B}$ azimuthal drift section could be configured to increase $\Delta\theta$ for the incident positrons.

The ideas presented here should apply to the trapping of other ions such as multiply charged ions which are difficult to cool by other means. In principle, these ideas would apply to cooling of antiprotons or other negative ions. This would require use of simultaneously stored laser-cooled negative ions. Unfortunately, laser cooling of negative ions has not been achieved so far because of the apparent lack of a suitable optical transition in a negative ion. Sympathetic laser cooling of negative ions might be achieved using a coupled trap geometry [26].

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