Practical Limits on Positron Accumulation and the Creation of Electron-Positron Plasmas

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Abstract. The tasks of accumulating large numbers of positrons, creating high-density positron plasmas, and confining electron-positron plasmas present a number of technical challenges. Some practical considerations and limitations of common confinement schemes are discussed. A novel design for a multi-cell Penning-Malmberg trap is proposed for the accumulation of large numbers of positrons (e.g., $> 10^{12}$ and $T \sim 0.5$ eV). A method is described to create a low-density, electron-positron plasma (e.g., $n \sim 10^7$ cm^{-3}) for basic plasma physics studies that uses a combination of radio-frequency and magnetic confinement. The possibilities for confinement of a hot (e.g., $T > 10$ keV) electron-positron plasma in a magnetic mirror are also discussed.

INTRODUCTION

Positrons are now used routinely for a wide range of applications, including the study of atomic and molecular physics [1], antihydrogen formation [2], plasma physics [3], and the characterization of materials and surfaces [4]. Further progress in many of these areas will be limited by improvements in positron sources and the ability to manipulate and cool large collections of antiparticles. In this paper we explore the possibilities for, and limitations on the accumulation of large numbers of positrons and the generation of high density positron plasmas.

There are a number of interesting phenomena that might be studied if one could create and confine neutral positron-electron plasmas. However, this is likely to be exceedingly challenging as compared with the study of single-component positron plasmas. We discuss briefly motivations for electron-positron plasma experiments and some relevant practical considerations. A scheme is proposed to create a low density, low temperature electron-positron plasma using a combination of radio frequency and magnetic confinement. Another scheme is described that could, in principle, permit confinement of a hot electron-positron plasma. While much more difficult, the latter experiment could enable studies of relativistic electron positron plasmas, an area which has been considered extensively theoretically and is important in a number of astrophysical contexts, but one in which there have been no experiments to date.

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POSITRON TRAPPING

Low energy positrons are obtained from either radioisotope sources [5] or from LINAC sources [6]. Radioisotope sources are currently limited to positron fluxes of $< 10^8$ slow positrons per second, while LINAC sources have the potential for positron fluxes greater than 10^9 s^{-1}.

There are a number of methods that have either been used or proposed for trapping low-energy positrons [7]. These include trapping by collisions with trapped ions [8, 9], trapped electrons [10], neutral gas [11], by stochastic orbits [12], in a magnetic mirror configuration [13], by electronic damping [14], and by field ionization of Rydberg positronium atoms [15].

The buffer-gas trapping scheme is by far the most efficient of any method used to date to accumulate and cool large numbers of positrons [7, 11]. Typically, $\sim$1% of positrons from a ^{22}Na source are slowed to a few electron volts using a solid neon moderator. They are then injected into a Penning-Malmberg trap in the presence of a buffer gas and an applied magnetic field $\sim$0.1 T. The accumulator has three stages, each at successively lower gas pressure and electrostatic potential. As many as 30% of the incident positrons become trapped in the third stage of the accumulator where they cool to room temperature in $\sim$0.1 s [16] using a mixture of N_2 and CF_4. Using this technique, 3×10^8 positrons have been accumulated in 8 minutes from a 70-mCi ^{22}Na source.

A separate cryogenic UHV trap is currently being constructed at UCSD [17]. Positrons from a buffer gas trap will be stacked into the UHV trap. This device is expected to enable the accumulation of large numbers of positrons ($> 10^{10}$), and the confinement of high density ($> 10^{10}$ cm^{-3}) cryogenic plasmas ($T < 10$ K) with long lifetimes (e.g., days to weeks).

All positron trapping to date has been conducted in Penning traps. For certain applications, however, trapping using rf fields (e.g., as in a Paul trap) or a magnetic mirror may be useful. One of the most attractive features of the Paul trap is its ability to trap both signs of charge simultaneously. This feature has already been demonstrated for plasmas consisting of both positive and negative ions [18]. This principle has also been applied in a hybrid Penning-Paul trap for the confinement of proton-electron plasmas [19]. Below we propose a similar configuration for the containment and study of a cool low-density electron-positron plasma. Paul trap is achieved using the ponderomotive force in a oscillating electric field.

CONFINEMENT OF SINGLE-COMPONENT POSITRON PLASMAS

In this section, we briefly discuss considerations involved in confining large numbers of positrons for long times. Besides the usual loss processes due to transport, annihilation on neutral background gas present in the vacuum system must also be considered.

Annihilation on neutral gas

Positron annihilation rates on a variety of atomic and molecular gases are well documented. They are conventionally expressed by comparison with annihilation on an uncorrelated electron gas

$$\Gamma = \pi r_0^2 c n_n Z_{\text{eff}}, \tag{1}$$

where r_0 is the classical radius of the electron, and n_n is the number density of the neutral gas molecules. In general, for atoms, small molecules, and fluorocarbon molecules, Γ is of the order of that corresponding to the uncorrelated electron gas limit with $Z_{\text{eff}} \sim Z$. For hydrocarbon molecules, on the other hand, Z_{eff} can exceed Z by many orders of magnitude. Table 1 presents the annihilation time for a selection of gases. These data show that positron annihilation can, in practice, be made negligible by maintaining a hydrocarbon free vacuum environment, e.g., by placing the electrodes in a cryogenic environment in the vacuum chamber.

TABLE 1. Annihilation times, τ_{ann} for a selection of gases typically found in vacuum systems, each at a partial pressure of 10^{-10} torr.

Gas	Formula	τ_{ann}
Helium	He	121 days
Nitrogen	N_2	17.4 days
Butane	C_4H_{10}	1 hour
Sebacic acid dimethyl ester	$C_{12}H_{22}O_4$*	5.5 seconds

*A common constituent of diffusion pump oil.

Radial Transport

For single component plasmas (SCP), cross-field transport will be the same for positrons as for electrons, and it is well documented that electron SCP's have excellent confinement properties [20]. At sufficiently low neutral gas pressure, electron transport is found empirically to scale as $\kappa(L/B)^2$, where L, is the length of the plasma, B is the magnetic field strength, and κ is a device-dependent constant. With careful experimental design, confinement times of hours or even days are attainable [21]. Transport rates also have a dependence on plasma density and temperature, although these are not as easily characterized [22]. Recently, it has been demonstrated that applying a rotating electric field ("rotating wall") to a single component plasma can counteract radial transport, and even lead to significant inward transport [23, 24]. Thus it now appears that radial transport is less likely to be a major obstacle to the confinement of high density positron plasmas.

Brillouin Density Limit

The maximum density of positrons that can be confined by a magnetic field, B, is given by the Brillouin limit [25],

$$n_{\mathrm{B}} = \frac{B^2}{8\pi mc^2}. \tag{2}$$

For example, for a 1 tesla magnetic field, $n_{\mathrm{B}} \simeq 5 \times 10^{12}$ cm^{-3}. Several schemes have been proposed for exceeding the Brillouin limit using non-uniform magnetic fields [26]. The factors that can be achieved, however, are only of the order of two, so the Brillouin limit remains a fundamental constraint on the storage of unneutralized plasmas. We note in passing that Eq. 2 is equivalent to the requirement that the energy in the magnetic field must always exceed the rest mass energy of the confined particles, so energy storage by accumulating unneutralized antimatter in the form of an SCP is not practical, regardless of whether positrons or antiprotons are used.

Space Charge Limit

The space charge at the center of a column of charged particles of radius R_p, confined within a cylindrical electrode of radius R_w is given by

$$V_s = \simeq 1.4 \times 10^{-7} \frac{N_t}{L} \left[1 + 2\log_e \left(\frac{R_w}{R_p} \right) \right], \tag{3}$$

where V_s is in volts, N_t is the total number of positrons, and L is the length of the plasma in centimeters. To confine a positron SCP in a Malmberg-Penning trap, one must apply a confining potential in excess of V_s on the end electrodes, and this is an important constraint on the maximum achievable value of N_t/L. For example, for $N_t = 3 \times 10^{12}$, $L = 10$ cm, and $R_w/R_p = 2$, $V_s \simeq 100$ kV.

A MULTICELL TRAP FOR STORAGE OF LARGE NUMBERS OF POSITRONS

For many applications, the accumulation of large numbers of positrons is desirable. As can be seen from Eqs. 2 and 3, the space charge limit is likely to be reached before the Brillouin limit. Since applying confining potentials greater than a few kilovolts in vacuum becomes technologically difficult, especially if they must be switched on a short timescale, it is desirable to develop geometries for accumulating large numbers of positrons with reduced space potential. One possible scheme is suggested by Eq. 3, which shows that the space charge of the plasma depends only on charge per unit length, and on the size of the plasma *relative* to the confining electrodes. The key point is that subdividing the plasma into n separate plasma columns using a multicell trap reduces the space charge potential by a factor of n.

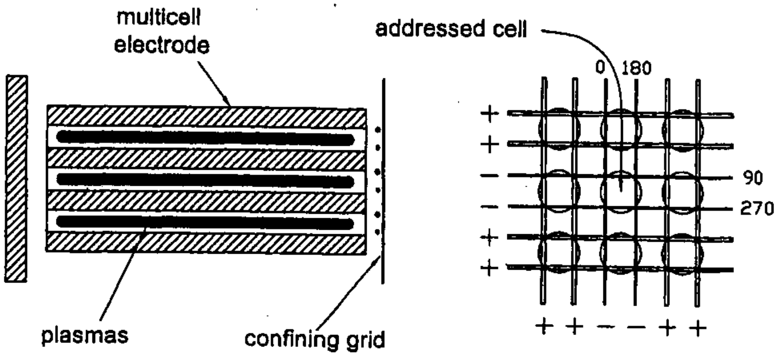

FIGURE 1. Possible multicell configuration for confining large numbers of positrons.

A possible geometry for accomplishing this is shown in Fig. 1. Here the main confining electrode is penetrated by multiple cylindrical openings to form a multicell array [27]. The confining potential at one end is applied using a plate electrode. In order to access the cells separately, individual cylindrical gate electrodes could be provided for each cell. An alternative to this approach could be to use a grid of wires that can be biased individually, as shown in Fig. 1. By reducing the potentials on the four wires adjacent to a particular cell, the potential barrier for that cell could be lowered selectively, thus permitting positrons to be loaded or unloaded. Capacitive coupling of phase-shifted sine waves to the wires, as shown in the figure for one cell, could be used to apply a "rotating wall" confining field.

One potential application of this device would be for use in a portable trap for positrons that could be used in place of a radioactive source. For example, an array of 10 cells by 10 cells, each 3 mm in diameter, and 10 cm long, containing plasmas 1 mm in diameter would be able to contain 10^{12} positrons with a confining potential of < 500 V. Such a trap would be able to supply a beam of 10^6 cold positrons per second (typical for laboratory positron beam systems) for more than 10 days before it would need to be refilled at a positron production facility, such as a LINAC. This approach would have the advantage of eliminating the radioactive source and associated moderating equipment, leading to improved safety, reduced cost, greater versatility, and higher beam quality.

ELECTRON-POSITRON PLASMAS

In this section we consider the factors relevant to the confinement of electron-positron plasmas. The problem is even more challenging than that of overcoming the transport problems associated with neutral electron-ion plasmas. In particular, one must also overcome positron loss due to annihilation of the positrons with the plasma electrons and the formation and subsequent loss of positronium atoms.

Motivation for electron-positron plasma experiments

Electron-positron plasmas are an example of equal-mass plasmas, whose behavior is fundamentally different than that of conventional electron-ion plasmas. They are important in astrophysical environments, such as pulsar magnetospheres and active galactic nuclei. Plasmas of this type have been studied theoretically [28–42]. We briefly discuss some motivations for laboratory studies:

Plasma confinement. The confinement of neutral plasmas by a magnetic field is fundamentally different from that of single-component plasmas, which are well-known to exhibit remarkably good confinement. Very long confinement times of single-component plasmas (i.e., hours or days) have been obtained by careful experimental design [43]. For two-species plasmas, however, unlike-particle collisions lead to cross-field transport many orders of magnitude larger than that observed in single component plasmas. It should be possible to study continuously the transition from a single-component positron plasma to a completely neutralized e^+/e^- plasma, thus providing new insights into (turbulent) transport processes in partially neutralized and neutral plasmas.

Plasma wave studies. The linear modes of electron-positron plasmas are similar to those in conventional plasmas [37]. However, in a seminal paper, Tsytovich and Wharton showed that the nonlinear processes in e^+/e^- plasmas are dramatically different [44]. For equal temperatures and equal densities of positrons and electrons, three-wave coupling vanishes identically, and so quasilinear relaxation of a beam-plasma instability is absent. Furthermore, because of the equal masses of both particle species, ordinary nonlinear Landau damping (NLLD) is larger by the ion-to-electron mass ratio. Consequently, nonlinear growth can overwhelm linear growth, and quasilinear relaxation is replaced by very strong nonlinear Landau damping. In one step, energy can be coupled directly into the bulk of the particle distribution.

Electron-positron vortices. Two-dimensional fluid vortex phenomena have been studied in electron plasma experiments. For a strongly magnetized electron plasma, the electron density is the exact analog of vorticity in a two-dimensional fluid, and electron plasmas closely approximate the ideal case of an inviscid fluid. A variety of interesting phenomena such as vortex merger, and vortex crystals have been studied with a precision not possible in ordinary fluids [45, 46]. In electron-positron plasmas, the more general case of a fluid with two signs of vorticity could be studied.

CONFINEMENT LIMITS FOR ELECTRON-POSITRON PLASMAS

In this section we discuss relevant confinement issues, and then propose two possible schemes for confinement of electron-positron plasmas. We note in passing that one might ask, for example, if this could be a way to store large numbers of positrons by avoiding the space charge limit. As we discuss below, the answer is 'no' due to the relatively poor confinement achievable for neutral plasmas.

Annihilation

In addition to annihilation on neutral gas, discussed above in the section on single component positron plasmas, two additional annihilation channels are present in electron-positron plasmas, namely annihilation on plasma electrons, and the formation (and subsequent annihilation) of positronium atoms. In an electron-positron plasma annihilation will occur at a rate given by:

$$\Gamma = \pi r_0^2 c n_e, \tag{4}$$

where r_0 is the classical radius of the electron, c is the speed of light, n_e is the electron density. The annihilation time, $\tau_a = 1/\Gamma$ is plotted in Fig. 2 as a function of plasmas density in the range of interest. From these data, it is clear that electron-positron annihilation is negligible at low plasma densities. For higher densities, experiments are still possible provided that the phenomena of interest can be studied on short timescales, and high positron throughput is possible.

Positronium Formation

In addition to direct annihilation, positrons can be lost from an electron-positron plasma by positronium formation. The most likely process is three-body recombination at a rate, Γ_{Ps}, given by [47]:

$$\Gamma_{Ps} \simeq A n b^2 v_{th} (n b^3) \tag{5}$$

where $v_{th} = \sqrt{k_b T/m}$ is the thermal velocity of the particles, $b = e^2/k_B T$ is the distance of closest approach, and $A \simeq 0.07$. This is an upper limit, including the formation of weakly bound high-Rydberg states. Figure 2 shows the dependence of direct annihilation and positronium formation on plasma density for three values of plasma temperature. From this Figure, it is clear that positronium formation is not a problem for either the low density electron-positron plasma or the high density relativistic plasmas described below. However, positron annihilation is likely to be a problem in low-temperature, high-density electron-positron plasmas.

Radial Transport

Radial transport in an electron-positron plasma will be qualitatively different from an SCP and is expected to scale as in a neutral plasma. The smallest rate that might be expected is that due to Coulomb collisions between the two species. In this case the diffusion coefficient is [48]:

$$D_c = \frac{4}{3}\sqrt{\pi} n v_{\mathrm{th}} b^2 \rho^2 \ln\left(\frac{\rho}{b}\right) \tag{6}$$

where ρ is the gyroradius. For a plasma of radius R, the typical confinement time will be

$$t_c \sim \frac{R^2}{2D_c}. \tag{7}$$

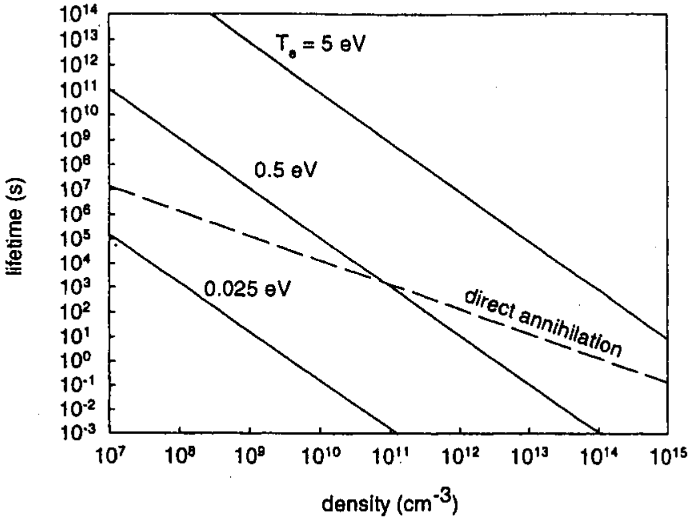

FIGURE 2. Electron-positron plasma lifetime due to direct annihilation (dashed line) and positronium formation (solid lines) as a function of plasma density.

In practice, however, diffusion rates are generally found to be larger than those predicted by this classical picture. As an upper bound, (e.g., for transport due to plasma turbulence) one can take the phenomenological Bohm diffusion coefficient

$$D_B = \frac{ckT}{16eB}. \tag{8}$$

In this case,

$$t_c \sim R^2/2D_B. \tag{9}$$

We note that many practical confinement schemes exhibit values of τ_c larger than Eq. 9 (i.e., confinement better than Bohm), so Eq. 9 is likely to be a lower bound on τ_c.

Plotted in Fig. 3 are values of τ_c predicted by Eqs. 7 and 9 as a function of plasma density. These results indicate that, for a neutral electron-positron plasma, cross-field transport is likely to be a serious concern.

NEAR-TERM POSSIBILITIES FOR EXPERIMENTS

The techniques described above to accumulate large numbers of positrons from a radioactive source in a Penning trap have enabled us to perform the first electron-positron plasma experiments by transmitting an electron beam through a stored positron plasma [3, 49]. These experiments deliberately avoided the problem of simultaneous confinement of electrons and positrons by introducing the electrons in a transient manner in the form of a beam. However in order to study phenomena in plasmas where there is no relative drift between the two charge species, simultaneous confinement of electrons and

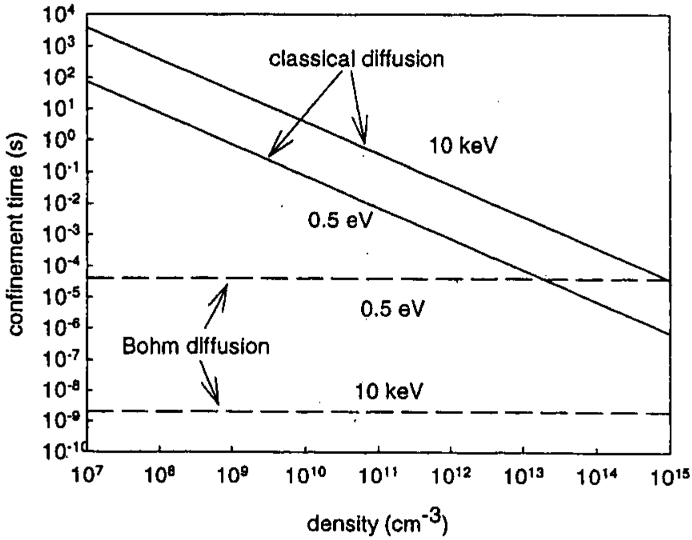

FIGURE 3. Calculated confinement times for 0.5-eV and 10-keV electron-positron plasmas, 0.5 cm in diameter, at $B = 1$ kG.

positrons is required. Since one can expect relatively poor confinement of the positrons in a neutral plasma, even under the best circumstances, being able to exploit a high-intensity positron facility for such studies (e.g., using a LINAC) would be a great advantage.

The design of such an experiment is "nontrivial". Unfortunately, the electrostatic confinement scheme of the Penning trap (which has been the basis of positron plasma experiments to date) is suitable for confining only one sign of charge. "Nested" potential wells cannot be used to achieve simultaneous confinement of electron and positron plasmas in the direction of a confining magnetic field, since overlap of the charge clouds can be achieved in this geometry only if one species is not in the plasma limit. This is due to the fact that, in the nested wells, overlap of the plasmas will occur only if one species has a Debye screening length large compared with the size of the other plasma, in which case the hotter species is not in the plasma limit.

Magnetic geometries such as mirrors (discussed below) and toruses are subject to relatively rapid losses, but might be usable at a high-intensity beam facility.

Combined trap for low-density electron-positron plasmas

We envision that the difficulties in simultaneous confinement of both charge species can be overcome by the use of a Paul trap, which confines charged particles by means of radio frequency (rf) fields. Because the confinement is dynamic in nature, particles of both signs of charge can be confined. Paul traps have already been used to confine quasi-neutral plasmas of positive and negative ions [18]. More recently, the simultaneous

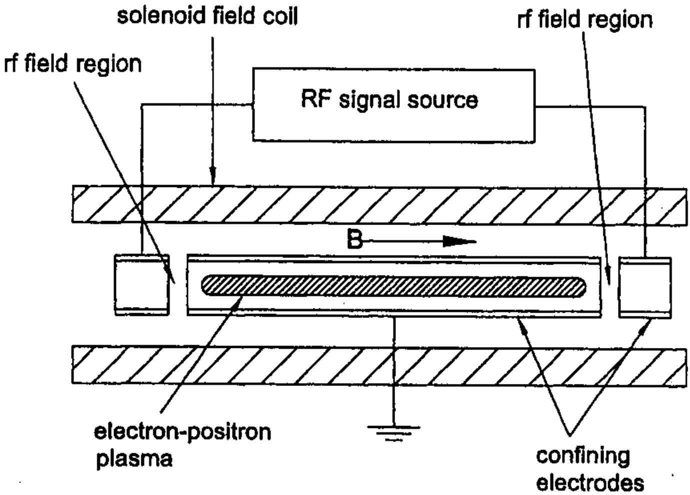

FIGURE 4. Possible combined Penning-Paul trap for studying electron-positron plasmas.

confinement of protons and electrons was demonstrated in a trap in which the electrons were confined by rf fields and the protons were confined in an overlapping Penning trap [19].

A natural extension of these experiments would be to use a combined trap to confine an electron-positron plasma. We envision that this might be done using a hybrid Penning-Paul trap where radial confinement is provided by a magnetic field, as in a Penning trap, but with the confinement at the ends provided by rf fields, in place of the electrostatic potentials of the Penning design. Heating of the species by the rf is a potential problem. We suggest that this might be overcome using the cooling provided by small amounts of a suitably chosen molecular gas, similar to the operation of the buffer-gas positron accumulator described above.

A possible geometry for such an experiment is shown schematically in Fig. 4. The design parameters of the experiment are given in Table 2. The depth of the potential well achievable using the Paul trapping technique is limited by practical considerations to a few electron Volts, thereby placing limits on the plasma temperature and acceptable amount of charge imbalance. For these experiments, the advantage of using an intense positron source would be that the experiments could be conducted with a rapid cycle time, even if confinement is poor (which is likely).

The heating rate in this trap can be estimated by balancing the heating of the particles, $\dot{\varepsilon}_{rf}$, due to the rf field with the cooling, $\dot{\varepsilon}_{col}$, due to electron-molecule and positron-molecule collisions. We find for the heating rate,

$$\dot{\varepsilon}_{rf} \simeq 2m\nu_c\overline{(\delta v)^2} \tag{10}$$

where ν_c is the Coulomb collision frequency and $\delta v = eE_{\rm rf}/m\Omega$ is the particle velocity due the rf field at frequency Ω. It is useful to note that

$$\dot{\varepsilon}_{\rm rf} \propto U_{\rm rf} = \frac{e^2\overline{E_{\rm rf}^2}}{m\Omega^2} \simeq m\overline{(\delta v)^2}, \tag{11}$$

where $U_{\rm rf}$ is the rf trapping potential energy.

This heating rate must be spatially averaged over the trajectory of the particles in the potential well. For a cylindrical plasma of length L, confined by cylindrical electrodes of radius R_w at $z = 0$ and $z = L$, the rf potential on the axis will be

$$V(z) \simeq \frac{V_{\rm rf}}{2}\left[\tanh\left(\frac{1.3z}{R_w}\right) - \tanh\left(\frac{1.3[z-L]}{R_w}\right) - 2\right], \tag{12}$$

where $V_{\rm rf}$ is the applied rf voltage. We assume a trapping well depth, $U_{\rm rf} = 5$ eV and a plasma temperature $kT = 0.5$ eV. The particles will be heated appreciably only near the ends of the plasma in a region of extent $\Delta z \sim 0.4R_w$. Here they experience an rf potential of strength $< kT/e$, but spend more time near these turning points than in other regions of the trap. Taking these factors into account and assuming $L = 30R_w$, we estimate the time-averaged heating rate to be,

$$\dot{\varepsilon}_{\rm rf} \simeq 0.05\nu_c kT \tag{13}$$

The collisional energy loss on molecules will be $\dot{\varepsilon}_{\rm col} \simeq -\nu_{\rm col}\delta\varepsilon_{\rm col}$, where $\delta\varepsilon_{\rm col}$ is the average energy loss per collision and $\nu_{\rm col}$ is the collision frequency. As an estimate, we assume cooling on CO_2 which has $\delta\varepsilon_{\rm col} = 0.3$ eV and a collision cross section $\sigma \sim 10^{-16}$ cm^2 [50]. With these assumptions

$$\nu_{\rm col} = n_n\sigma v_{th} \simeq 15 \times 10^4 P\ {\rm s}^{-1}, \tag{14}$$

where n_n is the CO_2 number density and P is the pressure in mTorr. Thus

$$\dot{\varepsilon}_{\rm col} \simeq 5 \times 10^4 P\ {\rm eV\ s}^{-1}. \tag{15}$$

For balance, we require $\dot{\varepsilon}_{\rm rf} = \dot{\varepsilon}_{\rm col}$. Thus from Eqs. 13 and 15, we find

$$\nu_c \sim 2 \times 10^6 P\ {\rm s}^{-1}. \tag{16}$$

For $n = 10^7$ cm^{-3} and $T = 0.5$ eV, $\nu_c \simeq 2 \times 10^3$ s^{-1}, requiring a CO_2 pressure of 1×10^{-6} torr.

At this pressure, the annihilation time is ~80 s, the diffusion time due to collisions with neutral gas is ~500 s, the diffusion time due to electron-positron collisions is ~ 200 s, and the Bohm diffusion time is ~ 100 μs. Thus the plasma can be expected to survive between 100 μs and several hundred seconds, depending on which transport process dominates. This is an interesting issue in its own right and would by its nature be the first phenomenon to be studied. Since the plasma frequency is ~ 30 MHz, plasma wave phenomena could be studied, even if the confinement time was as short as 100 μs.

While this combined trap is suitable for low-density electron-positron plasma studies, it is not likely to be a viable geometry for confining higher density plasmas. This is due to plasma heating, which will increase with plasma density, and the unavailability of a sufficiently rapid cooling mechanism.

TABLE 2. Design parameters of an electron-positron experiment using a combined Penning-Paul trap.

Parameter	Approx. Value
density	10^7 cm^{-3}
plasma length	30 cm
plasma radius	0.5 cm
wall radius	1 cm
particle number	5×10^8
rf frequency	200 MHz
rf voltage	100 V_{rms}
rf potential well	5 V
cooling gas	CO_2
CO_2 pressure	1×10^{-6} torr
plasma temperature	0.5 eV

A mirror geometry to confine hot electron-positron plasmas

Experimental studies of relativistic electron-positron plasmas will be much more challenging. The plasma limit requires $n\lambda_D^3 \gg 1$, and $\lambda_D \ll L$. In these expressions, L is the characteristic dimension of the charge cloud, n is the plasma density, and λ_D is the Debye screening length. Thus, in order to have λ_D as small as 1 cm at $T_e > 200$ keV (i.e., a mildly relativistic plasma), a density $n = 10^{12}$ cm^{-3} is required. At a minimum, we must have $L = 10\lambda_D$ (e.g., to study plasma wave phenomena), which in turn requires confining 10^{15} positrons. Beyond the challenge of accumulating such a large number of positrons, their confinement in a neutral plasma will be a great challenge.

One possible geometry for such an experiment is a magnetic mirror. Confinement in a mirror is better when the plasma is hot (i.e., thereby reducing the loss due to Coulomb collisions). In the mirror, it is also beneficial to arrange $T_\perp \gg T_\parallel$, where $T_\perp$ and $T_\parallel$ are the perpendicular and parallel temperatures of the particles. Both conditions can be achieved relatively easily for electron-mass particles by heating at the cyclotron frequency using microwave radiation. Confinement of the positrons could be further increased by placing electrodes on either end of the mirror, biased to as large a potential as possible. In this case, positrons exiting the usual "loss cone" in mirrors (i.e., particles with low values of $T_\perp/T_\parallel$ are not confined by the mirror fields) would be reflected back into the magnetic mirror. One unwanted side effect of the hot plasma will be intense cyclotron emission from the hot particles.

SUMMARY

In this paper we have discussed two key topics concerning positron plasmas, the practical considerations associated with the accumulation of large numbers of positrons, and the prospects for creating (neutral) electron-positron plasmas in the laboratory. Penning-Malmberg traps are a relatively simple and useful way to confine single component plasmas with densities from 10^{12} to even 10^{15} cm^{-3}. The multicell trap arrangement described here can potentially extend this upper limit by a few orders of magnitude. Since the largest densities achieved to date are $\sim 4 \times 10^9$ cm^{-3} [51], and the largest number of positrons confined are $< 10^9$, it is important to point out that these estimates are large extrapolations and should be regarded as a projection as to what might be possible rather than a certainty.

Possible schemes to avoid the Brillouin and space charge limits by neutralizing positron plasmas with electrons were discussed. They suffer from losses due to both annihilation and plasma transport. They do not appear to offer an advantage over positron SCP's in terms of achieving either high positron densities or large total numbers of positrons. The net result is that, while positrons can be accumulated and stored, in some cases for very long times (e.g., days to weeks), achieving very large particle numbers of antimatter in the laboratory is likely to be constrained for the foreseeable future by the considerations discussed above.

In contrast, with regard to creating and studying low density electron-positron plasmas in the laboratory, there are likely to be a number of potentially practical possibilities. Here we discussed only two of them, a combined trap, consisting of a linear magnetic field with rf confinement at the ends, and confinement in a magnetic mirror. The former scheme appears appropriate for confining and studying low-density, low temperature plasmas. The latter offers the possibility for confinement of a much hotter, high-density plasma (e.g., temperatures $>$10 keV). If either of these experiments were successful, they would permit study of a range of interesting topics associated with the unique and interesting electron-positron plasma system. As a practical note, however, judging from more than a half century of experience attempting to confine neutral plasmas, the first topic of study will most likely concern understanding the confinement of these unique, electron-mass, neutral plasmas.

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