Next Generation Trap for Positron Storage

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Abstract. Progress toward the development of a novel multicell Penning-Malmberg trap is described that will be capable of accumulating orders of magnitude more positrons than is possible presently. This design represents the next major step in antimatter storage technology. Experiments with test electron plasmas establishing techniques critical to the implementation of a practical multicell trap are presented. The latest design for a 21 cell trap capable of accumulating and storing more than 5×10^{11} positrons is described. This trap could facilitate multiplexing the output of the new generation of positron sources either operating now or currently under development, as well as the potential to provide record-high bursts of positrons for a variety of applications.

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I. INTRODUCTION

The accumulation of low-energy positrons (i.e., the antiparticles of electrons) has become increasingly important in many fields, including atomic physics, plasma physics, and materials science. In the laboratory, positrons are now being used, or are planned for use, in many applications, including atomic and molecular physics [1,2], the formation of low energy antihydrogen [3,4], and the characterization of materials [5]. On the technological side, a new generation of more intense positron sources is under development [6-10]. Full utilization of these facilities will require the development of new techniques to accumulate and store large quantities of positrons.

Much progress in science with low-energy antimatter has been, and is expected to continue to be enabled by the development of novel nonneutral plasma techniques to create and manipulate single-component plasmas (SCP) in Penning-Malmberg traps, such as the one shown in Fig. 1. This device uses a uniform axial magnetic field and cylindrical electrodes with electrostatic potentials on the ends to confine particles of a single sign of charge (e.g., positrons, electrons, ions, or antiprotons) [1,11]. While the principal objective is the accumulation, manipulation and storage of positrons, the experiments described here use conventional single-component electron plasmas for increased data rate and ease of handling. In an actual positron application, the electron source would be replaced by bursts of positrons that are now accumulated routinely and efficiently using the buffer-gas trapping technique [12].

Here, we review recent progress toward what we regard as the next major step in antimatter storage technology, namely the development of a novel multicell trap that will be capable of accumulating orders of magnitude more positrons than is

possible presently. This trapping concept was described in Ref. [13], and much of the more recent work reviewed here is described in more detail in Ref. [14]. When constructed, this multicell trap will provide record-high bursts of positrons for a variety of applications. It will also facilitate multiplexing the output of the new generation of positron sources either operating now or under development [6-10], thus enhancing their capabilities. The benchmark design goal described here is the trapping and storage of the order of 10^{12} positrons. They will be able to be stored for days and delivered rapidly for a variety of applications. The significance of this objective is illustrated in Fig. 2. Of considerable significance is the fact that the design is modular, and so larger or smaller antimatter storage capacities can be achieved by building the appropriate number of storage modules.
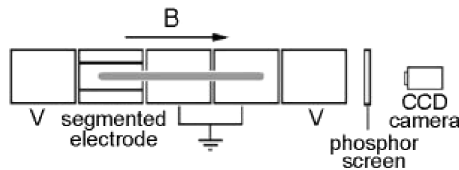

Figure 1. Schematic diagram of a Penning-Malmberg trap. As shown, it consists of five cylindrical electrodes, including one segmented azimuthally for radial plasma compression. Also shown is a phosphor screen and CCD camera that can be used to image radial density profiles.
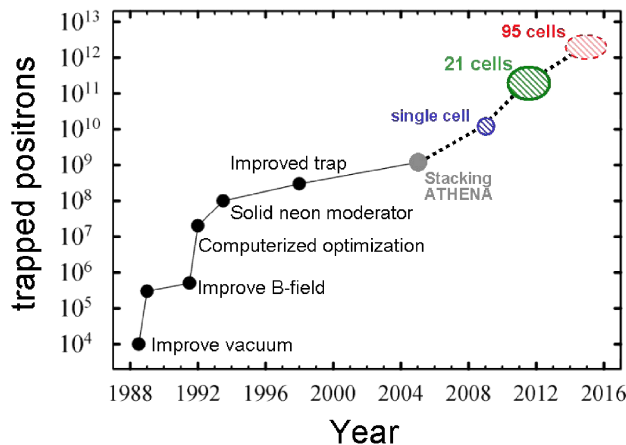

Figure 2. Progress in positron trapping from similar strength sources using a buffer-gas accumulator: actual record results (solid line), and projected capabilities (dashed lines). The projected capabilities of the 21-cell, multicell trap proposed here and a 95-cell trap (from Ref. [14]) are shown as shaded ovals.

II. MULTICELL TRAP CONCEPT

The concept of the multicell Penning-Malmberg trap is shown schematically in Fig. 3 [13,14]. The most severe limitation to confining plasmas consisting of large numbers of particles is that they have a large space charge potential, which in turn

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requires unacceptably large confinement voltages. In particular, for fixed plasma length, L_p, the number of particles, N, that can be stored in a trap is limited by the maximum potential, V_C, that can be applied to the electrodes. For a long, uniform plasma of radius R_p in a cylindrical electrode structure of radius R_w, the on-axis space charge potential, ϕ_o, (in Volts) is

$$\phi_o = 1.4 \times 10^{-7}(N/L_p)[1 + 2\ln(R_w/R_p)], \tag{1}$$

where L_p is in cm. From Eq. 1, for example, for a plasma of 10^{10} positrons with $L_p = 10$ cm and $R_w/R_p = 10$, $\phi_o = 785$ V, which in turn, requires a value of $V_C \sim 800$ V. In a similar size trap, 10^{12} positrons would require $V_C \sim 80$ kV, which is impractical.
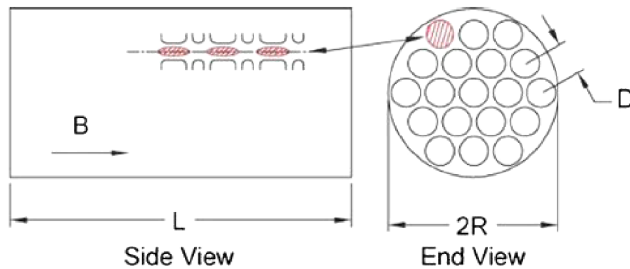

Figure 3. Conceptual design of the multicell trap from Ref. [14], showing the arrangement of cells parallel and perpendicular to B. This early design had 19 hexagonally close-packed (HCP) cells perpendicular to B. The parameters for the 21 cell trap (i.e., 3 banks of 7 HCP cells) described here are summarized in Table I.

Table I. Design parameters of a 21-cell multicell trap.

Number of cells ($m \times p = 7 \times 3$)	21
Total positron number, N (10^{11})	≥ 5.0
Magnetic field (T)	5
Total electrode length, L (cm)	100
Electrode-package diameter, $2R$ (cm)	> 7.5
Plasma radius, R_P (cm)	0.2
Plasma length, L_p (cm)	20
Confinement voltage, V_c (kV)	1.0
Cell spacing (cm), D	2.0
Space charge potential (V)	750
Rotating wall frequency (MHz)	4

In the multicell trap, this space charge potential is mitigated by dividing the plasma into m, rod-shaped plasmas of length L, each oriented along the magnetic field [e.g., in a hexagonal-close-packed (HCP) arrangement transverse to the field as shown in Fig. 3]. These rod-shaped plasmas are shielded from each other by close-fitting copper electrodes. For a given maximum confining electrical potential, V_C, applied to

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the electrodes, the number of stored positrons will be increased by a factor of m. The multicell design also breaks up each long rod of plasma into p separate plasmas in the direction along the magnetic field (i.e., separated by electrodes at potential V_c). This reduces the effects of electrostatic and magnetic nonuniformities and the associated asymmetry-induced radial transport that limits the plasma lifetime.

We have proposed previously several arrangements including a 95 cell trap to store $\geq 1 \times 10^{12}$ positrons. Based upon recent experiments, we propose here an improved and considerably simplified design for a 21-cell multicell trap ($m = 7$; $p = 3$) that will be able to store almost as many particles (i.e., in excess of 5×10^{11}), as summarized in Table I. The principal design change comes from the recognition that a larger number of positrons can be confined in a single cell than was assumed previously, and this reduces the number of cells required for a given total accumulation capacity.
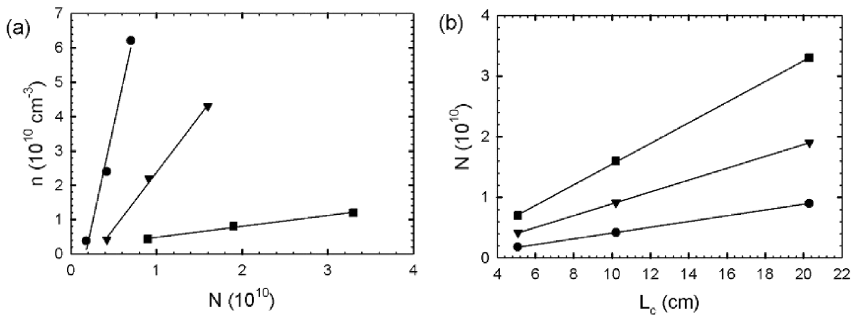

Figure 4. (a) Measured plasma density vs. total number, N, for three different confinement lengths L_c of ($\bullet$) 5.1, ($\blacktriangledown$) 10.2, and ($\blacksquare$) 20.3 cm; and (b) the dependence of N on L_c for three different fill voltages, V_f: ($\bullet$) 300, ($\blacktriangledown$) 600, and ($\blacksquare$) 900 volts. For all experiments, the confinement voltage $Vc = 1.0$ kV.

III. EXPERIMENTAL TESTS

There are a number of techniques that are necessary in order to realize a practical multicell trap. Here we describe several experiments that were done recently using test electron plasmas to demonstrate these techniques [14]. Specifically, we have explored the maximum trapping in a single cell, the operation of two (axial) plasma cells, off-axis plasma control, and plasma compression using rotating electric fields.

A. Trapping in a Single Cell

Plasmas were created and confined using a 1.0 kV confinement potential for three different confinement lengths, $L_c = 5.1$, 10.2 and 20.3 cm (see Ref. [14] for more details). The dependence of plasma density on the total number of particles, N, is illustrated in Fig. 4(a) for the three different confinement lengths, L_c. The dependence of N on L_c for the three different filling voltages, V_f, is illustrated in Fig. 4(b). Several

of the cases exceed the $N = 1$ x 10^{10} particle design goal. These experiments have verified the operation of a single cell using parameters that are in the range of those necessary for a practical multicell trap.

B. Trapping in Two Storage Cells

The ability to create and manipulate two, in-line plasmas was also investigated [14]. Plasmas were loaded in two separate axial cells of the high-field trap using a "fill-shuttle-fill-hold" protocol. This experiment is illustrated in Fig. 5. Following the "hold" stage, independent control of the plasmas was demonstrated by depositing them sequentially onto the phosphor screen where they could be imaged separately. Each plasma consisted of $N \approx 5.5$ x 10^{8} electrons. The plasmas were 10 cm long, 0.93 mm in radius, and were separated axially by 10 cm. It was confirmed that there was no increase in outward radial transport with the addition of the second plasma to the trap. The plasmas were confined for 30 seconds with no noticeable expansion. Additional studies will be required to investigate confinement of these multi-cell, trapped plasmas at higher densities and on longer time scales.
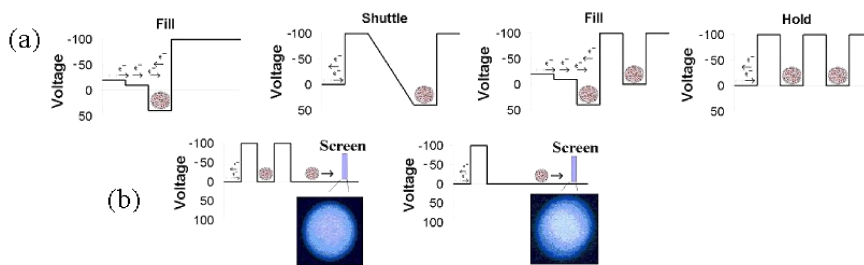

Figure 5. Schematic diagram of (a) the potential profile during the sequential filling of two, in-line plasma cells with electron plasma; and (b) the sequential dumping of these plasmas and the resulting images. From Ref [14]; see this reference for details.

C. Filling and Retrieving Plasmas from Off-axis Cells

One of the key features of the multicell trap is the utilization of off-axis cells for plasma storage. One critical aspect of this design is the ability to inject plasmas into the off-axis cells in an efficient manor and to be able to reverse this procedure to dump the contents of the cells. Recently we developed a method to transfer plasmas into and out of off-axis cells by the excitation and manipulation of a "diocotron" plasma mode [14]. This mode is the azimuthal rotation of a radially displaced plasma column around the center of the cylindrical electrode, excited by applying a low-frequency (typically ~ kHz) sinusoidal signal to a segmented electrode. The mode frequency is a nonlinear, increasing function of the plasma displacement, D, from the center of the electrode. When the drive frequency is swept from low to high, the mode can be made "autoresonant" with the drive signal so that the plasma locks to the drive [15,16]. The

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drive frequency determines the off-axis displacement, while the drive-signal phase sets the azimuthal position of the plasma. As illustrated in Fig. 6, plasmas can be translated radially across the field to a predetermined position, then dumped into an off-axis cell. Using this technique in reverse, plasmas can be extracted from off-axis storage cells, then returned to the symmetry axis for use at the output of the trap.
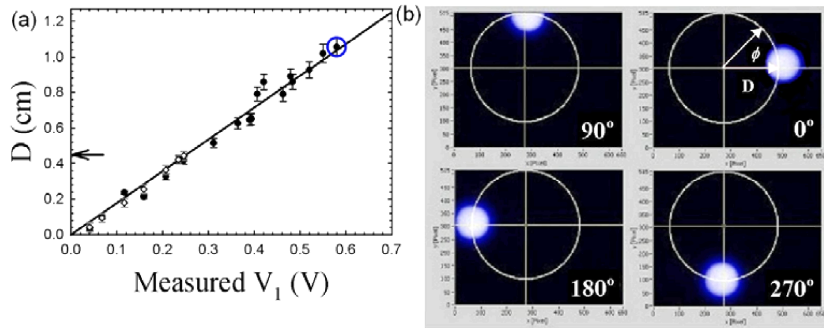

Figure 6. (a) Plasma displacement, D, as a function of the measured amplitude of the diocotron-mode signal. The circled point corresponds to 80% of the wall radius. (b) Plasma images for different drive-signal phases at a fixed displacement. From Ref [14]; see this reference for details.

D. Radial Plasma Compression with Rotating Electric Fields

In a Penning-Malmberg, the lifetime of the plasma is limited by the radial transport due to trap imperfections [17,18]. To mitigate this, we utilize the technique of rotating electric field compression (the so-called "rotating-wall" technique) [19-24]. This technique is now widely used and is cable of achieving essentially "infinite" confinement times. It relies upon an electric field, rotating in the plane perpendicular to the magnetic field, to inject angular momentum into the plasma and compress it radially. As originally developed [20,21], this technique required careful tuning to a mode in the plasma to compress weakly coupled plasmas (i.e., plasmas without crystalline ordering) that are relevant here. Recently, we discovered a new "strong drive" regime of operation that does not require mode tuning [22-24]. It works over a broad range of frequencies and compresses the plasma until the E x B rotation frequency, f_E, equals the applied rotating wall frequency, f_{RW}. The final density can thus be controlled by changing f_{RW} and does not depend critically on the RW amplitude. Furthermore, plasmas with a remarkably broad range of initial densities (e.g., varying by a factor of 20 or more) can be compressed by the application of a single, fixed value of f_{RW}.

This new regime of RW operation is expected to lead to considerable simplifications in the design of a practical multicell trap in that active control and interrogation of individual plasma cells is unnecessary. Very recently, much progress has also been made in understanding the coupling of the RW fields to the plasma [24]. This will aid greatly in being able to make accurate designs for advanced traps for long-term positron storage.

IV. NEXT GENERATION POSITRON TRAP

As indicated in Table 1 and shown schematically in Fig. 7, a 21-cell multicell trap will consist of 3 banks of storage cells with 7 individual cells in an HCP arrangement in each bank. The results shown in Fig. 4 indicate that with a 20 cm confinement length, we can store about 3×10^{10} particles per cell. With 21 cells total, this would result in the storage of a total of 6×10^{11} positrons. To fill this trap, we need a set of feed electrodes with a large radius to use the diocotron excitation technique to move the plasma off-axis and to perform the phase locked injection as shown in Fig. 6. After the first cell is filled, the "shuttle" procedure shown in Fig. 5 would be used to move the plasma from one bank of storage cells to the next. Finally, each individual cell would necessarily include an azimuthally segmented electrode for rotating electric field compression. This will allow for almost infinite confinement of the plasmas in each individual storage cell.

As shown in Fig. 7, each individual cell consists of four electrodes, including one segmented (multicolor) for the application of the necessary rotating electric fields. If more storage were desired, a larger bank of HCP cells could be used (e.g., the 19 cell arrangement in Fig. 3), or extra banks of cells could be added.
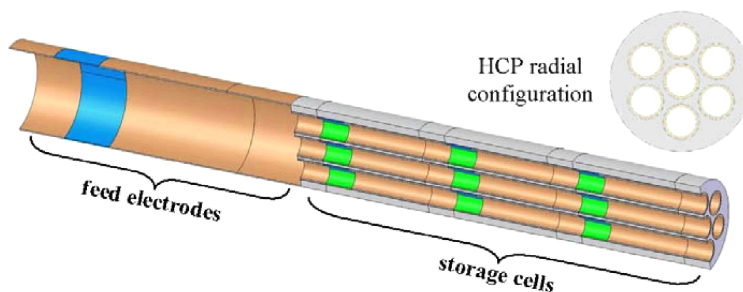

Figure 7. Schematic diagram of the 21-cell multicell positron trap, showing three banks of 7 cells in an hexagonally closed packed arrangement. Plasmas from the source will first enter the feed electrodes, then be moved off axis using autoresonant excitation of the diocotron mode to fill off-axis storage cells.

V. SUMMARY

It is our view that the development of the multicell Penning-Malmberg trap can represent the next major step in antimatter storage technology. The design described here would allow for the accumulation and storage of more than 5×10^{11} positrons. Experiments with test electron plasmas established several techniques critical to the implementation of a practical multicell trap. These experiments included storage of $>10^{10}$ particles in a single cell, operation of two cells simultaneously, and off-axis plasma manipulation for phase-locked plasma control.

One immediate application of this trap is to multiplex the outputs of the new generation of high-flux positron sources either in operation now [6, 7] or currently under development [8-10]. Further, the availability of such large numbers of positrons opens up many new possibilities, such as providing bursts of positrons far larger than available by any other means. Applications of these large pulses of positrons include the possible production of Bose-condensed positronium and the study of electron-positron plasmas. Lastly, the successful development of such a multicell trap will also be a major step toward the creation of a versatile *portable* antimatter trap.

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REFERENCES

1. R. G. Greaves and C. M. Surko, *Phys. Plasmas* **11**, 2333 (2004).
2. C. M. Surko, G. F. Gribakin, and S. J. Buckman, *Journal of Physics B* **38**, R57 (2005).
3. M. Amoretti, C. Amsler, G. Bonomi, *et al.*, *Nature* **419**, 456 (2002).
4. G. Gabrielse, N. Bowden, P. Oxley, *et al.*, *Phys. Rev. Lett.* **89**, 213401 (2002).
5. P. J. Schultz and K. G. Lynn, *Rev. Mod. Phys.* **60**, 701 (1988).
6. A. G. Hataway, M. Skalskey, W. E. Frieze, R. S. Valley, D. W. Gidley, A. I. Hawari, and J. Xu, *Nucl. Instrum. and Meth. in Phys. Res. A* **579**, 538 (2007).
7. C. Hugenschmidt, K. Schreckenbach, M. Stadlbauer, and B. Straßer, *Appl. Surf. Sci.* **252**, 3098, (2006).
8. A. P. Mills, Jr., D. B. Cassidy, and R. G. Greaves, *Mat. Sci. Forum* **445-446**, 424 (2004).
9. A. W. Hunt, L. Pilant, D. B. Cassidy, and K. G. Lynn, *Appl. Surf. Sci.* **194**, 296 (2002).
10. S. D. Chemerisov, C. D. Jonah, and H. Chen, *Nucl. Instrum. and Meth. in Phys. Res. B* **261**, 904 (2007).
11. C. F. Driscoll and J. H. Malmberg, *Phys. Rev. Lett.* **50**, 167 (1983).
12. T. J. Murphy and C. M. Surko, *Phys. Rev. A* **46**, 5696(1990).
13. C. M. Surko and R. G. Greaves, *Rad. Chem. and Phys.* **68**, 419 (2003).
14. J. R. Danielson, T. R. Weber, and C. M. Surko, *Phys. Plasmas* **13**, 123502 (2006).
15. J. Fajans, E. Gilson, and L. Friedland, *Phys. Rev. Lett.* **82**, 4444 (1999).
16. J. Fajans, E. Gilson, and L. Friedland, *Phys. Plasmas* **6**, 4497 (1999).
17. C. F. Driscoll, K. S. Fine, and J. H. Malmberg, *Phys. Fluids* **29**, 2015 (1986).
18. T. M. O'Neil, *Phys. Fluids* **26**, 2128 (1983).
19. X.-P. Huang, F. Anderegg, E.M. Hollmann, C.F. Driscoll, and T.M. O'Neil, *Phys. Rev. Lett.* **78**, 875 (1997).
20. F. Anderegg, E. M. Hollmann, and C. F. Driscoll, *Phys. Rev. Lett.* **81**, 4875 (1998).
21. E. M. Hollmann, F. Anderegg, and C. F. Driscoll, *Phys. Plasmas.* **7**, 2776 (2000).
22. J. R. Danielson and C. M. Surko, *Phys. Rev. Lett.* **94**, 035001 (2005).
23. J. R. Danielson and C. M. Surko, *Phys. Plasmas* **13**, 123502 (2006).
24. J. R. Danielson, C. M. Surko, and T. M. O'Neil, *Phys. Rev. Lett.* **99**, 135005 (2007).