Progress Towards A Practical Multicell Positron Trap

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Abstract. Described here is progress in an experimental program to develop a 21 cell multicell trap for the accumulation and storage of $\sim 10^{12}$ positrons. The basic architecture is an arrangement of multiple Penning-Malmberg (PM) trapped plasmas (i.e., cells) arranged in parallel in a common vacuum system and magnetic field. Experiments are described that are intended to address several key issues, including the effects of large space charge potentials and high plasma densities on: plasma heating, deterioration of confinement, and decreased efficiency of rotating electric fields in producing plasma compression. The confinement of PM plasmas displaced both radially and toward the ends of the uniform magnetic field region will also be investigated.

INTRODUCTION AND OVERVIEW

Positrons are important in a wide range of science and technology, and many of these applications require larger numbers of positrons accumulated and stored and/or delivered in intense bursts. One example is the long-term goal of creating portable traps for antimatter. Another is the quest to create a BEC gas of positronium atoms [1, 2] that, in turn, is expected to potentially enable the creation of an annihilation gamma-ray laser [3]. Another is the quest to create and study electron-positron plasmas [4-6]. These plasmas have unique and fascinating properties (e.g., the prominence of solitons and the absence of three-wave coupling) [7].

The approach described here to accumulate and deliver large particle numbers relies on the fact that antimatter can be stored indefinitely in the form of single component plasmas (SCP) in electromagnetic [i.e., Penning-Malmberg (PM)] traps. Plasmas can be cooled and manipulated, to then be released in tailored bursts or beams of antiparticles. Shown in Fig. 1 is an overview of positron trapping capabilities over three decades of progress. The principal impediment to confining plasmas consisting of large numbers of particles is their large space charge potential which necessitates the use of unacceptably large confinement voltages. In particular, for a long cylindrical plasma, the space charge potential, $\phi \propto N/L$, where N is the total number of particles, and L is the plasma length.

In order to circumvent this impediment, we are building a **multicell trap (MCT)** [8, 9]. [The term "cell" is used here to describe a single-component plasma in an

individual Penning-Malmberg trap.] In the MCT, the space charge potential for a given particle number N is mitigated by dividing the plasma into m separate, rod-shaped plasmas of length L [e.g., in a hexagonal-close-packed (HCP) arrangement transverse to the field]. In this manner, the plasmas are shielded from each other by copper electrodes. In this way, the number of stored positrons can be increased by a factor of m for a given confining potential. The MCT design also breaks up each long rod of plasma into p separate plasmas in the direction along the magnetic field. This reduces the effects of electrostatic and magnetic non-uniformities on the plasma and the associated outward, asymmetry-driven radial transport that is deleterious to good confinement. The trap can be made in a modular design to facilitate further increases in storage capacity. If successful, an MCT will potentially have a wide range of applications, some of which are illustrated in Fig. 2.
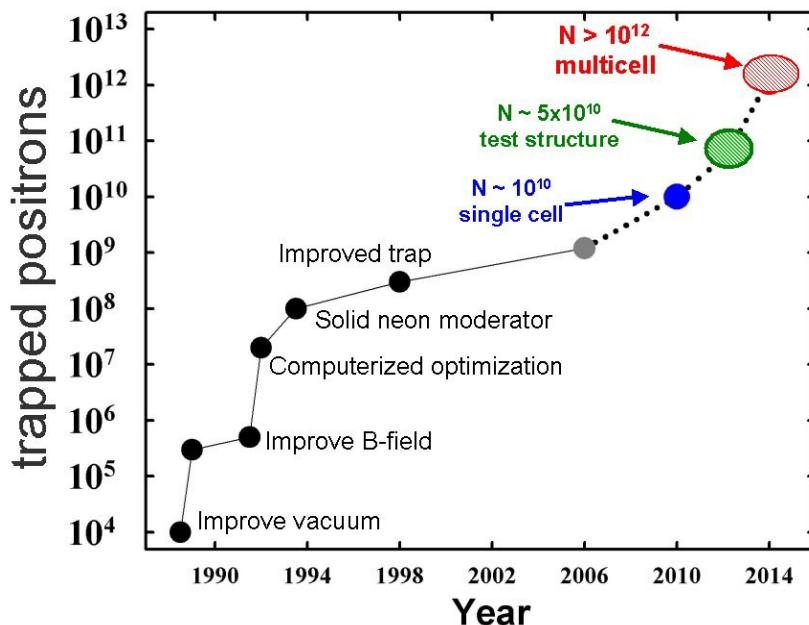

FIGURE 1. Progress in accumulating and storing positrons in Penning-Malmberg traps. The "test structure" point is a demonstration experiment using electrons. The goal of this project is to build the multicell trap with expected performance indicated by the red oval.

The immediate focus of work is to address questions related to the effects of large space charge potentials and high plasma densities as they relate to degradation of confinement, increased plasma heating, and the loss of efficiency in the ability of rotating electric fields to compress plasmas radially and increase plasma confinement. Also of interest is study of confinement of PM plasmas displaced both radially and toward the ends of the uniform magnetic field region. The work described here will be done with electron plasmas for higher data rates, since efficient filling of PM traps, in both low and high magnetic fields (i.e., 0.05 - 6 tesla), has been done in a number of laboratories and hence is now a solved problem [10, 11].
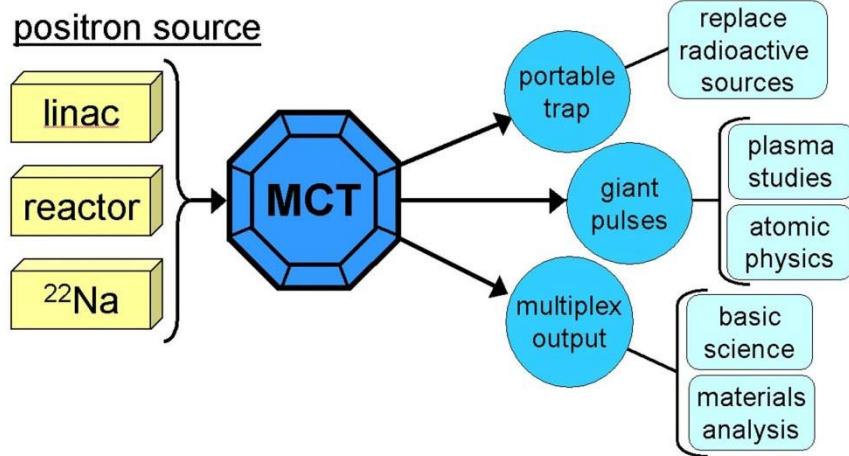
FIGURE 2. Applications of a multi-cell positron trap (MCT). In the multiplex application, the MCT is used to tailor positron plasmas and beams from an intense positron source for delivery to multiple end stations.

TOOLS FOR THE RESEARCH

The Penning-Malmberg Trap

The basic confinement device, an example of which is illustrated in Fig. 3, is a Penning-Malmberg (PM) trap. A uniform magnetic field B provides radial confinement, and electrostatic potentials in the field direction provide axial confinement. In the case of interest (i.e., $\rho_c \ll r_p$, where ρ_c is the gyroradius, which is easily achieved for cool, electron-mass particles), the canonical angular momentum, L, of the plasma in the B direction is proportional to the second radial moment of the particle distribution. In the case of positrons, the requisite plasma cooling can be provided either by collisions with a low-density molecular gas or by cyclotron emission in a large magnetic field. If there are no azimuthal asymmetries, L is constant, and the plasma cannot expand [12]. Plasmas can achieve approximate, constant-density equilibrium states that rotate at frequency $f_E = cne/B$, where n is the plasma density [13].
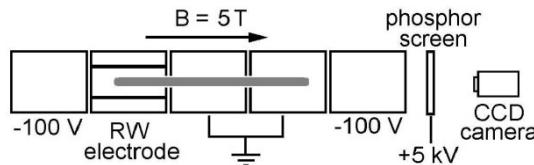

FIGURE 3. Schematic arrangement of the UCSD high-field PM trap biased for electron confinement, with a rotating-wall (RW) electrode for radial plasma compression, and a phosphor screen for (areal) plasma density measurements.

The research described here will be done using the UHV, high-field (e.g., ~ 5 tesla) storage (Penning-Malmberg) trap illustrated in Fig. 3. A phosphor screen and CCD camera will be used for two-dimensional plasma-density profile measurements. The positrons (or electrons) can be cooled efficiently by the emission of cyclotron

radiation at a rate Γ_c of $\Gamma_c \equiv (1/T)(dT/dt) \approx \tilde{B}^2/4$ [s^{-1}], where $\tilde{B}$ is the magnetic field strength in tesla [14]. In the 5 T fields of the UCSD traps, $\Gamma_c \approx 0.16$ s^{-1}.

As shown in Fig. 4, positrons will be accumulated in a buffer-gas trap, then transferred to the UHV multicell trap. Typical laboratory sources of positrons use the radioisotope ^{22}Na followed by a solid neon moderator to slow the positrons to electron volt energies. However, to achieve the full potential of the MCT, the initial source of positrons will need to be a strong one, such as those now operating at the Munich and North Carolina State reactors [15, 16].
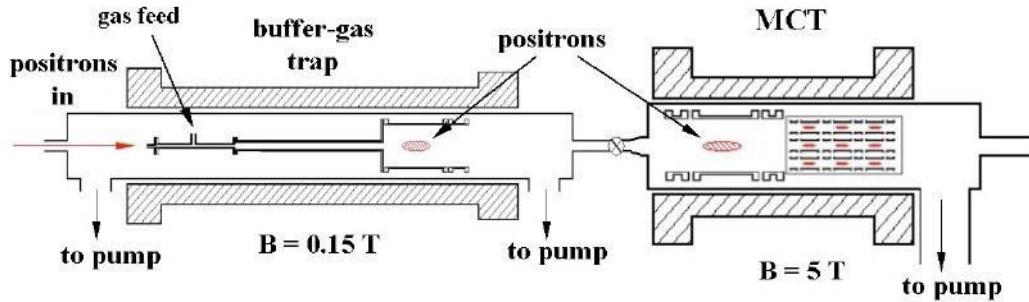

FIGURE 4. Schematic of the three-stage buffer-gas trap (left), connected by a pulsed valve to a high-field UHV storage trap (right). Positrons from the source enter the BG trap from the left [17].

Radial Plasma Compression Using Rotating Electric Fields

The use of rotating electric fields [i.e., the rotating wall (RW) technique] has proven to be a tremendously useful tool to compress SCP radially and to manipulate antimatter plasmas [18, 19]. This technique uses phased electric fields on azimuthally segmented electrodes to apply a torque on the plasma. When the applied frequency f_{RW} is greater than the plasma rotation frequency f_E, the RW fields inject angular momentum and thus compress the plasma.

If the RW fields are sufficiently large, a so-called "strong drive", high density regime can be achieved, limited only when the plasma rotation frequency f_E approaches the applied RW frequency f_{RW} [20, 21]. Compression can be done at fixed f_{RW} and coupling to plasma modes is unnecessary. This simplifies greatly implementation of the technique. The plasma density is set by f_{RW} (i.e., $f_{RW} \propto n$), which is useful for many applications. A critical outstanding question now is what is the maximum density that can be achieved.

DESIGN OF A 21 CELL POSITRON TRAP

The near-term goal is the implementation of a multicell trap for 10^{12} positrons, such as that illustrated in Fig. 5. It will consist of three banks of seven storage cells, in an HCP configuration, adjacent a master cell. Positrons from the buffer gas accumulator will be transferred to the master cell, then they will be moved off axis using autoresonant excitation of the diocotron mode [9]. Positrons will then be injected into the off-axis storage cells. To dump the trap, plasmas will be returned from the off axis cells to the master cell, then the diocotron mode damped to bring the plasma back on

axis. This procedure should take ~ milliseconds to accomplish per line of off-axis cells. The parameters of the 21 cell trap are summarized in Table 1. This design took into account the need to minimize the number of cells, while ensuring good confinement. Each cell will have a segmented electrode for RW plasma compression.
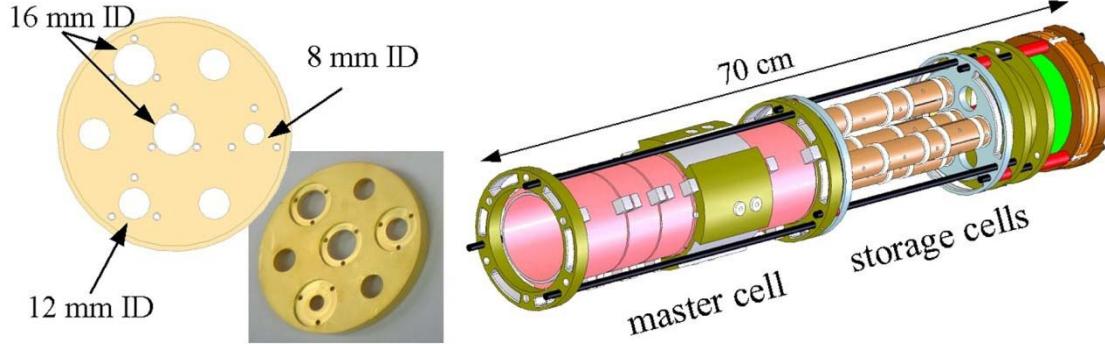

FIGURE 5. Schematic diagram of the 21-cell multicell positron trap, showing three banks of 7 cells in a hexagonally closed packed arrangement. Plasmas from the source will first enter the feed electrodes, then be moved off axis using autoresonant excitation of the diocotron mode to fill off-axis storage cells.

TABLE 1. Design parameters of a 21-cell multicell trap.

Number of cells *(m × p = 7 × 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

VALIDATING ASPECTS OF THE DESIGN

Confinement at High Densities and Large Plasma Potentials

The multicell trap will require optimizing N/L for a given space charge potential φ, since large N/L is key measure of good performance. As shown in Fig. 6 (left panel), we have demonstrated that we are able to work with kilovolt electrode potentials to confine particle numbers in excess of 3×10^{10} in a single plasma cell. As shown in the right panel, we have increased plasma densities to n ≥ 4×10^{10} cm^{-3}. However many open questions remain regarding the underlying plasma physics in these regimes; and

so future work will focus on understanding these regimes and improving these aspects of performance. Plans to address these issues are described here.
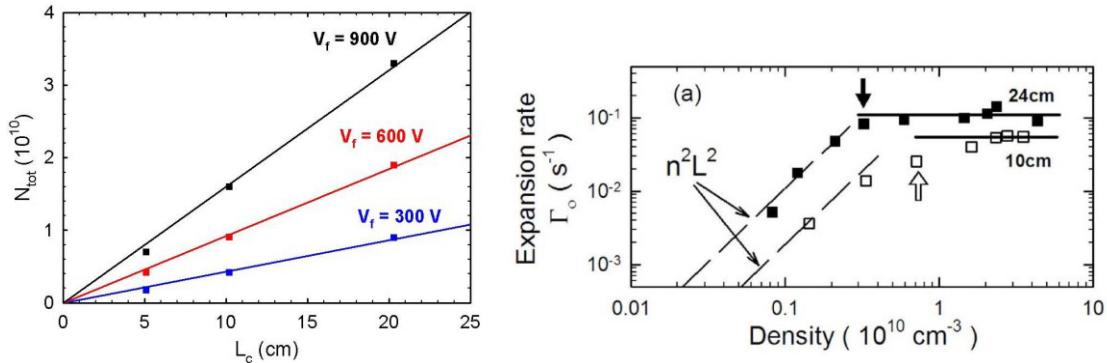

FIGURE 6. (left) number of particles confined in a PM trap as a function of cell length for different fill voltages [9]; and (right) plasma expansion rate as a function of plasma density [21].

Confinement at High Densities in the Presence of Large Space-Charge Electric Fields

A critical consideration for positron accumulation and storage is the ability to achieve good confinement of relatively cool, high-density plasmas. There has been relatively little exploration to date of the confinement properties of lepton plasmas for which $e\phi/T \sim (r_p/\lambda_D)^2 \geq 10^2$, where r_p is the plasma radius and λ_D the Debye length; yet this is precisely the range of parameters optimal for long-term positron storage. To construct a useful MCT, it is desirable to work with as large space charge (and hence as large plasma potential) as possible (i.e., $\geq$ kilovolts) in large-aspect ratio plasmas ($L/r_p \geq 100$, where L its length), and this is likely to cause significant heating. However, the plasma must remain cool [e.g., $T \leq 1.5$ eV] to avoid positron loss due to positronium-atom (Ps) formation on background neutral gas. These considerations provide the motivation for studying confinement and transport at high plasma densities, $n \geq 10^{11}$ cm^{-3}, with $r_p/\lambda_D >> 1$ and $N/L \geq 2 \times 10^9$ cm^{-1} − a regime in which space-charge electric fields can lead to both significantly reduced confinement and increased heating.

In the experimental apparatus described below, we plan to explore the confinement properties of very large SCP plasmas in 5 tesla strength fields, plasmas with particle numbers $N \geq 10^{10}$, space charge potentials $\sim$ 1 kV and densities approaching 10^{11} cm^{-3} (cf., Fig. 6). Confinement in these regimes has not been explored previously, and it will be critical to MCT performance and very important in other applications in which large, rapid bursts of positrons are required. Rotating wall compression will be used to increase confinement. A key goal is to determine the limits of confinement as a function of N, n, T and B. For long-term positron (antimatter) storage, the key question is for what optimized parameters (including minimum electrode radii) can "infinite" confinement time be achieved.

Limits of RW Compression

Radial compression of antimatter plasmas using rotating electric fields (the RW technique) has been enormously useful in achieving long confinement times and creating specially tailored, high-density plasmas [18, 20, 22-25]. In the highly desirable "strong drive" regime in which the plasma rotation frequency approaches the applied RW frequency f_{RW}; this, in turn, sets the density, namely $n_m = f_{RW}B/ce$ [20, 24]. For reasons not presently known, it has proven difficult to work at frequencies beyond about 15 – 50 MHz and this limits the maximum achievable density [21, 26-28]. An example is shown in Fig. 7, where continuous operation as a function of frequency is limited to 8 MHz, with more spotty operation possible up to ~ 17 MHz. While such impediments have been observed in literally all experiments to date using this technique, no systematic cause has been found. Thus a major physics objective with potentially huge technological payoff is to understand how to increase, or mitigate the apparent density limit of rotating-wall compression. We have now built new rotating wall circuits with a chip that has increased drive voltage; but more importantly, they permit independent adjustment of both the amplitudes and the phases of voltages on the four RW electrodes. We believe that this will go a long way toward controlling and/or eliminating electronic resonances as a possible cause of the frequency limit that we observe. Operation of the new circuits has been tested with plasmas, and we are ready to begin detailed studies.

Initial work will focus on more carefully constructed RW electrode structures and associated circuits to ensure that the signals on the segmented RW electrodes are carefully balanced. The ability to operate a second HF trap will allow us more flexibility in varying electrode structure geometries and construction techniques. It is presently unknown, for example, what effect the ratio r_p/r_w where r_w is the wall radius, has on the efficiency of RW compression.
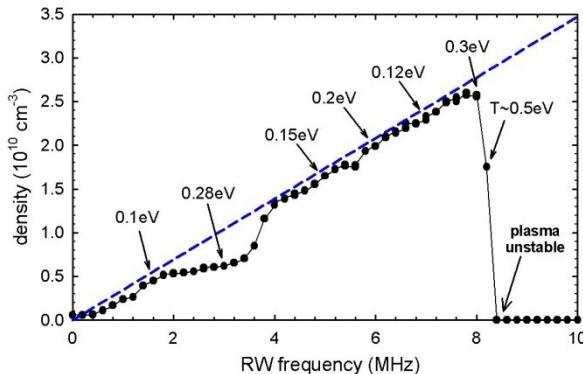

FIGURE 7. Density vs. f_{RW} for RW plasma compression. Plasma temperatures are indicated, and (---) is the condition $f_E \approx f_{RW}$. Failure to reach high densities for $f_{RW} \geq 8$ MHz is accompanied by excess heating. In the range $f_{RW} \geq 8$ MHz, $f_E \approx f_{RW}$ can be attained, but only at specific frequencies [21].

Another potential limiting factor in RW operation is plasma heating, particularly for plasmas with large space charge electric fields. We have evidence of deleterious heating effects in a number of experiments but little detailed understanding of the microscopic physics that underlies them. In the range of parameters optimal for the MCT, namely $r_p/\lambda_D \geq 100$, theory predicts that the emission and absorption of waves can dominate the heat transport [29]. We will be in a position to conduct experiments for the first time in this regime. Since RW compression is sensitive to heating,

operating in this wave-transport regime may offer possibilities for smoothing out "hot spots" and hence lead to improved RW performance.

Experiments with a Test Electrode Structure

To address these outstanding problems, we have constructed a test electrode structure, shown schematically in Fig. 8 and in its physical implementation in Fig. 9. It consists of a master cell that takes plasma from the buffer gas accumulator and an adjacent set of storage cells. Autoresonant excitation of a diocotron mode is then used to move the plasma off axis so that it can be delivered to the off-axis MCT cells [9]. In this technique, a frequency swept signal excites the plasma to a rotating off axis position. The radial position is determined by the applied frequency and the azimuthal position by the phase of the signal. Plasmas can be displaced to within 20 % of the inner radius of the confining electrode. This technique will be used to position plasmas precisely (+/- ~ 0.2 mm) off axis, then dump them into particular lines of storage cells. The test structure contains a central storage cell and three off-axis MCT cells having electrode IDs of 8, 12 and 16 mm. Each cell, including the master, has a segmented RW electrode.

Issues to be addressed are:

- **Determine the minimum diameter electrodes for good confinement**
- **Test confinement for off axis plasmas near the ends of the uniform field region**
- **Test off-axis cell loading using autoresonant diocotron-mode addressing**
- **Explore of the limits of RW operation**
- **Explore transport and heating effects in high space-charge plasmas**

This electrode structure is now operating in our 5 T UHV trap. We will use the results of these tests to design the final electrode structure for the 21 cell MCT. There are several goals for the final electrode design. One goal will be to build as compact an MCT electrode package as possible by use of electrodes with small interior diameters. Another goal will be to have the MCT electrodes as long as possible (i.e., utilizing as much of the uniform field as possible), while still exhibiting good confinement.
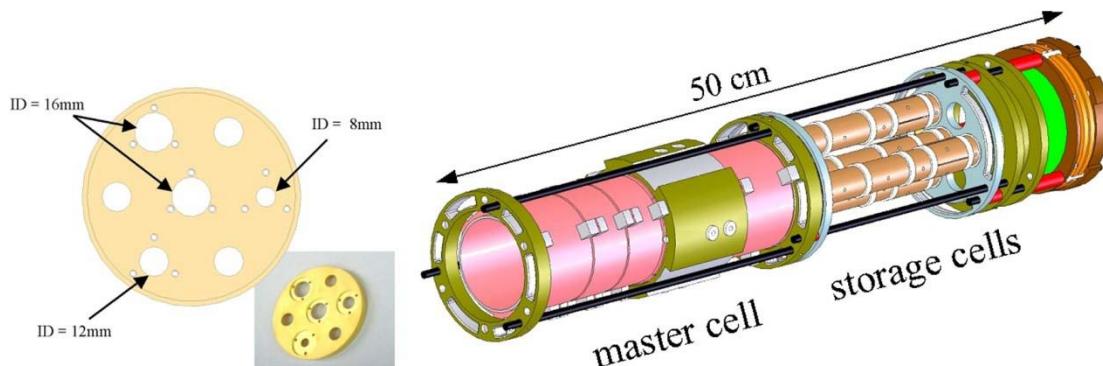

FIGURE 8. Test electrode structure (above) with the master cell on the left, followed by three off-axis and one on-axis storage cells. The end plate for these storage cells is shown in two views at the immediate left.

FIGURE 9. Electrode structure as built.

We will also try to use a more integrated approach to the electrode design for the final 21-cell trap electrodes, moving from a discrete-cell architecture, such as that shown in Figs. 8 and 9 to one in which a common electrode can be used for most of the cells arranged in parallel. So, for example, the confinement and RW electrodes in off-axis cells could potentially each be common for parallel cells, which in turn, simplifying the complexity of the electronic circuits.

USES OF A MULTICELL TRAP

An Electron-positron Plasma Experiment

Creating the ability to study "pair plasmas" in the laboratory for the first time (i.e., simultaneously confined electron and positron plasmas) is potentially groundbreaking. We are preparing to conduct such an experiment with Thomas Pedersen and collaborators at the Max Planck Institute for Plasma Physics, Greifswald, Germany, and Christoph Hugenschmidt and collaborators at the Munich Research Reactor positron source, NEPOMUC [15]. A recent paper [6] describes our experimental plans in some detail. Our involvement will emphasize the design of the required positron traps and development of the required positron manipulation techniques (e.g., bursts of $\geq 10^{11}$ positrons in ≤ 10 ms). Concepts from the MCT project described here will be a key part of this effort.

The NEPOMUC can provide positrons at a world-class rate of $\sim 10^9$ s^{-1}, which will feed a buffer-gas positron accumulator followed by a multicell, high-field storage trap (both of the UCSD design). Positrons will be injected into a novel superconducting stellerator (to be built in Greifswald) that has been pre-loaded with electrons. Injection must be in ≤ 10 ms bursts of $N \geq 10^{11}$ positrons.

Initial objectives are a plasma of $\geq 10^{11}$ electrons and positrons at a density n $\sim 10^7$ cm^{-3} with $T \leq 2.0$ eV. This corresponds to a minimum of ~ 40 Debye lengths across the plasma of minor radius 7 cm. Confinement times ≥ 0.1 s are expected (i.e., limited by transport and not annihilation) [6].

A BEC Positronium Gas and Work Towards a Gamma-ray Laser

The quantum many-electron, many-positron gas and plasma is also a fascinating physical system [30, 31]. Important goals include the creation and study of the positronium molecule (Ps_2) and a Bose-condensed (BEC) gas of Ps atoms; and ultimately, the creation of stimulated emission (lasing action) at 511 keV [3]. The Ps_2 molecule has been created and is currently being studied [1, 2]. Creation of a BEC Ps gas and development of a gamma-ray laser will require intense bursts of positrons delivered on short time scales (e.g., tens of ns). While an MCT, such as that described here, can be used for the accumulation of sufficiently large numbers of positrons for a gamma-ray laser (e.g., $\geq 10^{12}$), methods must be developed to achieve sufficiently rapid delivery of the entire burst of positrons to a sample; and this is a topic of current research.

Multiplexing the Output of Intense Positron Sources

A potentially important use of the MCT is to multiplex the output of the ultrahigh flux positron sources, either in place now, such as NEPOMUC, or others in stages of development [32-35]. This will be useful in cases where a particular experiment does not require the entire positron flux from the source, but can use a lower flux of positrons cooled and/or delivered in a particular manner. In this case, plasmas could be specifically tailored for particular end uses in cells of the MCT, then shuttled out for delivery to various end stations.

Portable Antimatter Traps

Successful development of a portable trap for antimatter is a potentially transformative advance. A portable trap would enable a wealth of new science and technology. With such a portable trap, measurements could be done in many settings, even on an electronic-chip manufacturing line. Described here are important steps toward that goal, namely the first practical MCT. The gamma rays from positron annihilation are easy to shield, in contrast to handling radioisotopes or dealing with other strong positron sources.

CONCLUDING REMARKS

Ongoing research is described to explore the limits of confinement in HF Penning-Malmberg traps and to explore and seek to understand the limits of RW plasma compression, with particular emphasis on high plasma densities and plasmas with large values of N/L. The near-term goal is the successful development of a MCT for 10^{12} positrons. Further, the storage cell design is modular, so the trap capacity can likely be further increased.

More generally, plasma physics has been, and will continue to be the driver for research with low-energy antimatter. Major broad impacts are expected from the new methods described here that are being developed to accumulate, store, manipulate and deliver positrons. These tools are expected to enable a range of important applications

of low-energy positrons in a variety of fields, including atomic and plasma physics and materials science. The long-term goal of a portable antimatter trap, which this research contributes to, would be a potentially transformative advance.

ACKNOWLEDGMENTS

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