Progress in Creating Low-energy Positron Plasmas and Beams

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Abstract. A summary is presented of recent research to create positron plasmas in new regimes of density, temperature, and particle number. The operation of a new, compact positron accumulator is discussed. It has a number of improvements including enhanced vacuum capabilities and an easily modified electrode structure. Using a 90 mCi ^{22}Na source and neon moderator, a plasma of 3 x 10^8 positrons, with a diameter of 6 mm (FWHM) and a density of 2 x 10^7 cm^{-3}, has been accumulated in 8 minutes. This is a factor of 50% more positrons and an order of magnitude increase in plasma density over the performance of the previous accumulator. Plans for a separate, high magnetic field (i.e., 5 Tesla), low-temperature (< 10 Kelvin) trap are described. This trap is expected to permit the creation and long-term storage of cryogenic plasmas with more than an order of magnitude larger particle number and more than two orders of magnitude in plasma density. A method is described that uses positron accumulation techniques to create a cold, bright positron beam (e.g., < 20 meV FWHM), tunable from ~ 0.1 eV upward. Results are described of studies of positron scattering from atoms and molecules in a new range of energies (e.g., < 1 eV) using this cold positron beam. Other applications of trapped cold positron plasmas and beams are briefly discussed.

INTRODUCTION

Once the province of high-energy physics, antiparticles such as the antiproton and the positron are now routinely used in a much wider range of applications. In the case of positrons, these uses include the study of atomic and molecular physics, antihydrogen formation, plasma physics, and the characterization of solids and solid surfaces [1, 2]. Further progress in many of these areas hinges on the ability to manipulate and cool large collections of antiparticles, relying in large part on nonneutral plasma techniques.

One benchmark for handling antimatter is the lifetime of antiparticles in the presence of matter. This time is of the order of a few nanoseconds for either positrons or antiprotons in solids or gases at atmospheric pressure. This fact leads immediately to the conclusion that, if antimatter is to be confined, accumulated and cooled, it must be done in a vacuum environment. Over the past decade, we have developed methods to accumulate large numbers of positrons [2,3], by exploiting nonneutral plasma

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techniques developed for electron plasmas [4]. Plasmas of greater than 10^8 particles and confinement times of many minutes to hours are now routine [2].

Using the positron accumulator, we have recently developed a new technique to create a state-of-the-art cold positron beam with an energy spread as small as 18 meV (FWHM), tunable from 0.1 eV upwards [5,6]. Recently, we used this technique to make the first measurements of the cross section for excitation of vibrational modes in a molecule (the asymmetric stretch mode in CF_4, $\Delta\varepsilon = 0.16$ eV, measured for positron energies from 0.2 to 1 eV) [7]. We also measured the differential cross section for elastic scattering of positrons from atoms in the range of energies between 0.4 and 2 eV [7]. These experiments are expected to provide important new information, such as understanding the role of virtual positronium states in positron interactions with matter and the mechanisms by which positrons bind to atoms and molecules.

In this paper, we review recent progress in positron accumulation and the development and use of the cold positron beam. We also discuss briefly other applications. For a discussion of the application of cold positron beams to condensed matter and surface physics and positron ionization mass spectrometry, the reader is referred to a complementary paper elsewhere in this volume by [8].

BUFFER-GAS TRAPPING AND A NEW ACCUMULATOR

The principle of the buffer-gas trapping scheme is illustrated schematically in Fig. 1. Inelastic collisions of positrons with N_2 molecules are used to trap positrons in a specially designed Penning-Malmberg trap [2,3,9]. Positrons from the source are slowed to a few electron Volts using a neon rare-gas "moderator," which consists of solid neon condensed on a metal surface at 7 Kelvin. There is an applied magnetic field of ~ 0.1 - 0.15 T in the z direction. The positrons are injected into the accumulator at energies ~ 30 eV. The accumulator has three "stages," I, II, and III, each with successively lower gas pressure and electrostatic potential. Following a series of inelastic collisions ("A", "B," and "C" in Fig. 1), the positrons are trapped in stage III where the pressure is lowest. The positrons cool to room temperature by collisions with the N_2 in ~ 1 s. The positron lifetime in the third stage is $\geq$ 40 s, limited by annihilation on the N_2 gas. Using this technique, we are able to accumulate > 10^8 e^+ in a few minutes from a 90 mCi ^{22}Na source. The lifetime of the plasma with the buffer gas removed ranges from tens of minutes to hours, depending upon the quality of the vacuum.

The design of the original positron accumulator (*circa* 1985) is shown in the upper part of Fig. 2. This design used a split magnet surrounding the accumulator electrodes to achieve the required differential pumping. One focus of our work in the last two years has been the completion of a new positron accumulator. A key feature of the new accumulator is elimination of the separate pumping port for the second stage.

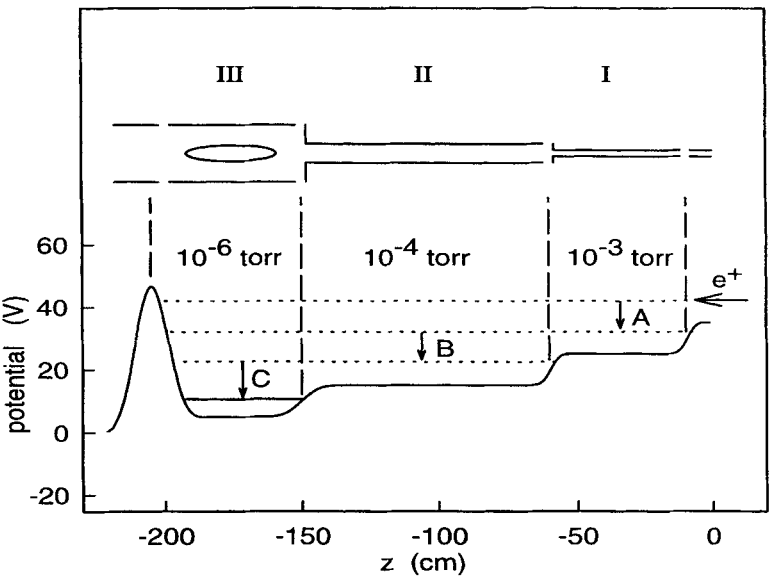

FIGURE 1. Schematic diagram of the three-stage positron accumulator, showing the electrode structure (above), which is used to create regions with different pressures of nitrogen buffer gas by differential pumping. The electrostatic potential profile along the direction of the magnetic field is also shown (below).

A new electrode structure with a much improved pressure profile was designed using a state-of-the-art molecular flow simulation program, provided by Dr. Tim Bartel of Sandia National Laboratory [10]. The calculated pressure profile along the magnetic axis of the trap is shown in Fig. 3. The new design is a significant improvement in terms of pressure differential and uniformity of pressure in stages II and III. The size of the electrodes and magnet were reduced, thereby reducing complexity and cost. The electrodes are made from gold-plated aluminum. They are designed for close fit to the vacuum chamber, thereby facilitating alignment. The new vessel is a ultra-high vacuum (UHV) system, bakeable to 130 ^{0}C, with a base pressure of $\leq 10^{-10}$ torr.

Shown in Fig. 4 are the radial profiles of the positrons in the filling beam from the source/moderator and in stages II and III of the trap. The diameter of the trapped plasma in stage III is 6 mm (FWHM), as compared with 1.5 cm in the previous design. Shown in Fig. 5(a) is the filling of the trap using a 10 Volt potential well in stage III. Note the super-linear filling rate as a function of time. This is evidence that we are entering a regime in which the positron density is large enough that positrons are trapped in stage III by scattering from positrons previously trapped in this stage. This is consistent with estimates for Coulomb scattering during the time (~ 10 ms) that the

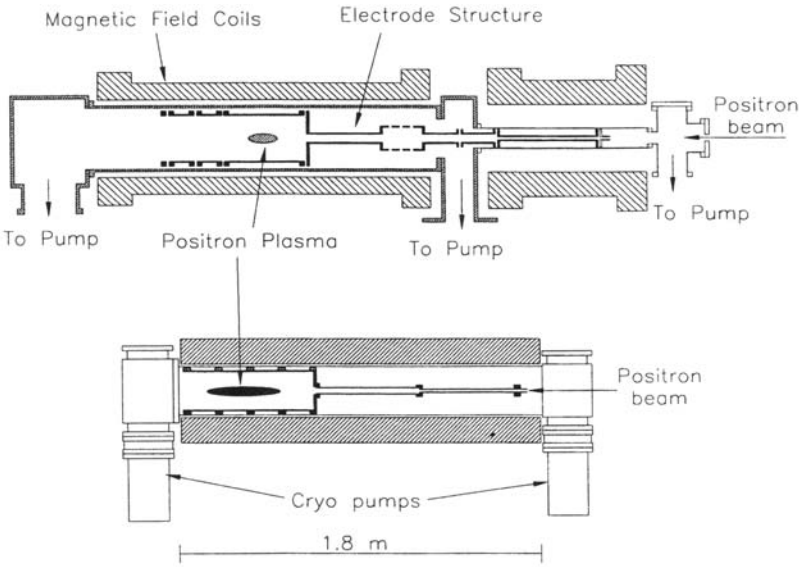

FIGURE 2. Shown to scale are the designs of the original (above) and the new positron accumulator (below). The new design provides a true UHV-quality vacuum and the ability to easily modify the electrode structure.

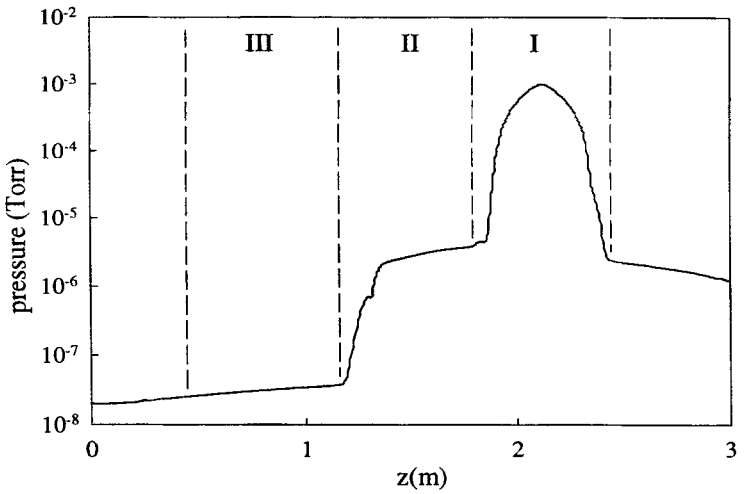

FIGURE 3. Calculated pressure profile as a function of distance along the magnetic axis in the new positron accumulator. This design improves the maximum pressure differential between each stage by an order of magnitude.

particles spend in stage II before becoming trapped in stage III. The maximum positron number in Fig. 5(a) is limited by the space charge of the positrons in stage III. Figure 5(b) shows data taken when the stage-III potential well was lowered from 10 to 15 Volts during filling. The maximum number trapped is just under 3×10^8. Note that the filling has not yet saturated for an 8 minute accumulation.

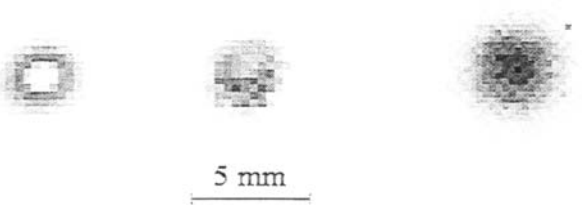

FIGURE 4. Radial profiles of the positron filling beam (left); the plasma accumulated in stage II after a 0.5 ms fill (center); and the plasma in stage III after a 10 s fill.

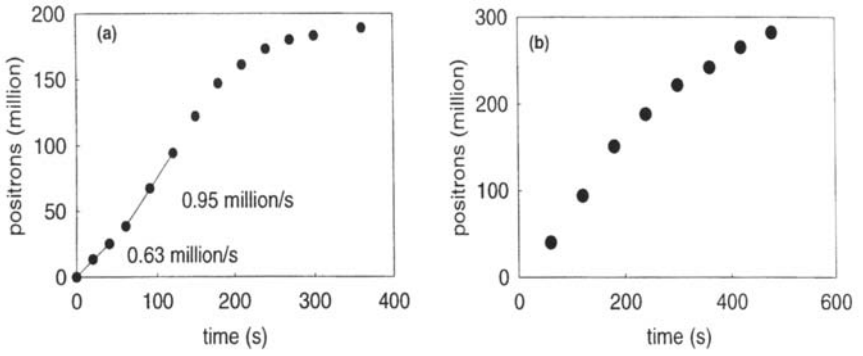

FIGURE 5. Positron filling of the accumulator: (a) filling with a 10 Volt potential well in stage III. The increase in filling rate appears to be due to scattering from positrons already in stage III; (b) filling curve taken when the well depth is lowered from 10 to 15 V during the fill.

A UHV environment is required for many applications, such as antihydrogen formation or studies of positron annihilation with test molecules. We have been able to accomplish this in the new buffer-gas trap by rapidly pumping out the gas after positron filling. As shown in Fig. 6, we are able to cycle stage III from an operating pressure of 3×10^{-7} torr to $< 1 \times 10^{-9}$ torr in a few seconds. This will also be useful in shuttling the positrons from positron accumulator into a separate UHV storage and experimentation trap (described below) through a fast pulsed valve.

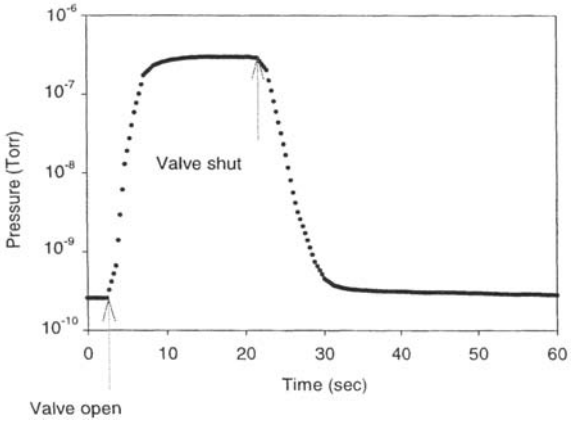

FIGURE 6. The pressure in the third stage of the new accumulator can be decreased by three orders of magnitude in 10 seconds.

A HIGH-FIELD LOW-TEMPERATURE TRAP [11]

The buffer-gas trap is attractive for a range of applications because of the high trapping efficiency. However, as mentioned above, many of these applications require an ultra-high vacuum (UHV) environment, and a limitation of the technique is that the positrons are initially in a background of nitrogen gas at a pressure $\geq 10^{-7}$ torr. As shown in Fig. 6, we can create a good vacuum in the trap rapidly by pumping out the buffer gas (e.g., in ~ 10 s) and then conduct the specific experiment of interest. However, this will interrupt the fill cycle. Thus, it is advantageous to combine the ability to pump down the accumulator rapidly with the ability to "stack" positron plasmas efficiently in a UHV environment. For this purpose, we are building an isolated UHV stage into which the positrons from the accumulator can be shuttled repetitively through a fast pulsed valve. In this way, we can isolate the efficient buffer-gas trap from the UHV stage. The proposed apparatus is shown in Fig. 7.

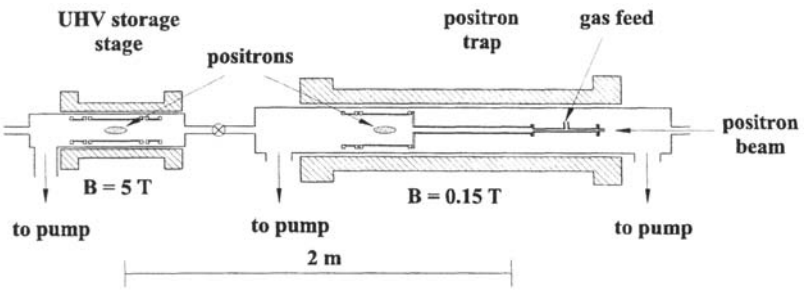

FIGURE 7. The UHV storage trap in relation to the three-stage positron accumulator.

During positron accumulation, the UHV storage stage will be isolated from the positron trap by a fast valve. Then the buffer-gas feed will be switched off and the trap will be pumped rapidly to base pressure (i.e., $\sim 1 \times 10^{-10}$ torr). The gate valve will then be opened for the brief time (≤ 1 s) required to transfer the positrons to the storage trap and the cycle repeated. Long confinement times and low plasma temperatures will be achieved by applying a magnetic field of 5 T in this region. In the 5 T field, the cyclotron radiation time is ~ 0.2 sec. We plan to cool the walls to 10 Kelvin, and so the plasma will cool radiatively to approximately the wall temperature. The cold walls should provide excellent vacuum (e.g., pressures $\leq 10^{-11}$ torr or better). The trap will have a "rotating wall" electrode for control of plasma density and confinement time [12]. Using this technique, we are likely to be able to achieve an "infinite" confinement time, as has been done in the case of electron plasmas.

In Table I, the operation of the old positron accumulator is compared with that expected for the new accumulator and UHV storage trap. We assume a six-minute trapping cycle including one minute to pump out the buffer gas. Presently, the positron loading rates are $\sim 3 \times 10^8$ per cycle or 3×10^9 per hour. With modest improvements, we expect that it will be possible to increase the number of positrons by a factor of as much as five, to $> 1 \times 10^9$ per cycle. These improvements include an increased source strength of 150 mCi and modest improvements in the source geometry, magnetic field, and vacuum system. With these modifications, positron accumulation rates of greater than 1×10^{10} positrons per hour are expected. With this filling rate and confinement times > 3 hours, the number of positrons accumulated will be limited by the space charge of the plasma. For example, an hour's accumulation of 1×10^{10} positrons in a plasma 1 mm in radius by 10 cm long corresponds to a plasma density of $> 1 \times 10^{10}$ cm^{-3} and a 1 kV space potential.

TABLE I. Expected Performance of the UHV Storage Trap*

Parameter	Old Positron Accumulator	New Accumulator and UHV Storage Trap
Source strength (mCi)	70	95
Positrons per cycle	2×10^8	$\sim 3 \times 10^8$
Cycles per hour	n.a.	10
Positrons per hour	n.a.	$\sim 3 \times 10^9$
Density (cm^{-3})	$\sim 2 \times 10^{6\,a}$	$> 1 \times 10^{10\,b}$
Base pressure (torr)	3×10^{-10}	$< 1 \times 10^{-11}$ (cold)

* Based on current new-trap performance

[a] One cycle in a 0.1 T magnetic field.

[b] One hour accumulation in a 5 T field.

A COLD POSITRON BEAM AND APPLICATION TO ATOMIC PHYSICS

While sources of cold electron beams are common, this is not true for positrons. Recently, we developed a method to create a state-of-the-art cold positron beam using trapped positron plasmas [6,7]. This technique can be used to increase the brightness of a positron or electron beam, and to create intense, short pulses of positrons with narrow energy spreads. The beam energy can be tuned over a wide range of energies, from ~ 0.1 eV to tens of electron Volts.

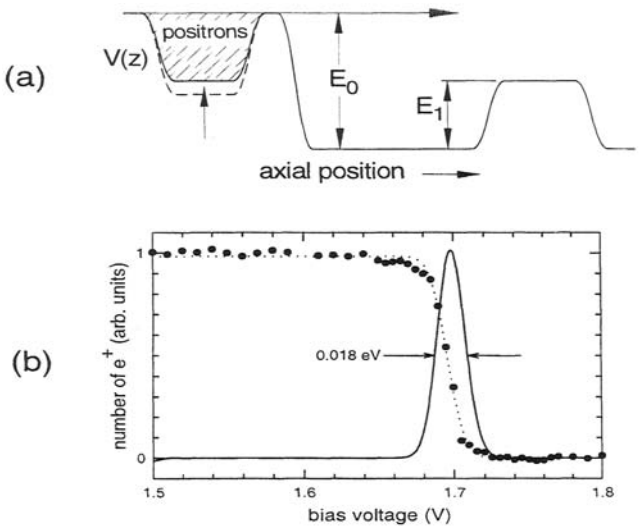

FIGURE 8. Schematic diagram of the arrangement used to create a cold positron beam (above), and the retarding-potential curve and energy distribution (below).

The experimental arrangement is illustrated in Fig. 8(a). Positrons are accumulated and cooled in a Penning-Malmberg trap. Then the potential of the bottom of the trap is raised, forcing the particles over a fixed-height potential barrier [energy E_0 in Fig. 8(a)], and this sets the energy of the beam. The spread in parallel energies of the beam can be as low as, or lower than, the temperature of the plasma in the potential well. However, care must be taken not to empty the trap too quickly, or space-charge effects will increase the energy spread of the beam. Shown in Fig. 8(b) are data for the energy resolution of a positron beam created using this technique. We have been able to operate the beam in both continuous and pulsed modes; the latter was accomplished by reducing the depth of the confining potential well in small steps.

Two topics that could not be addressed previously due to the lack of suitable low-energy positron sources were study of the excitation of molecular vibrations by positrons and measurement of low-energy differential scattering cross sections. We

have now been able to do both [7]. The experiments were done exploiting the fact that the cold positron beam is in a magnetic field. This is in contrast to contemporary electron scattering experiments which are typically done using electrostatic beams.

The first measurements of the differential elastic scattering cross section for argon at 1 eV positron energy are shown in Fig. 9(a). Comparison with theoretical predictions of McEachran, *et al.* and Duzba, *et al.* (solid and dotted curves, respectively, with no fitted parameters) [13,14] indicate excellent agreement. In the future, we hope to study elastic scattering in the important regime, $ka \sim 1$, where k is the momentum of the positron and a is the scattering length (in atomic units). In this limit, both the sign and magnitude of the s-wave scattering length, a, can be measured, and these quantities provide important information about positron-atom and positron-molecule bound states.

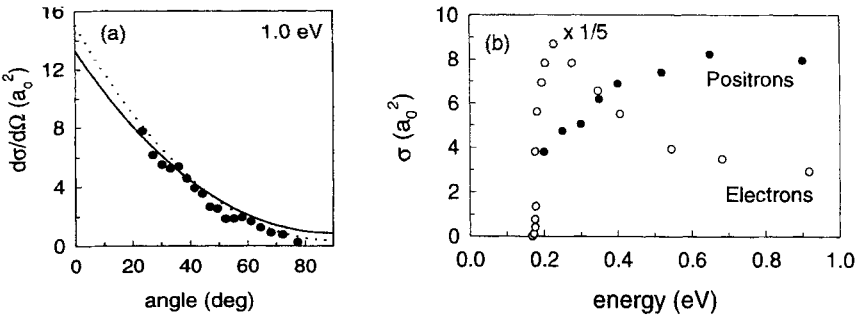

FIGURE 9. (a) differential elastic scattering cross section of positrons scattered from argon at 1.0 eV; (b) the cross section (in atomic units) as a function of positron energy for excitation of the asymmetric stretch mode in CF_4, which corresponds to an energy of 0.16 eV. Also shown is the cross section for electrons, taken from electron-swarm data. (See Ref. 7 for details.)

We have also used the cold beam to make the first measurement of the vibrational excitation of a molecule (CF_4) with positrons [7]. This was accomplished by locating the scattering event in a magnetic field of 1000 Gauss and analyzing the spectrum of parallel energies of the scattered beam in a smaller magnetic field. In this case, the (nominally parallel-energy) retarding-potential analyzer measures the *total* positron energy and therefore measures the energy loss due to scattering. Data for CF_4 are shown in Fig. 9(b). The asymmetric stretch mode that is excited has an energy of 0.16 eV. This is an absolute measurement and extends down to positron beam energies of 0.2 eV, which is possible only because of the excellent energy resolution of the cold positron beam.

CONCLUDING REMARKS

We are continuing to advance the technology of accumulating and cooling positrons. The new UHV trap should provide capabilities for a range of experiments, furnishing a

reservoir of cold, dense positron plasma in a high-quality vacuum environment that can be used as required for the particular experiment at hand. It should be well suited, for example, as a positron source for antihydrogen production. These efforts have now been extended to the creation of a state-of-the-art bright, pulsed positron beam, tunable over a wide range in energies. The new UHV trap and cold walls should be well suited for the creation of a new generation of positron beams [e.g., having an energy spread as low as 1 meV (FWHM)].

Driven by advances in this technology, we continue to use these antimatter beams and plasmas to study a range of scientific problems -- from the electron-beam positron-plasma instability and modeling of astrophysical processes to antihydrogen formation and the interaction of low energy positrons with atoms and molecules. In particular, the cold positron beam appears to be able to address many new problems in these areas.

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