New Tools for Physics with Low-energy Antimatter
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I. Overview

The overall objective of this research is to develop new tools to manipulate antimatter plasmas and to tailor them for specific scientific and technical uses. The work has two specific objectives. One is establishing the limits for positron accumulation and confinement in the form of single-component plasmas in Penning-Malmberg traps. This technique underpins a wealth of antimatter applications. A second objective is to develop an understanding of the limits for formation of cold, bright positron beams. The research done in this grant focused on particular facets of these goals. One focus was extracting tailored beams from a high-field Penning-Malmberg trap from the magnetic field to form new kinds of high-quality electrostatic beams. A second goal was to develop the technology for colder trap-based beams using a cryogenically cooled buffer gas. A third objective was to conduct the basic plasma research to develop a new high-capacity multicell trap (MCT) for research with antimatter. While the goal of this research is to develop new tools for manipulating positrons (i.e., the antiparticles of electrons), much of the work was done with test electron plasmas for increased data rate. Some of the techniques developed in the course of this work are also relevant to the manipulation and use of antiprotons.

II. Major Findings

A. Extracting High-quality Electrostatic Beams from Penning-Malmberg traps

Specially tailored particle beams have found a wealth of applications in science and technology, and this is especially true in studies involving antimatter. In the past, we exploited the physics of nonneutral plasmas to create beams of small transverse spatial extent. This was done by carefully lowering, in a pulsed manner, one of the confining end-gate potentials (see Fig. 1, left panel). A key result of previous work is that the minimum achievable beam diameter is limited to four Debye lengths [1, 2]. Another important outcome of this research was the development of an understanding of the physical effects responsible for determining the energy distribution of the extracted beam particles.

This beam extraction technique produces magnetically guided beams. However, there are a number of potential applications in which an electrostatic, as opposed to a magnetically guided beam, is desirable. While the former is most compatible with accumulation and storage in a Penning-Malmberg trap, the latter admits to the use of electrostatic focusing and the exploitation of ballistic trajectories in three dimensions.

In principle, we can create a state-of-the-art electrostatic beam consisting of pulses of several thousand particles with an energy spread of ~ 10 meV. This would be accomplished by creating a plasma with a temperature of 10 meV in a 5 T magnetic field, adiabatically transporting the beam to a region in which B = 5 gauss, then extracting these particles from the magnetic field. Such a beam would be a considerable advance for example, for positron-atomic physics scattering experiments, and could potentially be used to form microbeams for materials analysis.

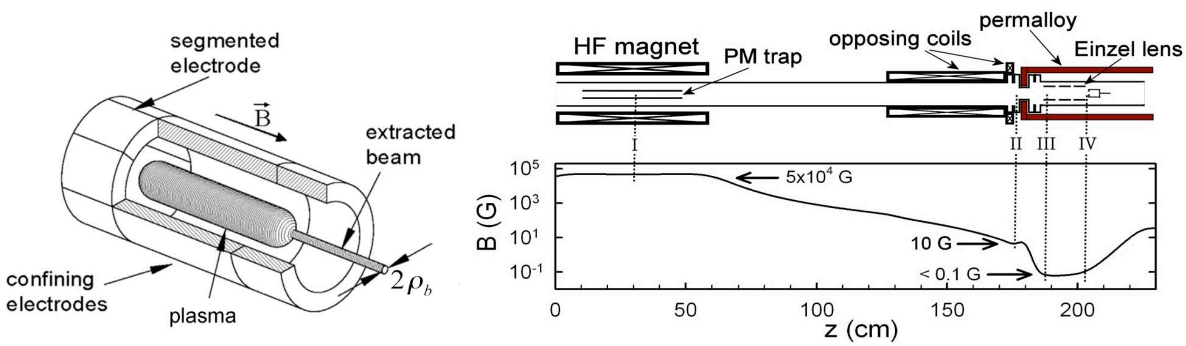

Fig. 1. (left) cartoon of beam formation in a high magnetic field; and (right) schematic of the transition to low field and focusing in a field-free region. See Ref. [3] for details.

We built the apparatus to create electrostatic beams and focus them electrostatically in a magnetic-field-free region [3]. Plasmas were compressed and cooled in a 5 T field. Pulsed beams were extracted by carefully lowering a trap exit-gate potential for a brief period (e.g., Δt ~ 10 μs). We explored the limits of this technique at B = 5 T to understand both the radial profiles and the beam energy distributions, and we developed theoretical expressions for these and other beam parameters [1, 2]. The primary challenge is to mitigate the "kicks" in perpendicular momentum that the particles experience upon nonadiabatic extraction from the field; namely $m\delta v_{\perp} = (eB/2c)r$, where r is the particle radius, m its mass, and B the field at the extraction point (i.e., the mean r is ~ the beam radius ρ).

As illustrated in Fig. 1 (right panel), the beam was adiabatically transported out of the high-field trap to a field of ~ 10 - 80 G [3]. Bucking coils were used to reduce the length of the experiment and to define precisely the 10 G field location. Then a non-adiabatic (fast) extraction was performed to create a beam in a field-free region. The beam extracted at the 1mT point was accelerated through a hole in a Permaloy magnetic shield. Experiments were conducted to extract ~ 20 - 30 eV beams with radii of several millimeters at the extraction point. The beams are then focused and collected with an apertured collector cup (aperture diameter 2.4 mm). A key point is that the beam energy spread (e.g., ~ 0.24 eV in one set of tests) is preserved in the process. Simulations were used to predict the beam properties [3]. As shown in Fig. 2, the results are in reasonable agreement with the measurements.

W. Stoeffl and collaborators at Lawrence Livermore National Laboratory developed a high-permeability extraction grid (named a "spider"), shown in Fig. 3, to minimize these momentum kicks [4]. The "kicks" from the spider can be approximated using $\delta v_{\perp} =$

$(eB/2mc)r$, where for the spider, r ~ d/4 ~ 0.25 mm, where d is the mean width of the gap between spokes. This reduces the mean kicks by a factor of 18 (i.e., beam radius ρ is a factor of 18 larger than d).

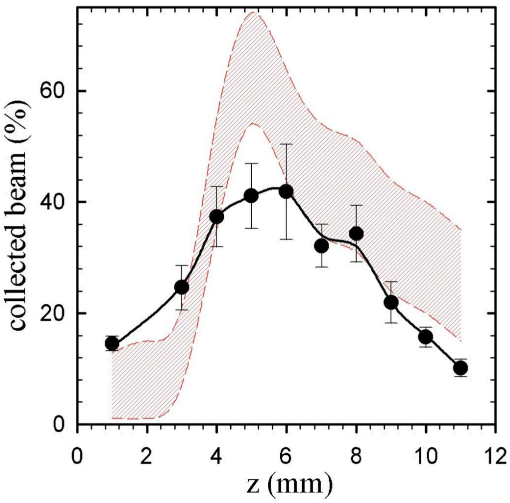

Fig. 2. The percentage of the beam that is transmitted through a collector aperture 2.4 mm in diameter as a function of the z-position of the aperture. Also shown by the shaded region are the predictions for this quantity based on numerical simulations of the particle trajectories. From Ref. [3].

We built such a spider following the LLNL design and installed it in the hole in the Permalloy shield described above. Experiments were conducted with magnetic fields, B_s, at the spider as low as ~ 5 G. The experiments showed good spider transmission and ability to focus the resulting electrostatic beam when the magnetic field at the spider is in the range from 60 to ≥ 15 gauss. As shown in Fig. 4, however, below 15 gauss, the transmission degrades significantly. The exact origin of this effect is not currently understood. It may have to do with the fact that a small field (e.g., ~ 1 G) in the plane of the spider can misalign the beam path sufficiently to cause the observed loss. While added benefit could be gained by operating at lower magnetic field (e.g., ≤ 10 gauss), 15 gauss operation is acceptable. The spider operation, even without further improvement, can produce bright beams that will be of use in a number of applications.

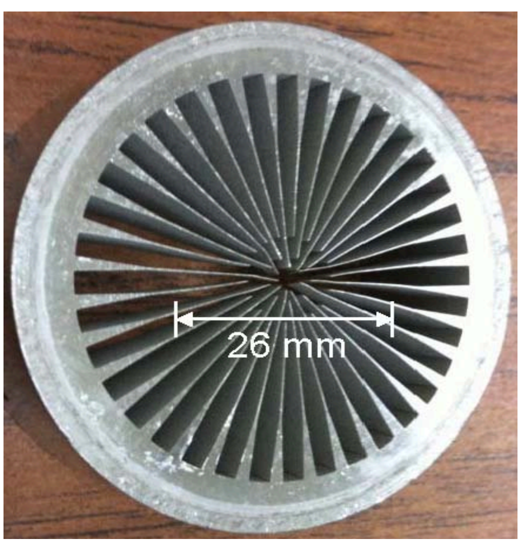

Fig. 3. Specially designed iron-alloy "spider" built to extract trap-based electron and positron beams from the magnetic field in order to create beams that can be guided using electrostatic techniques. The design reduces greatly the unavoidable increase in transverse energy that accompanies extraction from a magnetic field [5].

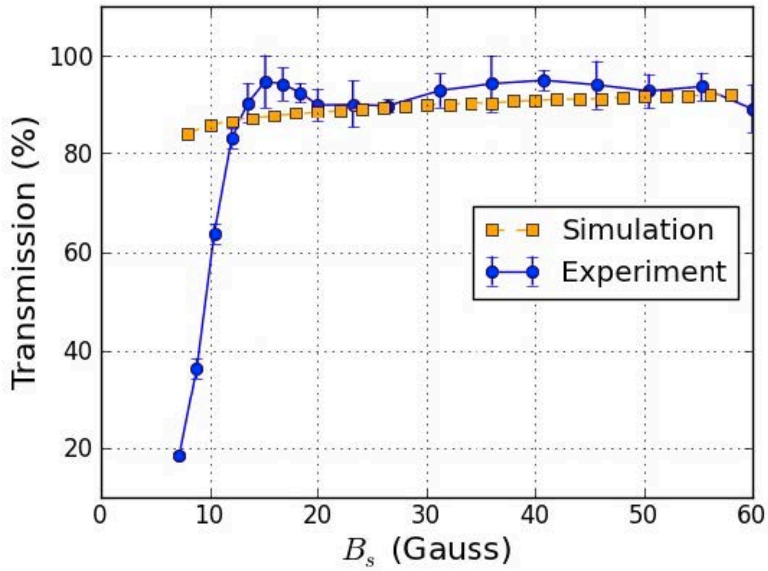

Fig. 4. Transmission of the spider as a function of magnetic field at the spider (i.e., the point of extraction) from experiment (●) and simulation (■). The rapid degradation of the transmission measured below ~ 15 gauss is not understood. From Ref. [5].

B. Colder Magnetically Guided Positron Beams from Buffer-gas Traps

We developed previously a method to create pulsed beams with small energy spreads [6]. Recently, we conducted new experiments and simulations to better understand the limits on energy resolution and minimum pulse duration τ. As illustrated in Fig. 5, the beam formation process is intrinsically dynamical. Adiabatic cooling, as the potential well flattens, competes with increased particle acceleration due to the changing potential on the electrode opposite the exit gate. The key parameters $\Delta E_{\|}$ and τ depend upon the ramp rate and initial positron temperature T_i. A key empirical discovery is that, at fixed ramp rate, $\tau\Delta E_{\|} \propto T_i$ (cf., Fig. 5, right

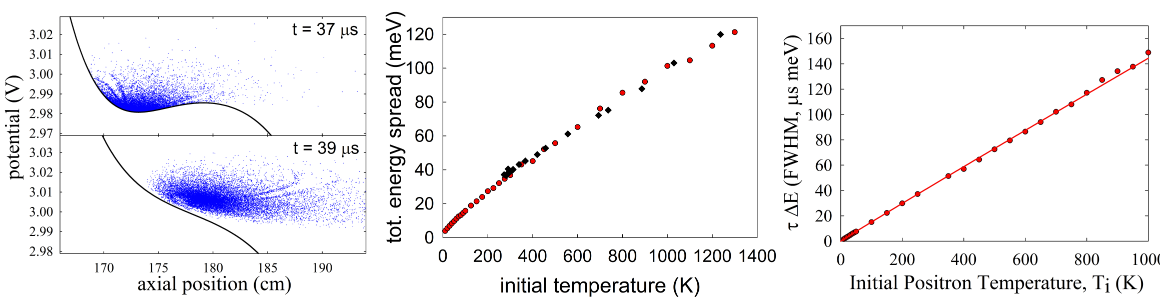

Fig. 5. (left) Simulation of a buffer-gas cooled positron beam; (left) particle positions at two times during a dump; (middle) energy spread ΔE and (right) $\tau\Delta E_{\|}$, both as function of T_i at fixed ramp rate. Red points are from simulation and black (middle panel) from the experiment. From Ref. [5].

panel). The origins of these scalings, possibly related to predictions by Cary *et al*. for the extraction of particles across a seperatrix [7], are the subject of continuing study. Our current goal, based on these results, is to create a beam with *a factor of five smaller total energy spread* using a buffer gas mixture cooled to 50 K.

C. Plasma Tools for Advanced Positron Traps

Many applications require high-density plasmas and/or large space charge potentials. We are continuing work to understand the ability to work in this parameter range and to understand the implications of currently achievable parameters for long-term plasma confinement and large trap storage capacities.

Improved radial compression with rotating electric fields. One objective is to compress plasmas radially using rotating electric fields [the so-called rotating-wall (RW) technique]. This technique, aspects of which we pioneered, is used worldwide to tailor positron plasmas for specific applications. Such good RW performance is very important. In particular, the regime of large $e\phi/T$, where ϕ is the space charge potential and T the plasma temperature, is not well studied for lepton plasmas. We now have new rotating wall circuits with a chip that has increased drive voltage; and more importantly, it permits 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 observed previously [8]. Currently under study is RW performance and long-term confinement in off-the-magnetic-axis storage cells (discussed below).

Electrode control using kilovolt electrical potentials. In order to increase storage capacity, we must work with large plasma potentials. This necessitates working with large voltages on the confining electrodes. We considered building special amplifiers to accomplish this, but found a commercial product that has acceptable specifications (e.g., in terms of maximum operating voltages and sufficiently fast rise and fall times). We now have these amplifiers in house in preparation for experiments using kilovolt confinement potentials.

Test electrode structure and progress toward a multicell trap (MCT) for positrons. One of our major goals is to develop a trap for massive positron storage in an MCT. We have begun to address several of these challenges. We constructed the test electrode structure illustrated in Fig. 6. It consists of three off-axis storage cells and one on-axis storage cell with different electrode inner diameters, as indicated in Fig. 6, each with RW compression and diocotron-mode damping capabilities. The design called for cells to be placed in as close proximity as possible. The smaller the cell diameter, the closer to the axis cells can be placed and hence the greater the ease of filling and emptying storage cells. Also there can be smaller radial separation between plasmas if they are subsequently guided to lower magnetic field. Ultimately this dimension will determine the number of cells that can fit in a given area transverse to $\boldsymbol{B}$.

Shown in Fig. 7 are images of plasmas transferred through the off-axis cells to a phosphor screen using autoresonant diocotron mode excitation [9]. They demonstrate excellent positioning accuracy. As shown in Fig. 8, plasmas have been transferred into all four storage cells. Plasmas have been held in the 12 mm diameter, off-axis cell for hours using RW compression.

Many of the procedures being developed for the MCT involve new plasma techniques and regimes (e.g., confinement and RW compression of high-density plasmas with very large values of eϕ/T). One example of a new effect is our recent discovery of novel dynamics in plasma transfer using autoresonant diocotron mode excitation. We had thought that the transfer time would be limited by the orbit velocity of the master cell plasma as it is swept past the storage cell (i.e., $\Delta\tau \leq 60$ μs). We discovered, however, that the image charges on the master- and storage-cell electrodes both contribute; and that the transfer is almost completely dominated by the smaller diameter electrode. Two such orbits are illustrated in Fig. 9. The result is that transfer can be much slower than thought previously (e.g., tens of milliseconds), leading to much greater freedom to tailor the transfer process. These novel dynamics can be expected in any experiment in which plasmas are off the magnetic axis in electrodes with differing diameters.

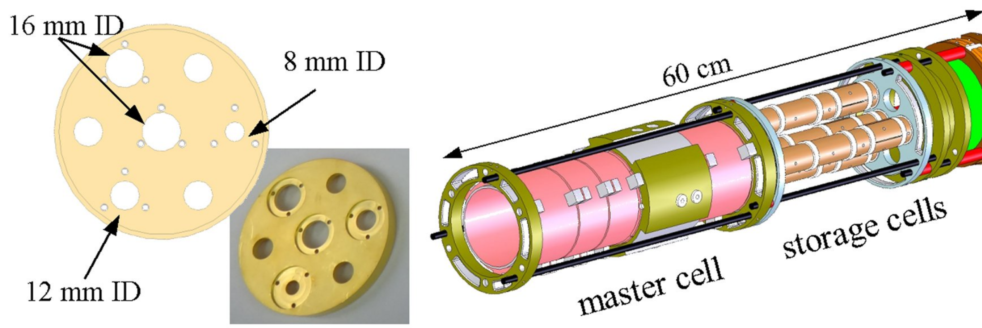

Fig. 6. Test electrode structure (right) with the master cell filled from the left, followed by three off-axis cells of different diameter and one on-axis storage cell. The end plate for these storage cells with I. D.s indicated is shown in two views at the left. From Ref. {Danielson, 2013 #1773}.

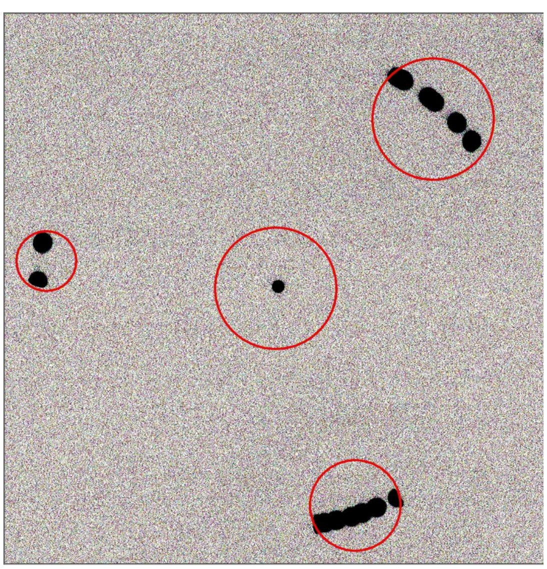

Fig. 7. Black circular images of plasmas transferred through the storage cells (red circles; one on axis and three off axis) to the phosphor screen. Note the good control of the positions at which the off-axis plasmas can be deposited.

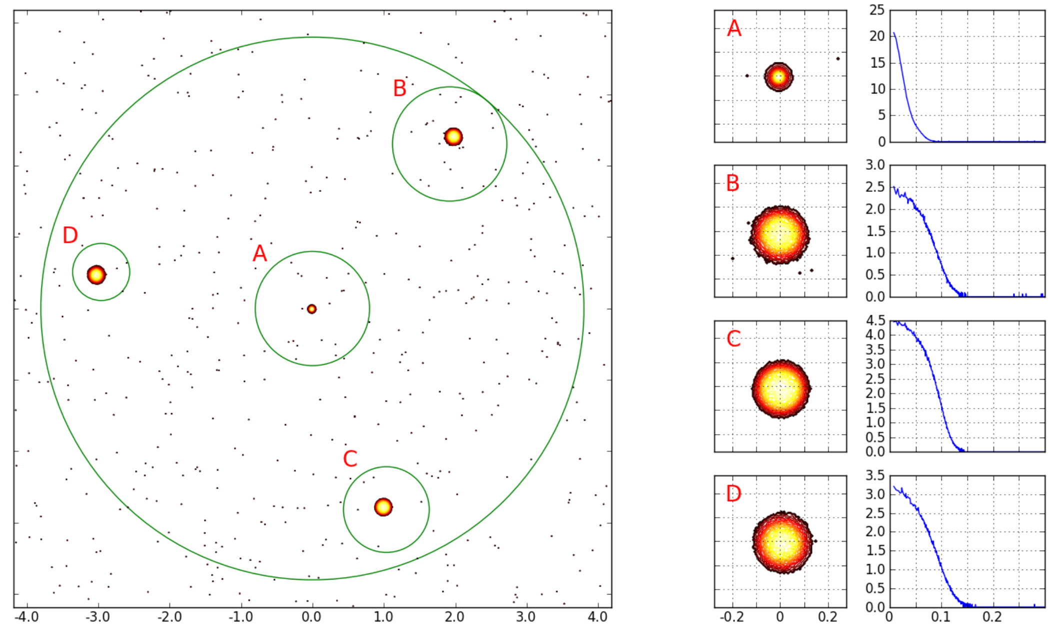

Fig. 8. (left) Images on the phosphor screen of trapped plasmas deposited in the four storage cells (three off axis, B, C, and D, and one on axis, A) and then imaged by dumping on a phosphor screen; (center) expanded images; and (right) radial profiles. This demonstrates successful plasma transfer from the master cell to all storage cells.

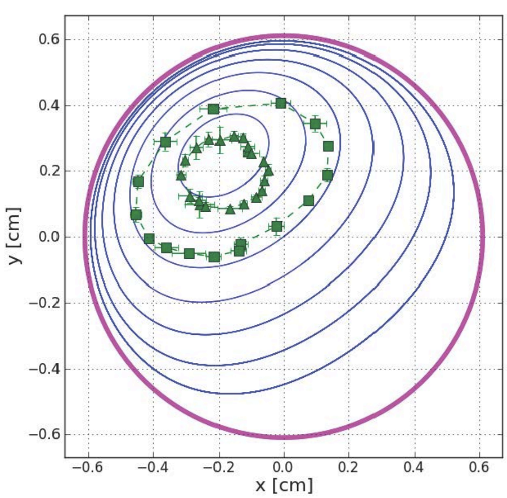

Fig. 9. Orbits of two plasmas (■, ▲; differing only by initial transfer position) ~ 2 mm in diameter that transit both the master cell and the 1.2 cm diameter, off-axis storage cell (i.e., cell C of Fig. 8). The plasma dynamics is dominated by interaction with the wall of the smaller cell. The bounce period is ~ 1μs, and the orbit period ~ 1 ms; (−) cell wall, and (−) predictions of a simple bounce-average-dynamics model. The closest edge of the master cell (7.6 cm in diameter), is off the picture at the lower right, as shown in Fig. 8.

D. An Electron-positron Plasma Experiment

Creating the ability to study "pair plasma" in the laboratory for the first time (i.e., a simultaneously confined electron- 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 Christof Hugenschmidt and collaborators at the Munich Research Reactor positron source, NEPOMUC [10]. The UCSD group helped guide the purchase and deployment in Greifswald of a commercial BG positron trap and sent them a UCSD ^{22}Na positron source to begin positron experiments. We are working with the Germans to outfit an existing 5 T magnet for high-field confinement experiments and an MCT.

A recent paper [11] describes our experimental plans. One significant difference from that description is that it is now planned to first use a magnetic dipole for confinement, and only later a stellarator. The change is due to recent impressive confinement results for levitated dipoles [12, 13], as well as the direct astrophysical relevance of the dipolar magnetic topology. Building upon our positron trapping expertise, UCSD involvement will emphasize the development of the positron traps and the required positron manipulation techniques (e.g., bursts of $> 10^{11}$ positrons in ≤ 10 ms). Two injection scenarios will be investigated. One involves preloading with electrons and then E x B drifting the positrons in using pulsed electrostatic potentials. In a second scenario, positrons will be converted to neutral positronium atoms, laser-excited for longer lifetime to transit into the device, then ionized with another laser. If successful, the adjustable wavelength of the second laser will permit variation of the positron temperature.

Initial objectives will be 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 ≥ 40 Debye lengths across plasma having a 7 cm minor radius. Confinement times approaching 1 second are expected, limited by transport and not annihilation. Monitoring the pair-plasma annihilation as well as that on injected, small pellets will be used to measure density and temperature [11].

III. Training and Development

Personnel on this project were two Ph.D. students, an undergraduate student, and a researcher. A new graduate student joined the effort this January and has come up to speed very quickly. A second graduate student took charge of developing the new cryogenically cooled positron beam. An undergraduate physics major, who was associated with the project, is now in medical school.

This research project provides excellent opportunities for training and mentoring undergraduate and graduate students and young researchers. They were able to use a state of the art low-energy positron physics facility. They learned state-of-the-art techniques for modern electronics, vacuum systems, mechanical systems design and operation, control and data acquisition software, and data analysis.

The P. I. continues to involve both students and researchers in all facets of the research to the maximum extent of which they are capable, including the planning and execution of experiments; writing papers; giving invited talks; writing research proposals; acting as representatives of the group and as scientific and technical advisors to those outside the group; and supervising younger members of the group. The experiments are small enough that the graduate students and researchers can, and do, take the lead in designing and conducting experiments.

The researcher on the project gained experience in new areas and in planning new experiments. For example, he has recently been the principal author on several positron-atomic physics papers, and he is currently assuming the major responsibility for designing a new multicell positron trap, a large and ambitious new hardware effort.

The researcher also aided in the supervision of the graduate students in the group. He has done an excellent job in helping to supervise and mentor the graduate students on the project. He has also done an excellent job in bringing on board new graduate students in the group.

IV. Outreach

The P. I. continues to take opportunities to talk to undergraduates and graduate students about the research. The group maintains a web site (http://positrons.ucsd.edu) describing the research techniques and results and connections to related research.

Members of the group frequently function in an informal consulting capacity to assist a number of groups worldwide who are interested in accumulating and manipulating positrons. For example, the work to optimize rotating-wall compression of positron plasmas is important for applications such as antihydrogen production, the production of positronium molecules (i.e., Ps_2), and the formation of cold positron beams. The latest beam-formation work is likely to have a number of applications in areas such as materials analysis and atomic physics.

V. Broader Impacts of the Work

1. Principal disciplines. This work is providing a quantitative understanding of the kinds of plasmas and beams that can be created in Penning-Malmberg traps, which in turn, are the method of choice to accumulate and store antimatter. The work is important in research designed to create and trap neutral antimatter (i.e., antihydrogen) for tests of fundamental symmetries in physics. It also provides a basis for the development of techniques to achieve 'massive' antimatter storage and to create portable antimatter traps.

2. Other disciplines. The research results from this project are important in developing new tools to use positrons for other applications. In particular, positrons offer unique advantages in studying a variety of physical phenomena, including the fragmentation of molecules of biological interest, and study of bulk solids, solid surfaces, atomic clusters, and nanoparticles. The small-beam-extraction techniques, which were a major focus of the present work, are expected to be particularly useful in many of these applications.

3. Beyond Science and Engineering. This research involves study of antimatter which is a subject regarded with considerable fascination by society at large. As such, the research helps make the public aware of this facet of forefront scientific research. The group encourages this interest and fosters this connection by frequently running lab tours and conducting introductory talks for visitors, including high school students.

VI. Dissemination of Results

Publications. As listed below, the plasma work done under this grant resulted in one paper in Physics of Plasmas [3], two papers in New Journal of Physics [11, 14], a Rev. Sci. Instrum. paper [15], two book chapters [16, 17] (now updated and being republished [18, 19]), and five conference proceedings papers [5, 20-23]. In addition, the Project Scientist associated with this work, James Danielson, was editor of the conference proceedings for the 2009 International Workshop on Nonneutral Plasmas [24]. A review article on antimatter plasmas and beams is currently in preparation for Reviews of Modern Physics, with expected submission in January 2014.

1. T. R. Weber, J. R. Danielson, and C. M. Surko, Electrostatic Beams from Tailored Plasmas in a Penning-Malmberg Trap, Phys. Plasmas 17, 123507, 123501 - 123510 (2010).
2. T. S. Pedersen, J. R. Danielson, C. Hugenschmidt, G. Marx, X. Sarasola, F. Schaue, et al., Plans for the Creation and Studies of Electron–Positron Plasmas in a Stellarator, New J. Phys. 14, 035010 (2012).
3. C. M. Surko, J. R. Danielson, G. F. Gribakin, and R. E. Continetti, Measuring Positron-Atom Binding Energies through Laser-Assisted Photo-Recombination, New J. Phys. 14, 065004 (2012).
4. T. R. Weber, J. R. Danielson, and C. M. Surko, Electrostatic Beams from a 5 T Penning-Malmberg Trap, Rev. Sci. Instrum. 82, 016104 (2011).
5. C. M. Surko, Accumulation, Storage and Manipulation of Large Numbers of Positrons in Traps I. – the Basics, in Physics with Many Positrons, edited by A. P. Mills and A. Dupasquier (IOS Press, Amsterdam, 2010), p. 511-543.
6. C. M. Surko, J. R. Danielson, and T. R. Weber, Accumulation, Storage and Manipulation of Large Numbers of Positrons in Traps II. – Selected Topics, in Physics with Many Positrons, edited by A. P. Mills and A. Dupasquier (IOS press, Amsterdam, 2010), p. 545-574.
7. J. R. Danielson, N. C. Hurst, and C. M. Surko, Progress Towards a Practical Multicell Trap, edited by X. Sarasola and T. S. Pedersen (American Institute of Physics, 2013), Nonneutral Plasmas VIII, p. 101-112.
8. C. M. Surko, Accumulation, Storage and Manipulation of Large Numbers of Positrons in Traps I - the Basics, in Physics with Trapped Charged Particles, edited by M. Kroop, N. Madsen and R. C. Thompson (Imperial College Press, London, U. K., in press).
9. J. R. Danielson, T. R. Weber, and C. M. Surko, in Cold Antimatter Plasmas and Application to Fundamental Physics, edited by Y. Yamazaki (American Institute of Physics Press, Melville, NY, 2008), Vol. 1037, p. 84.
10. J. R. Danielson, T. R. Weber, and C. M. Surko, New Plasma Tools for Antimatter Science, edited by Y. Kanai and Y. Yamazaki (AIP Press, Melville, NY, 2009), Vol. 1114, p. 84-95.
11. T. R. Weber, J. R. Danielson, and C. M. Surko, in Nonneutral Plasma Physics VII (AIP Press, Melvile, NY, 2009), p. 171.
12. M. R. Natisin, N. C. Hurst, J. R. Danielson, and C. M. Surko, (AIP Conf. Proc. 1521, AIP Press, 2013), p. 154 - 164.

13. J. R. Danielson, in Nonneutral Plasma Physics VII, edited by J. R. Danielson and T. S. Pederson (AIP Press, 2009), p. 199.

Invited talks. The P. I. gave the lead-off talk at a special symposium on antimatter physics, highlighting the plasma work, at the annual meeting of the American Association for the Advancement of Science (AAAS), January 2011. Other invited talks on the work were given at the DPP meeting (Weber, '09); the ICOPS conference (Danielson; '09); and the CAARI accelerator conference (Weber, '10). Surko gave one of the four plenary review talks at the 2010 DPP meeting emphasizing the plasma work, and he gave a plenary talk at the SLOPOS conference in August 2013 with similar emphasis. Danielson gave an invited talk at the recent International Nonneutral Plasma Workshop (August, 2012) and is scheduled to give another invited talk at the 2013 DPP meeting this October.

Web site. We maintain an active web site, positrons.ucsd.edu, to inform the public of our research, including access to all our publications.

VII. Summary

During the grant, much progress was made to develop new tools to manipulate antimatter plasmas for scientific and technical use. Further progress was made in delineating the limits for positron accumulation and confinement in the form of single-component plasmas in Penning-Malmberg traps. A more complete understanding was achieved of the limits for formation of cold, bright positron beams extracted from Penning-Malmberg traps in a 5 T magnetic field. Further progress was made extracting beams tailored in the 5 T trap from the magnetic field to form new kinds of high-quality electrostatic beams. Progress was also made in developing plans to create colder trap-based beams using a cryogenically cooled buffer gas. Finally the basic plasma research was conducted to develop a new high-capacity multicell trap (MCT) for research with antimatter. As noted above, some of the techniques developed in the course of this work are also relevant to the manipulation and use of antiprotons.

VIII. References

[1] T. R. Weber, J. R. Danielson, and C. M. Surko, Creation of Finely Focused Particle Beams from Single-Component Plasmas, Phys. Plasmas 13, 123502 (2008).
[2] T. R. Weber, J. R. Danielson, and C. M. Surko, Energy Spectra of Tailored Particle Beams from Trapped Single-Component Plasmas, Phys. Plasmas 16, 057105 (2009).
[3] T. R. Weber, J. R. Danielson, and C. M. Surko, Electrostatic Beams from Tailored Plasmas in a Penning-Malmberg Trap, Phys. Plasmas 17, 123507, 123501 - 123510 (2010).
[4] W. Stoeffl, P. Asoka-Kumar, and R. Howell, The Positron Microprobe at Lawrence Livermore National Laboratory, Appl. Surf. Sci. 149, 1-6 (1999).
[5] M. R. Natisin, N. C. Hurst, J. R. Danielson, and C. M. Surko, (AIP Conf. Proc. 1521, AIP Press, 2013), p. 154 - 164.

[6] S. J. Gilbert, C. Kurz, R. G. Greaves, and C. M. Surko, Creation of a Monoenergetic Pulsed Positron Beam, Appl. Phys. Lett. 70, 1944-1946 (1997).

[7] J. R. Cary, D. F. Escande, and J. L. Tennyson, Adiabatic-Invariant Change Due to Separatrix Crossing, Phys. Rev. A 34, 4256 -4275 (1986).

[8] J. R. Danielson and C. M. Surko, Radial Compression and Torque-Balanced Steady States of Single-Component Plasmas in Penning-Malmberg Traps, Phys. Plasmas 13, 055706-055710 (2006).

[9] J. R. Danielson, T. R. Weber, and C. M. Surko, Plasma Manipulation Techniques for Positron Storage, Phys. Plasmas 13, 123502 (2006).

[10] C. Hugenschmidt, C. Piochacz, M. Reiner, and K. Schreckenbach, The Nepomuc Upgrade and Advanced Positron Beam Experiments, New J. Phys. 14, 055027 (2012).

[11] T. S. Pedersen, J. R. Danielson, C. Hugenschmidt, G. Marx, X. Sarasola, F. Schaue, *et al.*, Plans for the Creation and Studies of Electron–Positron Plasmas in a Stellarator, New J. Phys. 14, 035010 (2012).

[12] H. Saitoh, Z. Yoshida, J. Morikawa, Y. Yano, N. Kasaoka, W. Sakamoto, *et al.*, Stable Confinement of Electron Plasma and Intital Results on Positron Injection in Rt-1, in Non-Neutral Plasma Physics Viii (AIP Conference Proceedings, Melville, NY, 2013), Vol. 1521, p. 63-72.

[13] Z. Yoshida, H. Saitoh, Y. Yano, H. Mikami, N. Kasaoka, W. Sakamoto, *et al.*, Self-Organized Confinement by Magnetic Dipole: Recent Results from Rt-1 and Theoretical Modeling, Plasma Phys. Control. Fusion 55 (2013).

[14] C. M. Surko, J. R. Danielson, G. F. Gribakin, and R. E. Continetti, Measuring Positron-Atom Binding Energies through Laser-Assisted Photo- Recombination, New J. Phys. 14, 065004 (2012).

[15] T. R. Weber, J. R. Danielson, and C. M. Surko, Electrostatic Beams from a 5 T Penning-Malmberg Trap, Rev. Sci. Instrum. 82, 016104 (2011).

[16] C. M. Surko, Accumulation, Storage and Manipulation of Large Numbers of Positrons in Traps I. – the Basics, in Physics with Many Positrons, edited by A. P. Mills and A. Dupasquier (IOS Press, Amsterdam, 2010), p. 511-543.

[17] C. M. Surko, J. R. Danielson, and T. R. Weber, Accumulation, Storage and Manipulation of Large Numbers of Positrons in Traps Ii. – Selected Topics, in Physics with Many Positrons, edited by A. P. Mills and A. Dupasquier (IOS press, Amsterdam, 2010), p. 545-574.

[18] C. M. Surko, Accumulation, Storage and Manipulation of Large Numbers of Positrons in Traps I - the Basics, in Physics with Trapped Charged Particles, edited by M. Kroop, N. Madsen and R. C. Thompson (Imperial College Press, London, U. K., 2013), p. in press.

[19] C. M. Surko, J. R. Danielson, and T. R. Weber, Accumulation, Storage and Manipulation of Large Numbers of Positrons in Traps Ii: Selected Topics, in Physics with Trapped Charged Particles, edited by M. Kroop, N. Madsen and R. C. Thompson (Imperial College Press, London, U. K., 2013), p. in press.

[20] J. R. Danielson, T. R. Weber, and C. M. Surko, in Cold Antimatter Plasmas and Application to Fundamental Physics, edited by Y. Yamazaki (American Institute of Physics Press, Melville, NY, 2008), Vol. 1037, p. 84-95.

[21] J. R. Danielson, T. R. Weber, and C. M. Surko, New Plasma Tools for Antimatter Science, edited by Y. Kanai and Y. Yamazaki (AIP Press, Melville, NY, 2009), Vol. 1114, p. 84-95.

[22] T. R. Weber, J. R. Danielson, and C. M. Surko, in Nonneutral Plasma Physics VII (AIP Press, Melvile, NY, 2009), p. 171.

[23] J. R. Danielson, N. C. Hurst, and C. M. Surko, edited by X. Sarasola, L. Schweikhard and T. S. Pedersen (American Institute of Physics, 2013), Vol. Nonneutral Plasmas VIII, p. 101-112.

[24] J. R. Danielson, in Nonneutral Plasma Physics VII, edited by J. R. Danielson and T. S. Pederson (AIP Press, 2009), p. 199.