REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01-04-2004

2. REPORT TYPE
Final Technical Report

3. DATES COVERED *(From - To)*
1/1/02 - 1/31/04

4. TITLE AND SUBTITLE
Positron Plasmas in the Laboratory

5a. CONTRACT NUMBER

5b. GRANT NUMBER
ONR grant N00014-02-1-0123

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Clifford M. Surko

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Regents of the University of California; University of California, San Diego
Office of Contracts & Grants Administration 0934
9500 Gilman Drive, La Jolla CA 92093-0934
Physics Department

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Physical Sciences S & T Division, Code 331
800 N. Quincy Street
Arlington, VA 22217

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Final

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited

20040426 078

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The focus of this project was the development of efficient methods to accumulate low-energy positrons in the laboratory and to create positron plasmas and beams in new regions of parameter space. A new high-magnetic-field, cryogenic positron storage trap was put into operation. Rapid cooling is achieved by cyclotron emission in a 5 tesla magnetic field. Radial plasma compression is achieved using a rotating, radio-frequency electric field. New plasma operating regimes were explored that offer the potential to produce higher density positron plasmas, infinite confinement times, and a new generation of cold, bright positron beams. Techniques were developed to efficiently compress plasmas without the need to carefully tune the frequency of the rotating electric field. A method of beam extraction was demonstrated that can produce a finely focused beam with a diameter of four Debye lengths. At the end of the project, research was in progress to explore and understand the limits of plasma density compression with the goals of massive positron storage and the creation of brighter positron beams.

15. SUBJECT TERMS
antimatter, positrons, plasmas, beams, antimatter storage

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	8	Clifford M. Surko
					19b. TELEPHONE NUMBER *(Include area code)* 858-534-6880

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

4/15/04

Final Technical Report
Positron Plasmas in the Laboratory
Office of Naval Research Award N00014-02-1-0123
(January 1, 2002 – January 30, 2004)

Clifford M. Surko
Department of Physics
University of California, San Diego
La Jolla, CA 92093-0319

Abstract: The focus of this project was the development of efficient methods to accumulate low-energy positrons in the laboratory and to create positron plasmas and beams in new regions of parameter space. A new high-magnetic-field, cryogenic positron storage trap was put into operation. Rapid cooling is achieved by cyclotron emission in a 5 tesla magnetic field. Radial plasma compression is achieved using a rotating, radio-frequency electric field. New plasma operating regimes were explored that offer the potential to produce higher density positron plasmas, infinite confinement times, and a new generation of cold, bright positron beams. Techniques were developed to efficiently compress plasmas without the need to carefully tune the frequency of the rotating electric field. A method of beam extraction was demonstrated that can produce a finely focused beam with a diameter of four Debye lengths. At the end of the project, research was in progress to explore and understand the limits of plasma density compression with the goals of massive positron storage and the creation of brighter positron beams.

I. Introduction and overview

The goal of this project is to create antimatter plasmas consisting of positrons (i.e., the antiparticle of the electron) in new regimes of density, temperature and particle number, and to use these plasmas for a range of scientific and technological applications. Scientific questions of current interest include understanding the interaction of low-energy positrons with atoms and molecules, laboratory modeling of astrophysical processes, and the study of electron-positron plasmas. Applications of this work include antihydrogen formation, the analysis of materials and material surfaces, plasma diagnostics and mass spectrometry (via positron ionization). The high-density cryogenic plasmas created in this project can be used to create colder, brighter positron beams than are available currently. These beams will be used, in turn, for a new generation of high-resolution positron-matter studies. Of interest, for example, are studies of positron-atom and positron-molecule interactions and positron interactions with atomic clusters, dust grains and solid surfaces, particularly at low values of positron energy, $\varepsilon \leq 0.1$ eV.

II. Technical approach

The focus of this project was to create cryogenic (T ~ 10 K), high-density, positron plasmas (particle numbers, $N \geq 10^{10}$) in a 5 tesla magnetic field. The apparatus is shown schematically in Fig. 1. The basic confinement device is a Penning-Malmberg trap, which uses a linear magnetic field and electrical potentials on cylindrical electrodes (aligned with the magnetic field direction) to confine a single-component positron plasma. The research includes further development of techniques to compress radially both room-temperature and cryogenic positron plasmas using a rotating electric field. This technique can produce high plasma densities and long confinement times that are crucial for many applications.

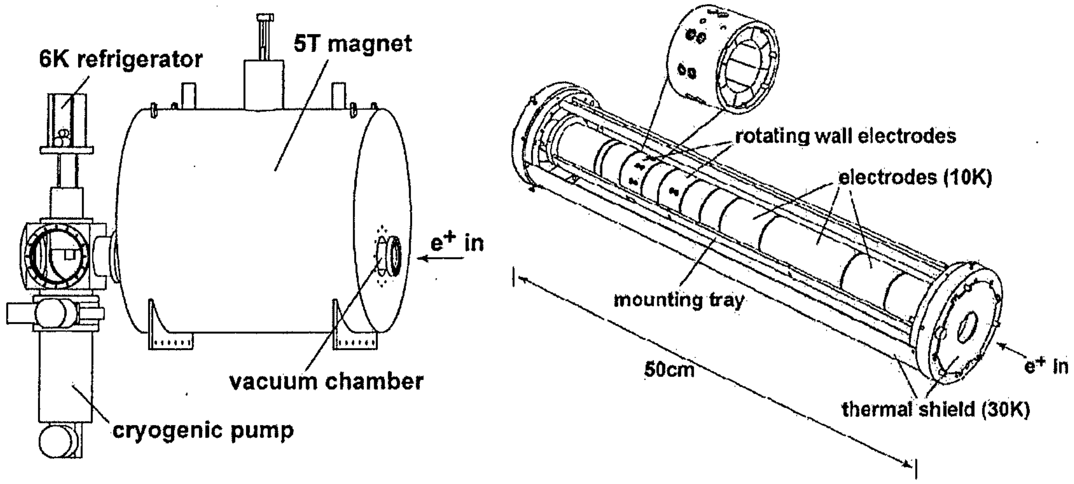

Fig. 1. Overview of the cryogenic high-field trap (left) and electrode structure (right) with the top of the 30K thermal radiation shield removed.

Another facet of the research was the continued development of methods of creating cold, bright positron beams using trapping techniques. The 10 K plasmas will allow us to create a new generation of ultra-cold positron beams with energy spreads as small as 1 meV. This would improve the state-of-the-art (a previous result of this project) by a factor of 20 in achievable energy resolution. This new positron accumulator will also be useful to further develop a multicell approach to increasing the capabilities for positron accumulation by additional orders of magnitude. One application of this device would be a portable antimatter trap.

III. Scientific results

The cryogenic high-field trap. During the project we were able to bring the new device into operation and to begin to explore interesting new ranges of plasma parameters using test electron plasmas. There are several aspects of the work. One is benchmarking the confinement properties with high density plasmas. This involves measuring the plasma density, density profile, and temperature. The results of our experiments show that the confinement in the new trap is as good as, or better than, that achieved previously in any

Penning-Malmberg trap. Furthermore, we were able to access a new, high-density confinement regime that will lead to improved performance.

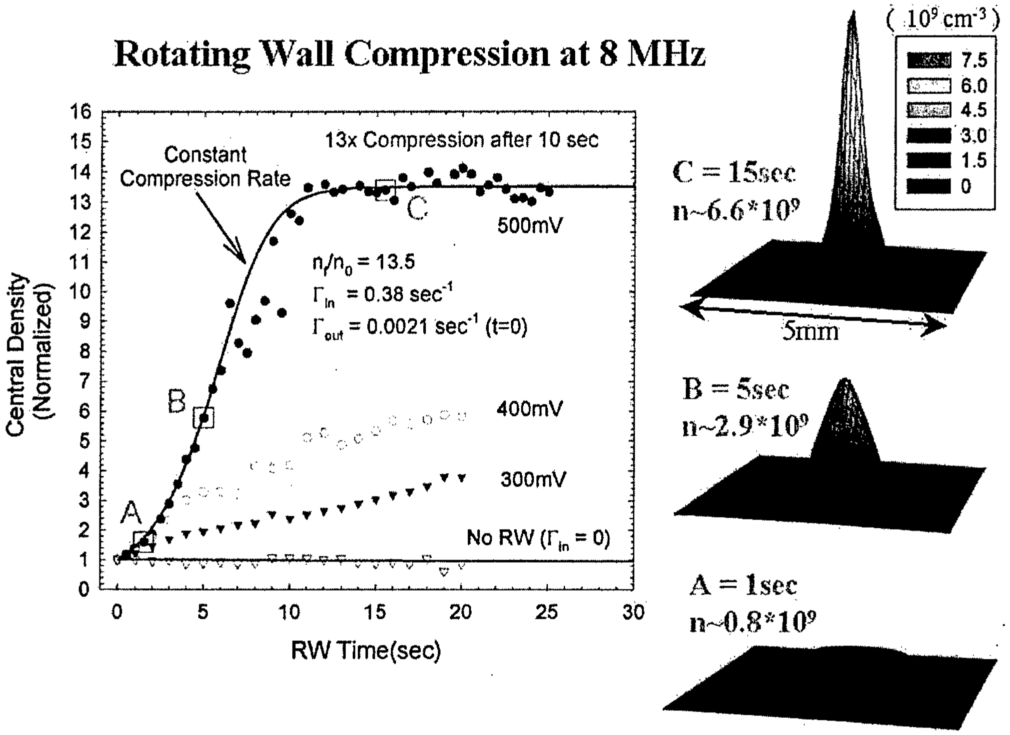

Figure 2. Radial compression of a test electron plasma using a "rotating wall" (RW) electric field. The plasma is transported across the magnetic field, inward and up the density gradient. Left: central density as a function of time for different RW amplitudes; Right: two-dimensional density profiles at three times. The data for 500 mV RW field amplitude (left panel) fits the predictions (–) of a simple model.

The development of operating scenarios was begun with experiments to compress test electron plasmas using rotating electric fields. Good compression was achieved without the need for careful tuning of rotating wall frequency. Shown in Fig. 2 is an example for a test electron plasma. This is an important practical result. The data show a

Table I. Typical parameters for plasma rotating wall compression in the new high-field trap operated with room-temperature electrodes (i.e., T = 300 K ≡ 25 meV) and B = 5 tesla, for an initial fill of 2 x 10^8 particles and a plasma length of 8.4 cm.

	Uncompressed	Compressed
Radius (mm)	1.0	0.2
Density (10^9 cm^{-3})	1.5	38
Temperature (meV)	25	100
Debye length (mm)	0.03	0.01
Space charge potential (V)	19	40

compression ratio of a factor of 4 in radius and 15 in central plasma density. Typical operating parameters of the rotating wall compression are shown in Table I. To date we have achieved a factor of up to 50 in density increase, corresponding to a factor of 7 decrease in plasma radius. The physical mechanism limiting plasma compression and the limits of this technique are currently being explored.

Another aspect of the work is testing a technique to brightness-enhance beams created from the trapped plasmas by taking particles off of the magnetic axis of the plasma. These experiments were very successful: beams were extracted with diameters ~ 4 λ_D, where λ_D is the Debye screening length. Theoretical calculations, done in connection with these experiments, predict a beam diameter in agreement with the measurements. This technique will be of great value in the development of cold beam sources from the trapped plasmas.

Design of a multicell trap. We also developed a novel design of multicell Penning-Malmberg trap (shown schematically in Fig. 3) that has the potential to increase positron plasma density and total number of positrons stored by orders of magnitude [1]. The device overcomes two limitations on positron storage as a single-component plasma. The required confining potential, V, must exceed the space charge potential which, for a cylindrical plasma containing N positrons in a length L, is proportional to N/L. This then sets an upper limit on N/L in order to avoid electrical breakdown.

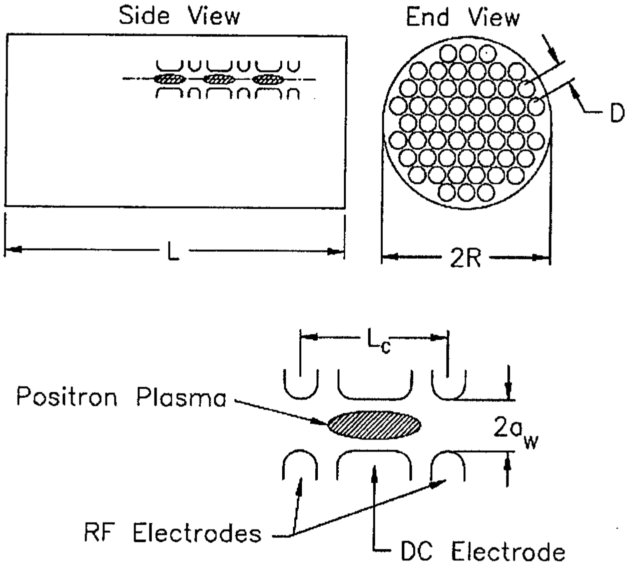

Figure 3. Schematic diagram of the multicell trap, showing arrangement of the cells parallel to *B* and m = 19 cells perpendicular to *B*. The electrode structure will be immersed in the 5 T magnetic field of the apparatus described above and cooled to 10 K. Typical dimensions (in cm): L = 36, L_c = 6, and D = 1.3.

We propose to break up the plasma into a number m of parallel, rod-shaped plasmas separated by close-fitting copper electrodes. For fixed V, this will increase the maximum number of particles confined by a factor of m. The second limitation is radial outward transport, which is known to occur at a rate Γ given by $\Gamma = An^2/L^2$, where n is the plasma density and A is a constant. To minimize this transport, we propose to break up the plasma in the direction along the field, so that each of the m rods is separated by electrodes at potential V into n separate plasmas. This has the consequence of reducing Γ by a factor of m^2. This level of transport will be counteracted (on average) by radially inward-directed compression using a rotating electric field.

Assuming that resources can be found for continuation of this research, the cryogenic high-field trap will be used to develop this novel, multicell positron storage device.

Applications of positron beams. We continue a successful collaboration with R. G. Greaves (FPSI) on problems of mutual interest, improving positron trapping and positron beam technology. Specific problems include creating brighter positron beams using the rotating wall technique, creating electrostatic positron beams from trapped plasmas, creating giant pulses of positrons, and understanding molecular fragmentation occurring as a result of positron annihilation and positronium formation [2-4] .

IV. Training of scientific personnel

The grant provided partial support for the training of three graduate student researchers and three postdoctoral researchers.

V. Summary - ONR funding of positron plasma research

This grant is the latest in a series of ONR grants to the P.I. dating from 1988 to develop techniques to accumulate, cool and store positron plasmas and to use them in scientific and technological applications. The positron traps and beams developed in this work led to a number of firsts, including:

- *Record numbers of positrons accumulated* [5, 6]
- *Radial compression of positron plasmas* [7]
- *State of the art, tunable positron beam with 20 meV energy resolution* [8]
- *First experimental studies of the electron-positron plasma* [9]
- *Buffer-gas trap design for commercial positron beam sources and production of the first low-energy antihydrogen atoms* [10]

A buffer-gas trap of the UCSD design was used in the first experiment to create low-energy antihydrogen in the laboratory [10] . Positron traps of the type developed in this research are now sited at leading laboratories for low-energy antimatter research around the world, namely in the U.K. (M. Charlton, U. Swansea), the U.S. (A. P. Mills, U.C. Riverside), at CERN (for antihydrogen experiment), and in Russia (I. Meshkov, Dubna). Prototype positron beam systems for materials characterization are now being produced commercially by First Point Scientific, Inc., under the direction of former UCSD researcher, Dr. Roderick Greaves.

The P.I. thanks ONR for the support that enabled this series of discoveries and accomplishments.

VI. References

[1] C. M. Surko and R. G. Greaves, A multi-cell trap to confine large numbers of positrons, *Rad. Chem. and Phys.* **68**, 419 (2003).

[2] R. G. Greaves, S. J. Gilbert, and C. M. Surko, Trap-based positron beams, *Appl. Surf. Sci.* **194**, 56 (2002).

[3] R. G. Greaves and C. M. Surko, Positron trapping and the creation of high-quality trap-based positron beams, *Nucl. Inst. Meth. in Phys. Res. B* **192**, 90 (2002).

[4] R. G. Greaves and C. M. Surko, Practical limits on positron accumulation and the creation of electron-positron plasmas, *Non-Neutral Plasma Physics IV,* edited by F. Anderegg, L. Schweikhard and C. Driscoll (American Institute of Physics, 2002), 10 (2002).

[5] T. J. Murphy and C. M. Surko, Positron trapping in an electrostatic well by inelastic collisions with nitrogen molecules, *Phys. Rev. A* **46**, 5696 (1992).

[6] C. M. Surko, S. J. Gilbert, and R. G. Greaves, Progress in creating low-energy positron plasmas and beams, *Non-Neutral Plasma Phys. III,* edited by J. J. Bollinger, R. L. Spencer, and R. C. Davidson (American Institute of Physics, New York, 1999), 3 (1999).

[7] R. G. Greaves and C. M. Surko, Inward transport and compression of a positron plasma by a rotating electric field, *Phys. Rev. Lett.* **85**, 1883 (2000).

[8] S. J. Gilbert, C. Kurz, R. G. Greaves, *et al.*, Creation of a monoenergetic pulsed positron beam, *Appl. Phys. Lett.* **70**, 1944 (1997).

[9] R. G. Greaves and C. M. Surko, An electron-positron beam-plasma experiment, *Phys. Rev. Lett.* **75**, 3846 (1995).

[10] M. Amoretti, C. Amsler, G. Bonomi, *et al.*, Production and detection of cold antihydrogen atoms, *Nature* **419**, 456 (2002).

VII. Publications during the current grant period

The project resulted in 10 papers in refereed journals and 5 conference proceedings during the grant period, as listed below. The reader is referred to these publications for a more detailed discussion of many of the results summarized here.

A. Refereed journal articles.

1. Vibrational-resonance Enhancement of Positron Annihilation in Molecules S. J. Gilbert, L. D. Barnes, J. P. Sullivan and C. M. Surko, *Phys. Rev. Lett.*, **88**, 043201-1-4 (2002).

2. Trap-Based Positron Beams, R. G. Greaves, S. J. Gilbert, and C. M. Surko, *Appl. Surface Sci.* **194**, 56 - 60 (2002).

3. Low Energy Positron Scattering and Annihilation Studies Using a High Resolution Trap-Based Beam, J. P. Sullivan, S.-J. Gilbert, J. P. Marler, L. D. Barnes, S. J.

Buckman, and C. M. Surko, *Nuclear Instrum. and Meth. For Physics Res.* **B 192**, 3 – 16 (2002).

4. Positron Trapping and the Creation of High-Quality Trap-Based Positron Beams, R. G. Greaves and C. M. Surko, *Nuclear Instrum. and Meth. for Physics Res.* **B 192**, 90 - 96 (2002).

5. Positron Scattering from Atoms and Molecules Using a Magnetized Beam, J. P. Sullivan, S. J. Gilbert, J. P. Marler, R. G. Greaves, S. J. Buckman, and C. M. Surko, *Phys. Rev. A* **66**, 042708, 1 - 12 (2002)

6. A Multicell Trap to Confine Large Numbers of Positrons, C. M. Surko and R. G. Greaves, *Radiation Physics and Chemistry* **68**, 419 - 425 (2003).

7. Energy-resolved Positron Annihilation for Molecules, L. D. Barnes, S. J. Gilbert, and C. M. Surko, *Phys. Rev. A* **67**, 032706, 1 - 11 (2003).

8. Emerging Physics and Technology of Antimatter Plasmas and Trap-Based Beams, C. M. Surko and R. G. Greaves, *Phys. Plasmas*, 15 pages, to be published, May 2004.

9. Positron Scattering and Annihilation Studies Using a Trap-Based Beam, L. D. Barnes, J. P. Marler, J. P. Sullivan and C. M. Surko, Proc., *Physica Scripta*, to be published, 2004.

10. Experimental Studies of the Interaction of Low-energy Positrons with Atoms and Molecules, J. P. Marler, L. D. Barnes, S. J. Gilbert, J. P. Sullivan, J. A. Young, and C. M. Surko, *Nuclear Instrum. and Meth. B*, 9 pages, to be published, 2004.

B. Conference proceedings.

1. Vibrational Excitation Cross Sections for Low Energy Positron Molecule Scattering, J. P. Sullivan, S. J. Gilbert, J. P. Marler, S. J. Buckman, and C. M. Surko, *Proceedings of the 22nd International Conference on Photonic, Atomic, and Electronic Collisions*, J. Burgdorfer, *et al.*, Eds. (Rinton Press, Princeton, N. J., 2002), pp. 365 – 368.

2. Low-Energy Positron-Matter Interactions Using Trap-Based Beams, S. J. Gilbert, J. P. Sullivan, J. P. Marler, L. D. Barnes, P. Schmidt, S. J. Buckman and C. M. Surko, *Nonneutral Plasma Physics IV.*, F. Anderegg, L. Schweikhard, C. F. Driscoll, Eds. (AIP Conf. Proc. #606, AIP Press, Melville NY, 2002) pp. 24-34.

3. Practical Limits on Positron Accumulation and the Creation of Electron-Positron Plasmas, R. G. Greaves and C. M. Surko, *Nonneutral Plasma Physics IV.*, F. Anderegg, L. Schweikhard, C. F. Driscoll, Eds. (AIP Conf. Proc. #606, AIP Press, Melville NY, 2002) pp. 10-23.

4. A Cryogenic High-field Trap for Large Positron Plasmas and Cold Beams, J. R. Danielson, J. P. Sullivan, P. Schmidt, and C. M. Surko, *Nonneutral Plasma Physics V.*, M. Schauer, *et al.*, Eds. (AIP Conf. Proc. #692, AIP Press, Melville NY, 2003) pp. 149 - 61.

5. Scattering and Annihilation Experiments Using a Trap-Based Beam, J. P. Sullivan, L. D. Barnes, J. P. Marler, S. J. Gilbert, and C. M. Surko, *Materials Science Forum*, to be published, 2004.