Transfer, stacking and compression of positron plasmas under UHV conditions

D. P. van der Werf[1],[*], M. Amoretti[†], G. Bonomi[**], A. Bouchta[**], P. Bowe[*], C. Carraro[†‡], C. L. Cesar[§], M. Charlton[*], M. Doser[**], V. Filippini[¶], A. Fontana[¶‖], M. C. Fujiwara[††‡‡], R. Funakoshi[††], P. Genova[¶‖], J. S. Hangst[§§], R. S. Hayano[††], L. V. Jørgensen[*], V. Lagomarsino[†‡], R. Landua[**], E. Lodi Rizzini[¶], M. Macrì[†], N. Madsen[§§], G. Manuzio[†‡], P. Montagna[¶‖], H. Pruys[¶¶], C. Regenfus[¶¶], A. Rotondi[¶‖], G. Testera[†] and A. Variola[†]

[*]*Department of Physics, University of Wales Swansea, Swansea SA2 8PP, United Kingdom*
[†]*Istituto Nazionale di Fisica Nucleare, Sezione di Genova, I-16146 Genova, Italy*
[**]*EP Division, CERN, Geneva, Switzerland*
[‡]*Dipartimento di Fisica di Genova, I-16146 Genova,Italy*
[§]*Instituto de Fisica, Universidade do Brasil, Rio de Janeiro 21945-970, Brazil and CEFET-CE, Fortaleza 60040-531, Brazil*
[¶]*Istituto Nazionale di Fisica Nucleare Sezione di Pavia, I-27100 Pavia, Italy*
[‖]*Dipartimento di Fisica Nucleare e Teorica, Universita' di Pavia, I-27100 Pavia, Italy*
[††]*Department of Physics, University of Tokyo, Tokyo 153-8902, Japan*
[‡‡]*Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan*
[§§]*Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark*
[¶¶]*Physik-Institut, Zürich University, CH-8057 Zürich, Switzerland*

Abstract. A ballistic method is presented for transferring positron plasmas emanating from a region with a low magnetic field and relatively high pressure into a 15 K Penning-Malmberg trap immersed in a 3 T magnetic field with a base pressure of the order of 10^{-13} mbar. Subsequent stacking resulted in a plasma containing 4.2×10^8 positrons. Using a rotating wall electric field a plasma containing 90 million positrons was compressed to a density of 3.6×10^9 cm^{-3}.

INTRODUCTION

Recently, large amounts of cold antihydrogen atoms have been produced by the ATHENA collaboration [1] at the CERN Antiproton Decelerator. Subsequently, a similar result was reported by the ATRAP collaboration [2]. In both experiments antihydrogen atoms are formed by mixing antiprotons and positrons in a nested Penning trap [3]. The expected reaction mechanisms are radiative and 3-body combination [4], the reaction rates being proportional to the positron density, n, and n^2, respectively. In order to rapidly acquire large numbers of positrons to mix with antiprotons we have constructed a positron accumulator utilising nitrogen as a buffer gas [5, 6]. This type of accumulator currently has the highest reported trapping efficiency. The ATHENA

---

[1] Corresponding author (D.P.van.der.Werf@Swansea.ac.uk)

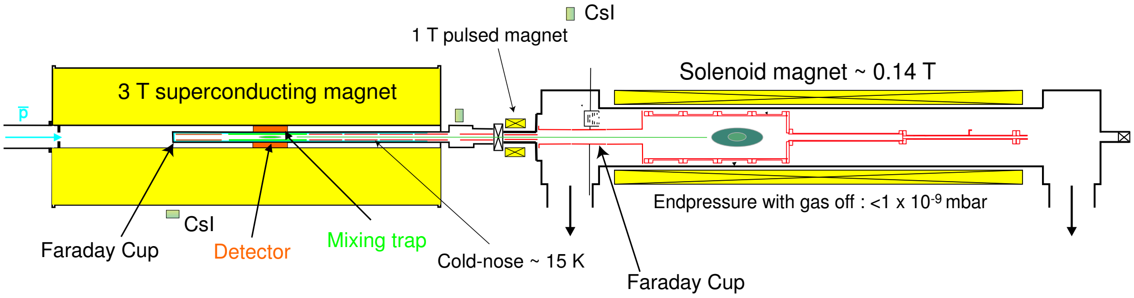

FIGURE 1. Schematic of the ATHENA experimental apparatus

antihydrogen apparatus [7] is designed using a modular approach. It consists of four main parts: a positron accumulator, an antiproton catching trap, a mixing trap and an antihydrogen annihilation detector as shown in Fig. 1. The accumulator, with a relatively high gas pressure, and the ultra high vacuum (lower than 10^{-13} mbar) mixing trap are connected by a transfer section consisting of a vacuum separation valve, a pumping restriction, a number of transfer electrodes and a pulsed transfer magnet with a field of 1 T. The transfer magnet is necessary because the magnetic field in the narrow-bore pumping restriction due to the accumulator solenoid and the superconducting magnet around the mixing region is not high enough to allow all the positrons to pass through. The number of particles caught in the mixing region can be detected destructively by dumping them onto a Faraday cup. Measures of both the total charge and the positron annihilation signal are recorded. As described below, positrons can be repeatedly stacked in the mixing region thus increasing the total number of positrons available for antihydrogen experiments. In order to increase the density of the plasma inside the 3 T solenoid it can be compressed by employing a rotating wall electric field [8]. A non-destructive diagnostic technique has recently been developed/improved using electrostatic mode analysis [9, 10] and we are now able to measure the compression in real time while using the rotating wall. In this paper we will describe the method used for the magnet-to-magnet transfer of positron plasmas and report the results of transfer, stacking and compression experiments.

TRANSFER

Experimental

Positrons are accumulated in a relatively low (0.14 T) magnetic field and at nitrogen buffer gas pressures of 10^{-6} mbar while applying a rotating wall electric field in order to compress the plasma [6]. After 200 seconds, obtaining a plasma consisting of about 150 million positrons with a diameter of 4-5 mm, the buffer gas is pumped out until a pressure of the order of 10^{-9} mbar has been reached. Subsequently, the vacuum separation valve is opened and the transfer magnet is energized for 1 second. The positrons in the accumulator are released by lowering the gate electrode of the accumulator (see Fig.

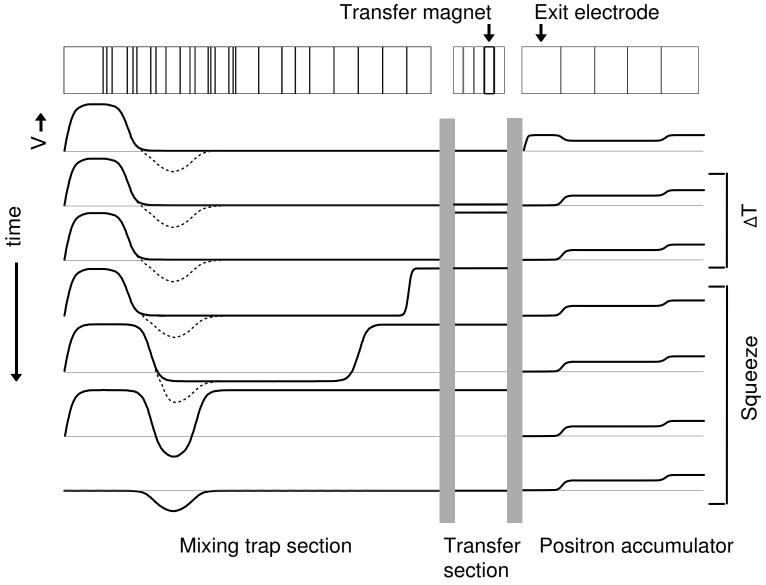

FIGURE 2. The potentials of the electrodes during positron transfers. Note that the time step between the subsequent potential lines is not uniform. The dashed lines represent the potentials when stacking subsequent plasmas.

2) from 140 V to 0 V with a fall time of 35 ns and retrapped in the mixing section by closing the electrodes in the transfer section a time ΔT later. The positrons are initially trapped in the entire length of the mixing trap and subsequently sqeeuzed into the central part. There they cool to the ambient temperature of 15 K by emission of synchrotron radiation. After cooling the high potential walls surrounding the positrons are lowered until the well becomes harmonic.

Simulations

We simulated the transfer process using SIMION [11] assuming single particle trajectories confined to the axis of the instrument. The magnetic field was not taken into account. We presume the plasma to be intact just after the gate electrode has opened since the fall time of the voltage on this electrode is of the order of 1 ns over the plasma space charge of around 5 V. In order to mimick the space charge, we assign each particle a kinetic energy, randomly distributed between 0 and 5 eV, on top of the 25 eV orginating from the bottom of the well in the accumulator. We simulated trajectories for 36 values of ΔT starting at 0 with a spacing of 0.2 μs. For each point we used 2001 particle trajectories.

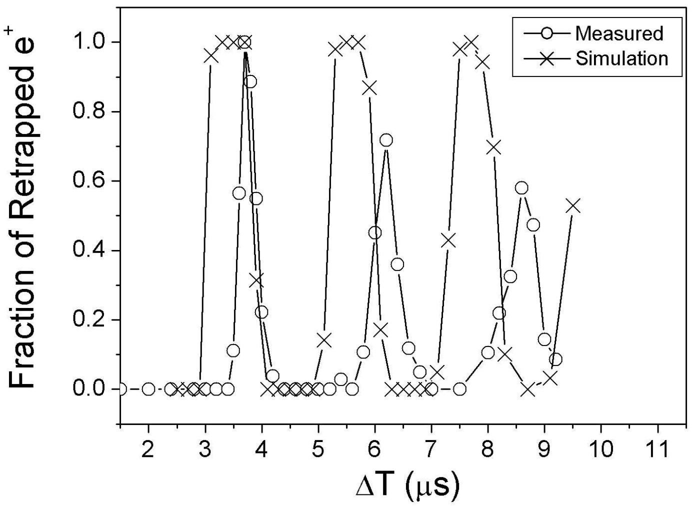

FIGURE 3. Fraction of retrapped positrons as a function of the time difference, ΔT, between opening the gate electrode and closing the transfer section. The curves are normalized on the first peak.

Results

In Fig. 3 we plot the fraction of positrons transferred before squeezing as a function of ΔT for the experiment and the simulations. The experimental data were obtained by dumping the positrons on the Farady cup in the 3 T magnet 50 ms after retrapping. In both cases it is clear that the plasma can move back and forwards a number of times showing that ballistic transport is possible. The width of the recaptured peak increases due to the initial energy spread. The difference in bouncing time between the experiment and the simulation is attributed to the change of parallel (with respect to the magnetic axis) energy into perpendicular energy (not simulated) when the particles enter the 3 T field present in the mixing area. Based upon this we estimate that the particles lose about 3 eV of axial kinetic energy entering the mixing area, which corresponds to a perpendicular energy of about 0.14 eV in the 0.14 T field of the accumulator and about 20 meV in the regions of lowest magnetic field in the transfer section. The value of the perpendicular energy can most likely be attributed to imperfect alignment of the successive solenoids and/or electrodes giving the positrons an extra angular deviation. While there are no losses at the first peak in the simulation, the experimental efficiency of the transfer before squeezing is 55%. The squeeze itself gives rise to losses up to 38% giving a overall efficiency of about one third, *i.e.* we are able obtain about 50 million transferred positrons each time we transfer. These losses are not understood in detail but could also be a result of imperfect alignments.

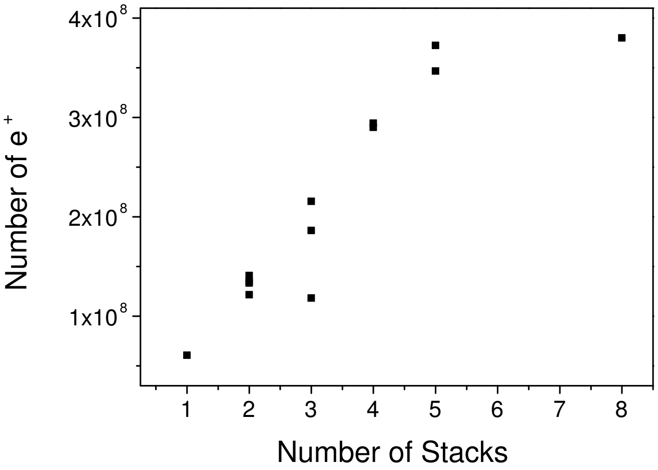

FIGURE 4. Number of positrons as a function of the number of stacks. Each shot contains 75 million positrons

STACKING

Positrons have been stacked before [12] but within a homogenous magnetic field. Here the positrons transit different fields between about 0.02 and 1 T before stacked in a 3 T field. We performed a number of stacking experiments using the dashed potentials as depicted in Fig. 2 after the first shot. These potentials ensure that the positrons which have already been transferred cannot escape. The results are shown in Fig. 4 where each point has been measured by dumping the plasma onto the Faraday cup. The low point at 3 stacks is probably the result of a missed transfer in the stacking sequence. The stacking curve is linear up to 5 stacks after which it levels off. This is due to reaching the space charge limit given by the well depth. In a different set of measurements where the well depth was gradually increased we were able to obtain a plasma containing 4.2×10^8 positrons.

COMPRESSION

After positron transfer a rotating wall electric field with a freqeuncy between 2.5 and 3.5 MHz was applied to the plasma for a duration of 200 seconds. During the process the plasma parameters were measured using mode analysis, in particular the (1.0) dipole and (2.0) quadrupole frequencies (as described in [10]), as a function of time. For a plasma containing 90 million positrons with a initial density of 3.0×10^8 cm^{-3} we were able to compress the plasma by a factor of about 10 resulting in a density of about 3.6×10^9 cm^{-3}. This number is close to the previously reported maximum positron density of 4×10^9 cm^{-3} [13] but there the plasma contained only a couple of thousand particles.

We are not yet able to reliably measure the (compressed) densities of plasmas with a larger number of positrons because of the limitation of the mode analysis detecting system and/or non-linearities in well potentials [10].

CONCLUSIONS

We have been able to transfer positron plasmas between two solenoids with an overall efficiency of 34 %. Subsequently, stacking of a number of positron shots shows a linear behaviour until the space charge limit of the well has been reached obtaining a plasma containing 380 million positrons. Compression by a rotating wall electric field of 90 million positrons resulted in a positron plasma with a density of 3.6×10^9 cm^{-3}.

ACKNOWLEDGMENTS

This work was supported in part by MEXT and RIKEN (Japan), CNPq (Brazil), SNF (Denmark), INFN (Italy), SNF (Switzerland), and the EPSRC (UK).

REFERENCES

1. Amoretti, M., *et al., Nature*, **419**, 456 (2002).
2. Gabrielse, G., *et al., Phys. Rev. Lett.*, **89**, 213401 (2002).
3. Gabrielse, G., Rolston, S. L., Haarsma, L., and Kells, W., *Phys. Lett.*, **A 129**, 38 (1988).
4. Holzscheiter, M. H., and Charlton, M., *Rep. Prog. Phys.*, **62**, 1 (1999).
5. Murphy, T. J., and Surko, C. M., *Phys. Rev. A*, **46**, 5696 (1992).
6. Jørgensen, L. V., van der Werf, D. P., Watson, T. L., Charlton, M., and Collier, M. J. T., , in *Nonneutral Plasma Physics IV*, edited by F. Anderegg, L. Schweikhard, and C. F. Driscoll, AIP Conference Proceedings 606, American Institute of Physics, New York, 2002, p. 35.
7. Amoretti, *et al., submitted to NIM A (e-print archive: CERN-EP/2003-051)* (2003).
8. Huang, X., Anderegg, F., Hollmann, E., Driscoll, C., and Neil, T. O., *Phys. Rev. Lett.*, **78**, 875 (1997).
9. Amoretti, M., *et al., Phys. Rev. Lett.*, **91**, 55001 (2003).
10. Amoretti, M., *et al., Phys. Plasmas*, **10**, 3056 (2003).
11. Dahl, D., *Simion 3D Version 7.0*, Bechtel BWXT, Idaho, 2000.
12. Greaves, R. G., Tinkle, M. D., and Surko, C. M., *Phys. Plasmas*, **1**, 1439 (1994).
13. Jelenković, B. M., Newbury, A. S., Bollinger, J. J., Itano, W. M., and Mitchell, T. B., *Phys. Rev. A*, **67**, 063406 (2003).