Antimatter Plasmas used for Antihydrogen Formation.

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Current attempts to trap antihydrogen require the formation of antimatter atoms sufficiently cold to be confined in a magnetic minimum trap [1]. The radial profiles and densities of the antimatter plasmas are important for the controlled production of antihydrogen [2]. We present techniques used to prepare cold, compressed plasmas in the ALPHA apparatus [3], [4].

The antihydrogen atom is of fundamental interest as it offers the potential for a sensitive test of CPT symmetry through comparison of the spectra of antihydrogen and hydrogen. Cold antihydrogen was first produced by the ATHENA collaboration [5] and shortly afterwards the ATRAP collaboration [6] at the CERN Antiproton Decelerator (AD) in 2002. In these experiments the neutral antihydrogen, synthesized from antiprotons and positrons held as non-neutral plasmas in Penning-Malmberg traps, were not confined and escaped the production region either to annihilate or be ionized by the electric fields in the trap. For precision experiments to be carried out on antihydrogen, it is highly desirable to trap and hold the neutral antiatoms. Antihydrogen atoms possess a small magnetic moment and can be held in a three-dimensional minimum of a magnetic field [7]. The ALPHA apparatus superimposes a multipole magnetic minimum trap on a charged particle trap [8]. Only those antihydrogen atoms with kinetic energy less than trap depth (0.6 K for ground state atoms) can be trapped. Cold antiprotons and positron plasmas are therefore important for trapping antihydrogen.

The charged particle trap is of the Penning-Malmberg type, with a 1 T external solenoid field providing radial confinement and electric fields providing axial confinement for the plasmas. The magnetic minimum trap for neutral atoms is a variation of the Ioffe-Pritchard configuration, replacing the typical quadrupole with an octupole [8], as this configuration results in a lower transverse magnetic field close to the trap axis, and smaller perturbations to plasmas stored in the Penning-Malmberg traps [9]. A 3-layer silicon detector is used to reconstruct the tracks of charged pions from antiproton and antihydrogen annihilations and locate the annihilation vertices [10]. An external set of plastic scintillator paddles read out by photomultiplier tubes is also used to monitor antiproton annihilations.

Plasma characteristics are measured using two main diagnostics, which allow destructive measurements of the plasma radial profile and temperature. The radial density profile is measured by extracting the plasma onto a microchannel plate (MCP) and phosphor screen assembly, the result being imaged by a CCD camera [11], [12]. The plasma temperature in a known electrostatic well can be measured by slowly (with respect to the bounce frequency in the well) lowering one side of the well so that the first particles to escape the well originate from the tail of a Boltzmann energy distribution [13]. The escaping particles are detected using the MCP phosphor screen as a charge pickup for lepton plasmas; antiprotons are allowed to escape in the opposite direction onto an aluminium foil, with the annihilation products being detected by the external scintillators [14]. The absolute plasma temperature can be calculated by an exponential fit to the released particle number as a function of well depth. By a numerical solution of the Poisson-Boltzmann equation, the density distribution and space charge of the plasma can then be calculated [15].

The transverse multipole magnetic fields introduced to the Penning-Malmberg trap by the octupole magnet induce a critical radius beyond which the charged particles will follow the field lines to the wall [16]. Closer to the axis, perturbations from the asymmetric magnetic field may still cause heating and radial expansion of the plasma [17]. It is therefore desirable that the plasmas used for antihydrogen formation be radially compressed well below the critical radius. This is achieved by applying a rotating electrostatic potential to a sectored electrode, which applies a torque to the plasma in order to adjust its radius, a technique known as a rotating wall potential (RW) and commonly used in non-neutral plasma research [3], [18], [19].

The magnetic field in the antiproton capture region is increased to 3 T by addition of a variable 2 T internal solenoid to the 1 T external solenoid. This improves antiproton trapping and cooling efficiency [20]. An electron plasma containing 1.5×10^7 electrons is loaded from an electron gun mounted at the opposite end of the trap. Approximately 3×10^7 antiprotons are delivered by the AD every 100 seconds with energy 5.3 MeV. After entering the apparatus and passing through a 218 μm aluminium degrader, a fraction of these are then trapped between two high-voltage (4 kV) electrodes. They cool through collisions with the pre-loaded electron plasma, the electrons cooling through synchrotron radiation [21]. A RW sweep is used to radially compress the two-component plasma [3], which contains 4.5×10^4 antiprotons in a radius of 0.5 mm. The internal solenoid is ramped down to leave the plasma in the 1 T external field, and the plasma is moved to the antihydrogen production region of the trap. The electrons are removed from the antiprotons by a series of electric field pulses which momentarily remove the confining potential on one side of the electrostatic well, allowing the electrons to escape, but restore it before the antiprotons can follow. We find that this procedure tends to heat the antiprotons; careful tuning of the electron removal process results in final antiproton temperatures around 200 K, compared to pure electron plasma temperatures of around 50 K. The radius of the antiprotons in 1 T is 0.8 mm, with density $10^6\ cm^{-3}$.

During the antiproton catching and cooling process, the positron plasma is prepared. We accumulate 5×10^7 positrons in 200 s from a ^{22}Na source in a Surko-type device using N_2 buffer gas [22]. They are transferred into the main experiment and retrapped. Positively charged ions, which cause expansion of the positron plasma, are removed by a process similar to that used to remove the electrons from the antiprotons; positrons are allowed to escape from an initial well into a neighbouring well, while the ions remain in the initial well and are subsequently ejected from the trap. A RW sweep compresses the positron plasma to approximately 1 mm radius, slightly larger than the antiprotons. We can adjust the density by cutting the plasma. Depending on the number of particles chosen, positron plasma temperatures prior to antihydrogen production are between 70 and 150 K. Typical peak densities are between 10^7 and $10^8\ cm^{-3}$.

We have described the techniques used to prepare antimatter plasmas for antihydrogen formation in the ALPHA experiment. ALPHA has been successful in forming antihydrogen in the magnetic minimum trap [2], and we hope to soon report trapping of antihydrogen atoms. Full discussion of the results of the 2009 run trapping attempts will be presented in a forthcoming publication. ALPHA has also developed an evaporative cooling technique for antiprotons which, though not used in the experiments discussed in this paper, offers considerable promise for future trapping experiments [14]. Our continuing efforts to trap antihydrogen are greatly aided by our ability to characterise the plasmas used for the experiments.

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References

[1] G. Andresen, W. Bertsche, A. Boston, et al., *Physics Review Letters*, **98**, 023402 (2007).

[2] G.B. Andresen, W. Bertsche, P. D. Bowe, et al., *Physics Letters B*, **685**, 141-145 (2010).

[3] G.B. Andresen, W. Bertsche, P. D. Bowe, et al., *Physics Review Letters*, **100**, 203401 (2008).

[4] G.B. Andresen, W. Bertsche, P. D. Bowe, et al., *Physics of Plasmas*, **15**, 032107 (2008).

[5] M. Amoretti, C. Amsler, G. Bonomi, et al., *Nature*, **419**, 456 (2002).

[6] G. Gabrielse, N. S. Bowden, P. Oxley, et al., *Physics Review Letters*, **89**, 213401 (2002).

[7] D. E. Pritchard, *Physics Review Letters*, **51**, 1336 (1983).

[8] W. Bertsche, A. Boston, P. D. Bowe, et al., *Nucl. Inst. Meth. A*, **566**, 746 (2006).

[9] J. Fajans and A. Schmidt, *Nucl. Inst. Meth. A*, **521**, 318 (2004).

[10] M. C. Fujiwara, *AIP Conference Proceedings*, **793**, 111 (2005).

[11] G. B. Andresen, W. Bertsche, P. D. Bowe, et al., *Review of Scientific Instruments*, **80**, 123701 (2009).

[12] A. J. Peurrung and J. Fajans, *Review of Scientific Instruments*, **64**, 52 (1993).

[13] D. L. Eggleston, C. F. Driscoll, B. R. Beck et al., *Phys. Fluids B*, **4**, 3432 (1992).

[14] G. B. Andresen, M. D. Ashkezari, M. Baquero-Ruiz, et al., *(Accepted, awaiting publication)*

[15] R. L. Spencer, S. N. Rasband and R. R. Vanfleet, *Phys. Fluids B*, **5**, 4267 (1993).

[16] J. Fajans, N. Madsen and F. Robicheaux, *Physics of Plasmas*, **15**, 032108 (2008).

[17] M. Amoretti, C. Canali, C. Carraro, et al., *Physics Letters A*, **360**, 141 (2006).

[18] X. P. Huang, F. Anderegg, E. M. Hollmann, et al., *Physics Review Letters*, **78**, 875 (1997).

[19] R. G. Greaves and C. M. Surko, *Physics Review Letters*, **85**, 1883 (2000).

[20] G. B. Andresen, W. Bertsche, A. Boston, et al., *Journal of Physics B*, **41**, 011001 (2008).

[21] G. Gabrielse, X. Fei, L. A. Orozco, et al., *Physics Review Letters*, **63**, 1360 (1989).

[22] L. V. Jørgensen, M. Amoretti, G. Bonomi, et al., *Physics Review Letters*, **95**, 025002 (2005).