3.3 The Beauty of the ATRAP-Experiment and its Performance in 2009

The scientific goal of cold antihydrogen studies is a precise comparison of observables from antihydrogen and hydrogen atoms to check if their structure or gravitational interactions differ. CPT invariance implies that antihydrogen and hydrogen atoms have the same structure and interactions. Such invariance follows from axiomatic quantum field theories that are Lorentz invariant like the Standard model, and is thus a well established fundamental symmetry. Caution seems appropriate given that the physics community once incorrectly thought that reality was invariant under parity transformations, and later (also incorrectly) that reality was invariant under CP transformations. The precise comparison of the simplest atoms of antimatter and matter should produce the most stringent test of CPT symmetry with leptons and baryons. Highest precision CPT tests are of great interest and if CPT violation could be detected it may be the key to the explanation of the imbalance of matter and antimatter in the universe. The ATRAP apparatus, displayed in Figure 41, has a vertical magnetic field for its cryogenic Penning traps, and a positron accumulator ~ 10 meters apart. A pulse of antiprotons from the antiproton decelerator (AD) of CERN

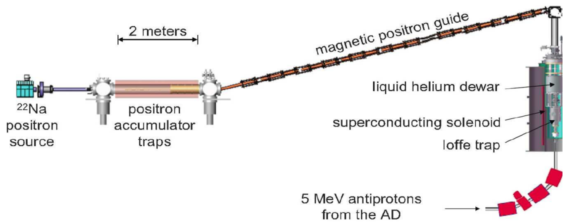

Fig. 41: Overview of the ATRAP antihydrogen apparatus.

is directed by bending magnets into the superconducting solenoid every ≈ 100 s. They are captured in the lower section of a series of Penning traps — shown in the right part of Figure 42 together with a photo of the apparatus — made by applying voltages to ring electrodes with a magnetic field (up to 3 Tesla) along their axis.
Antihydrogen atoms are normally produced within a nested Penning trap which includes a short inverted potential well filled with positrons within the $\bar{p}$ potential well by reducing the potentials to mix the two particle species. Another, in view of very slow antihydrogen promising method, is the laser-controlled production via Cs Rydberg atoms which has also been demonstrated at ATRAP. Antihydrogen trapping requires magnetic field gradients contradicting to the constant field necessary for the stability of charged particles trapping. Recently ATRAP succeeded in producing antihydrogen atoms within a Ioffe trap field, but no trapped antihydrogen atoms could yet been reported. Better control of the antihydrogen formation seems crucial for their trapping. Therefore serious studies of temperatures and distributions of the cold antiproton and positron plasmas are demanded to better understand and control the formation of

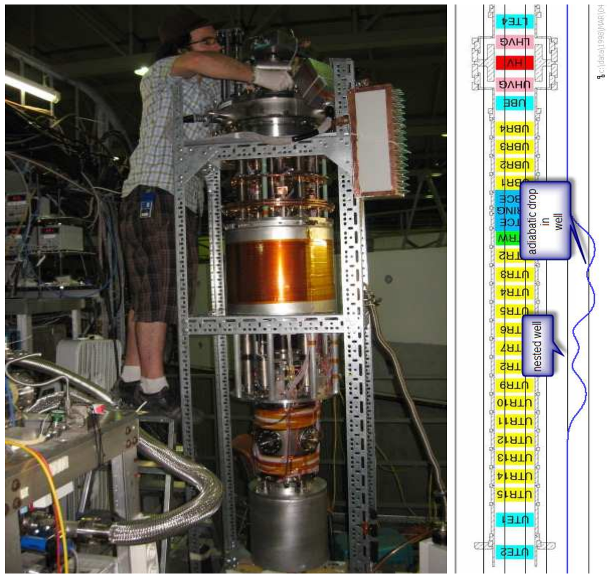

Fig. 42: The ATRAP antihydrogen apparatus and the Penning trap arrangement.

antihydrogen atoms.
After these general considerations the achievements of the ATRAP collaboration during the last year 2009 should briefly be summarized:
The main focus for 2009 was the search for signals of trapped antihydrogen. Three-body recombination experiments were used in attempts to trap antihydrogen. For these trials a heater was used to induce a quench in the superconducting Ioffe trap quadrupole which reliably quickly reduces the field and would release any trapped atoms. Experiments were done with up to 4 million antiprotons and 60 million positrons with the Penning trap at temperatures as low as 1.2 K.
Low temperatures are crucial for these experiments considering the Ioffe trap depth of about 400 mK. The reduction of the electrode temperature from the 4.2 K liquid Helium surrounding down to 1.2 K will increase the fraction of trappable $\bar{\mathrm{H}}$ atoms by a factor of about 7 if the low temperature can be transferred to the produced antihydrogen. Studies on electrons and positrons indicate plasma temperatures in the 1.2 K region but the reproducibility to prepare these low temperature plasmas need more basic studies and the cooling of the antiproton plasma down to 1.2 K has still to be shown.
Techniques for fast measurements of plasma modes and temperatures have been developed and are now integrated into the antihydrogen production experiments. Figure 43 shows the result of such a temperature measurement. Presently antiproton clouds as low as 30 K have occasionally been observed by this method. Further investigations are necessary here.
In order to reduce the radius of electrons, positrons, and antiprotons and thereby the particle loss, a split electrode with rotating electric field has been used. The compression of electron-antiproton plasmas by increasing the ro-

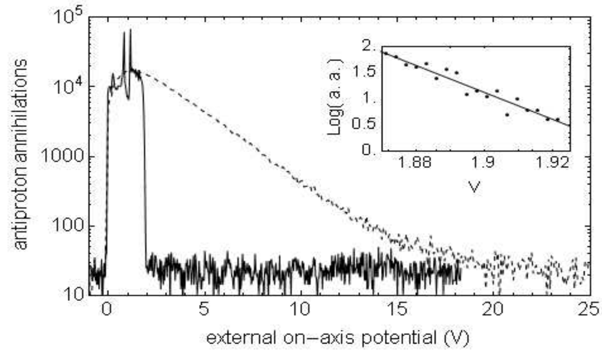

Fig. 43: Energy distribution of antiprotons, determined by measuring annihilation events while reducing the potential well height. The exponential distribution of the antiproton annihilations (straight line on the log plots) is due to the thermal axial energy distribution. The dashed-line distribution results when heating with a noise drive to 15,000 K. The solid-line distribution has been cooled to 100 K by adding electrons. The inset is a blowup of the start of the solid-line distribution fitted by an exponential.

tation frequency has allowed to stack 6 million antiprotons as is demonstrated in Figure 44 which is about 3 times more $\bar{p}$'s than last year. Without the rotating wall, when many $\bar{p}$'s are loaded the plasma expands and a high loss is observed when the $\bar{p}$ solenoid, used to increase the magnetic field for an improved trapping efficiency, is ramped down after loading.

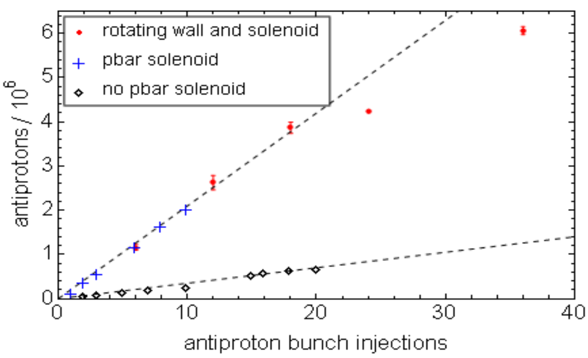

Fig. 44: An extension of ATRAP's stacking procedure up to nearly 6 million $\bar{p}$'s.

This previously limited the trapping of antiprotons to approximately 2 millions. The largest stacks achieved with increased plasma rotation of 4 and 6 million $\bar{p}'s$ fall below the linear stacking line due to initial losses when applying the rotating wall drive. Developments will follow next year to remove these losses and possibly the stacking will continue to even larger numbers.

During 2009 ATRAP has started to study the antihydrogen production as a function of plasma shape and density. In studies with ≈ 2.5 million antiprotons more than half of the antiprotons are lost if no rotating wall is used ($r = 8$ mm). If the cloud is compressed to $r = 2.5$ mm the loss is reduced to less than 5%.

The radius is determined in these measurements from the two mode frequencies for the center-of-mass and the quadrupole axial oscillations with the known particle number. The rotating wall technique appears to work similarly in the cases of only electrons using about 100 million e^- and electrons with antiprotons using about 100 million e^- and 2.5 million $\bar{p}$'s as demonstrated in Figure 45.

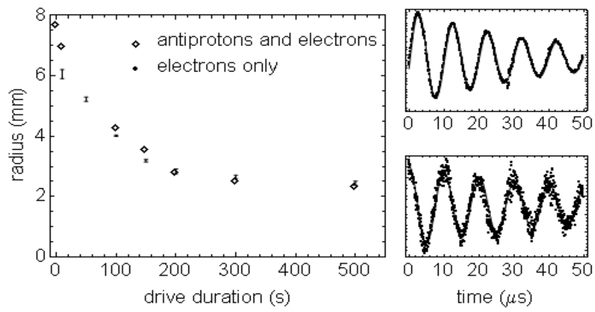

Fig. 45: Plasma radius that results from applying plasma rotation for a certain duration (left). Center-of-mass (top right) and quadrupole (bottom right) axial oscillations (plasma modes) used to determine the radius.

Besides the optimization of the three body recombination schemes a system for the alternative antihydrogen production technique via charge exchange using Rydberg Cs atoms has been commissioned in the second generation trap arrangement including the Ioffe-trap system during the last year, see Figure 46. The advantage of this technique is the low expected antihydrogen velocity given by the temperature of the $\bar{p}$ plasma. Rydberg Cs atoms have been detected before and after they pass through the Penning trap within a 1 T magnetic field. Antihydrogen charge-exchange experiments have been started, but $\bar{\mathrm{H}}$'s have not yet been observed.

Fig. 46: Cs apparatus mounted on a Ioffe trap with feedthroughs for photodiodes, Stark shifting plates, field ionization plates, getter current, and temperature sensor. The optical fiber at the top carries both excitation wavelengths.