First Attempts at Antihydrogen Trapping in ALPHA

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Abstract. The ALPHA apparatus is designed to produce and trap antihydrogen atoms. The device comprises a multifunction Penning trap and a superconducting, neutral atom trap having a minimum-B configuration. The atom trap features an octupole magnet for transverse confinement and solenoidal mirror coils for longitudinal confinement. The magnetic trap employs a fast shutdown system to maximize the probability of detecting the annihilation of released antihydrogen. In this article we describe the first attempts to observe antihydrogen trapping.

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INTRODUCTION

Antihydrogen is of fundamental interest for use in precision tests of CPT symmetry and in investigations of antimatter gravitation. Following the first synthesis of antihydrogen from trapped antimatter plasmas in 2002 [1, 2], the recent focus of the two operational antihydrogen experiments at CERN's Antiproton Decelerator (AD) [3] has been on trapping of the produced anti-atoms. Early experiments in the second-generation antihydrogen devices (ALPHA and ATRAP2) addressed the longevity of trapped plasmas

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in combined Penning/neutral atom trapping fields [4, 5]. In this article we demonstrate the complete sequence of manipulations comprising an antihydrogen trapping experiment in the ALPHA device, and we discuss the results of the first effort to trap neutral antimatter.

THE ALPHA APPARATUS

The ALPHA apparatus is schematically depicted in Figure 1. Antiprotons from the AD are dynamically captured and electron-cooled in a Penning trap (3 T solenoidal field, 5 keV well depth). Typically, 3×10^7 extracted antiprotons from the AD result in 40000 captured and cooled antiprotons in the catching trap. The catching trap includes a "rotating wall" electric field system which can be used either to expand the electron cloud radius for maximizing antiproton capture efficiency or to reduce the antiproton cloud radius to maximize the probability of antihydrogen formation and trapping [6, 7].

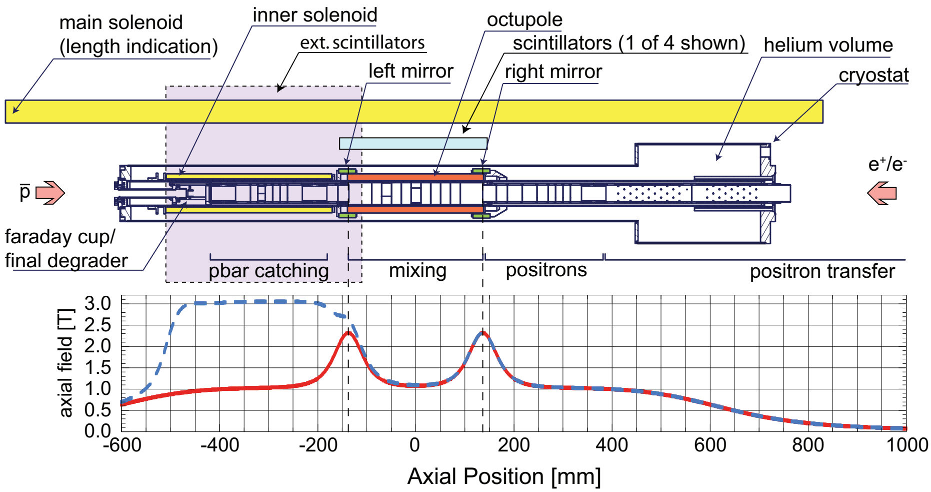

FIGURE 1. Schematic diagram of the ALPHA apparatus. The graph shows the on-axis longitudinal magnetic field due to the solenoids and mirror coils. The blue (red) curve is the field with (without) the inner solenoid energized.

Positrons from a Surko-type accumulator [8] are loaded into the mixing region of the device, trapped dynamically, and allowed to cool by cyclotron radiation. The solenoidal field in the mixing region is only 1 T, in order that the trap depth of the neutral atom trap surrounding this region is as large as reasonably possible [9, 10]. ALPHA generates the necessary two-region solenoid field using an outer 1 T, warm bore magnet, and an inner 2 T winding on the Penning trap vacuum chamber. All Penning traps in the ALPHA device are cooled through contact with the liquid helium system for the superconducting magnet coils comprising the neutral atom trap and inner solenoid (Figure 1). Typical positron plasmas for the mixing experiments described here contained 30-50 million positrons.

The mixing region is surrounded by a multipole trap for confining neutral anti-atoms. The transverse confinement is by an eight-layer octupole winding, and the longitudinal confinement is by solenoidal mirror coils generating a peak field of 2 T [9]. The maximum achievable neutral trap depth, in temperature units, is about 0.7 K for ground state antihydrogen. Slightly smaller depths were employed here.

The ALPHA design features the capabilities for fast ramp-up of the neutral atom trapping coils and for very fast shutdown of the entire system. The fast ramp-up is desirable so that the antiprotons and positrons can be accumulated and manipulated into proximity without the perturbing, transverse fields present in the experimental volume. The fast shutdown feature is incorporated to optimize the detection of trapped antihydrogen atoms by quickly turning off the trapping fields and looking for antiproton annihilations in the detectors surrounding the trapping region (Figure 1). Since trapping an anti-atom in the first place is a potentially rare event, it is desirable to maximize the signal to noise ratio of the annihilation detector by dumping the trap in a narrow time span. The ALPHA magnets feature a fast energy extraction system that employs an isolated gate bipolar transistor (IGBT) current switch [11] to dump the excitation current into a resistive load. This same circuit also functions as a part of the quench protection system for the magnets.

Figure 2 shows the voltage across the octupole during a fast shutdown from 950 A. (Note that the maximum design current is 1100 A.) The e-folding time is 9.6 ms. The resistance in the circuit is about 330 mΩ, and the magnet inductance is 3.2 mH. We have no direct measurement of the field decay in the superconducting magnet. The mirror coils have a slightly faster e-folding time of 8.3 ms.

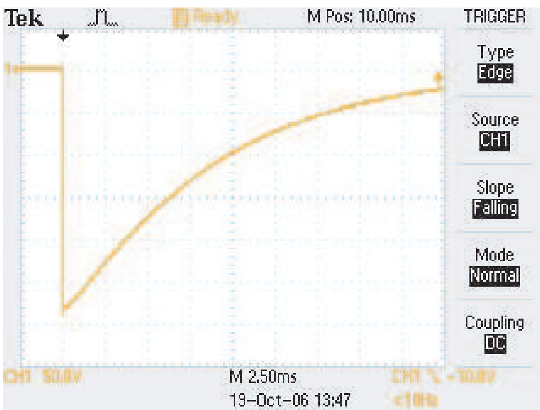

FIGURE 2. Voltage induced across the octupole magnet during a fast shutdown event. See text for details.

For the measurements described in the following section, the apparatus was equipped with scintillation detectors read out by avalanche photodiodes (APD) [12]. The detectors were placed inside the outer solenoid and adjacent to the mixing trap (Figure 1). The geometry of the detector assembly is shown in Figure 3. Four of the seven positions contained scintillation detectors, and two contained three-layer, position sensitive, silicon detectors. An event was registered if two or more of the scintillation detectors fired in coincidence (100 ns window). The solid angle subtended by the scintillation detectors was about 50% of 4π, with respect to the center of the mixing region. The background rate for the scintillation detectors in this coincidence mode is about 2 Hz.

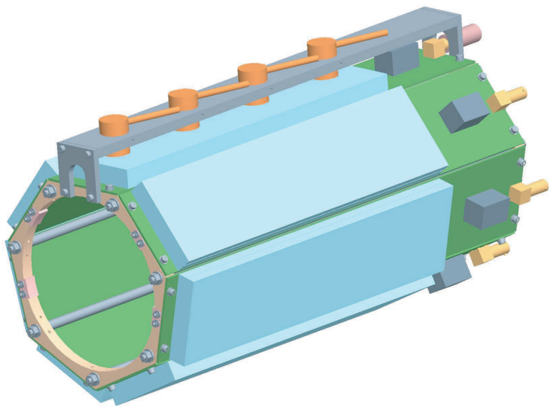

FIGURE 3. Mounting geometry for the scintillators surrounding the mixing region. For the measurements reported here, three of the seven modules were replaced with two layers of position sensitive silicon strip detector. The small detectors (orange) are CsI crystals for looking at positron annihilations. A similar, seven-segment scintillation detector surrounds the degrader foil.

THE TRAPPING EXPERIMENT

The trapping experiment begins with the transverse octupole turned off, but the mirror coils energized. Antiprotons from the AD are accumulated for up to eight AD cycles. The AD cycle time was about 70 s. The resulting antiproton stack of roughly 3×10^5 particles was transferred to the mixing region after dynamic removal of the cooling electrons. Positrons accumulated during the antiproton accumulation were transfered to a potential well adjacent to the antiprotons. With both species of particle in the mixing region, the octupole field was ramped up from 0 to 900 A in 45 s. The antiprotons are then injected into the positron plasma using the nested Penning trap [13] configuration as employed for the first antihydrogen production in ATHENA [1] .

The antiprotons are cooled by collisions with the positron cloud, and this mixing/cooling process is monitored by recording scintillation events in the scintillators surrounding the mixing region. Two other sets of scintillators, one external to the main solenoid and one adjacent to the degrader, are also sensitive to antiproton annihilations, but with much smaller solid angle and efficiency. The time development of the scintillation signal during mixing in the combined trap is shown in Figure 4. For comparison, the scintillation signal for the same procedure, but without positrons, is also shown (in red). The scintillation trigger rate evolves in qualitatively the same fashion as is observed in previous antihydrogen production cycles in ATHENA [14] and in ALPHA [10] without the presence of the neutral atom trapping fields. There is an initial rise in annihilations as the antiprotons cool and interact with the positrons, followed by a slow decay of the annihilation signal. These annihilation events are presumably related to neutral antihydrogen production, with the neutrals annihilating on the Penning trap wall. Another possibility is that antihydrogen is field-ionized at a radius at which antiprotons follow field lines to the trap wall and annihilate (see reference [7]). Without positrons, there is no evidence of antiproton annihilation, except for the immediate loss associated with the injection manipulations.

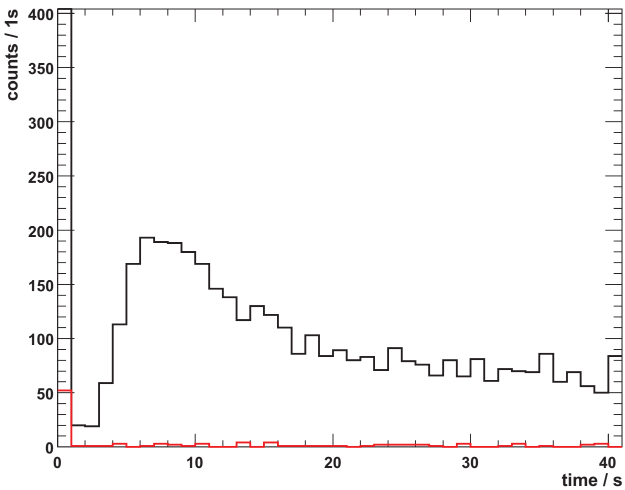

FIGURE 4. Scintillation triggers versus time after the start of mixing for normal mixing (black) and for the same sequence but without positrons present (red). The octupole was at 900 A, corresponding to a trap depth of about 0.5 K, for these measurements.

Further evidence for antiproton-positron interaction is obtained by releasing the remaining antiprotons from the trap after the end of the mixing cycle. This is done by lowering the confining potentials in a controlled way, such that particles with higher energies escape the trap first. The two side wells of the nested trap ("left" and "right") can be emptied separately, see Figure 5. Antiprotons which lie above the energy of the central positron well emerge in the left dump, which occurs first. Antiprotons that are cooled by the positrons but have not formed antihydrogen emerge later in time as the electrodes are ramped down. The results of these energy dumps are shown in Figure 6.

With no positrons present, antiprotons remain at the energy at which they are injected into the nested well, and they are all released early in the left dump. When positrons are present, the antiprotons can cool to the level of the positron cloud, and interactions between the two can yield antihydrogen. Thus with positrons present, we also observe an annihilation signal in the right dump, and the left dump antiprotons are shifted to lower energy. No antiprotons were present in the right well after mixing without positrons. Note that it is also possible for antihydrogen atoms to field-ionize at the edges of the nested well, leading to additional accumulation of antiprotons in each side well.

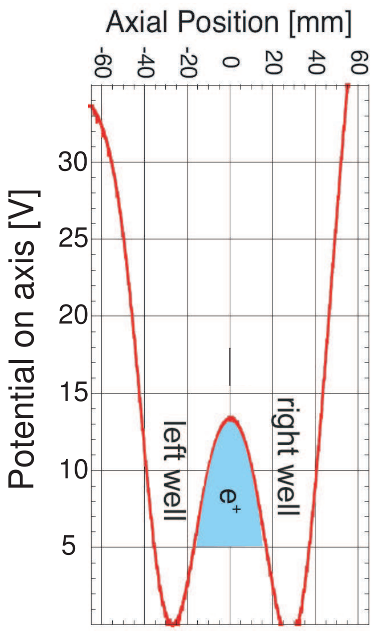

FIGURE 5. Potential on the axis of the nested well used for positron-antiproton mixing. The antiprotons are injected into the nested well with a potential of about 23 V on this diagram. The blue shaded region represents the approximate spacecharge potential of the positron cloud.

The data in Figures 4 and 6 are consistent with antihydrogen production in the combined trap. At the end of each mixing cycle, the mixing region was emptied of charged particles using applied electric fields. To look for evidence for trapped antihydrogen, the neutral trap was then rapidly de-energized, and the signal from the trap scintillators was scrutinized for evidence of annihilations from released antihydrogen atoms. The integrated number of particles mixed using this sequence during the 2007 run was about 2.3 million antiprotons and 5.6×10^9 positrons.

With this data sample, we observed no evidence for annihilations above the background level in the 10 ms time window immediately following the trap turn-off. There was thus no indication that antihydrogen atoms had been trapped and released. As we do not yet know the absolute antihydrogen production rate, we are unable to put an upper

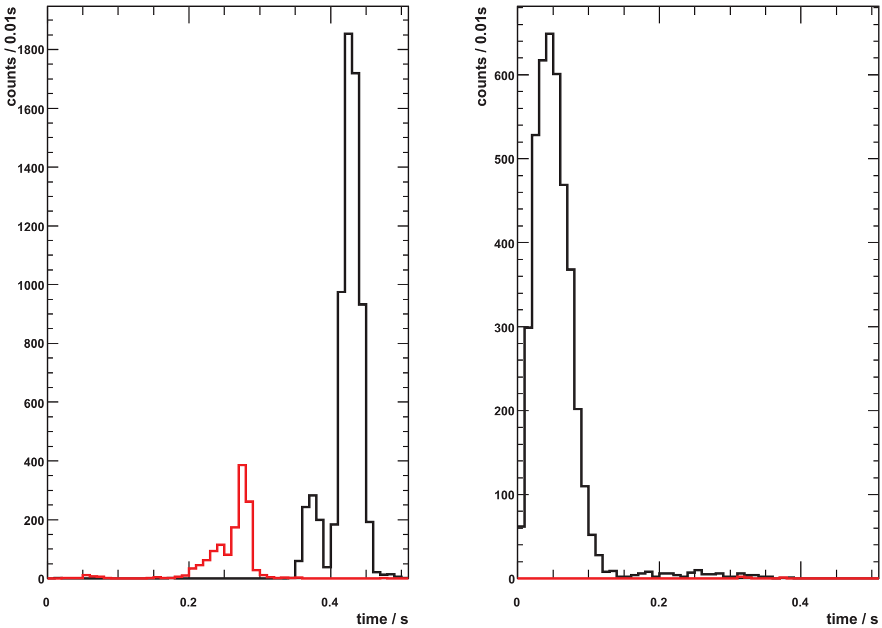

FIGURE 6. Antiproton annihilation signals observed while ramping down the left potential wall (left panel) followed by the right potential wall (right panel), after the mixing cycle was completed. The black (red) curves are with (without) positrons. The voltage ramp-down rate is about 70 V/s. This signal is for a single mixing cycle with eight AD shots.

limit on trapping probability.

In addition to the obvious statistical limitations of the data sample, there are several possible explanations for the lack of a trapping signal. It is of course possible that no antihydrogen is being produced in the combined trap, and that the annihilation signal observed in Figure 4 is just due to loss of antiprotons from the trap. This is highly unlikely, due to the corroborating evidence of antiproton cooling, but we have not yet systematically ruled out this scenario. A second possibility is that the antihydrogen produced is too energetic to be trapped in the 0.5 K well depth employed here. This is quite likely, as it was shown in both ATHENA [16] and ATRAP [17] that antihydrogen formation in this mixing scheme takes place before the antiprotons come into equilibrium with the positron cloud, which is presumably in equilibrium with its cryogenic surroundings. There is in fact no evidence to date for cryogenic antihydrogen production by any method in any device, and there are no direct measurements that show that the positrons in fact cool to the 4.2 K temperature of the apparatus. A third possibility is that some antihydrogen is trapped initially in an excited internal state having a large magnetic moment, but escapes the trap during decay to more tightly bound levels. We currently have no way of testing this hypothesis, although some of us have addressed this question theoretically [15]. Other loss mechanisms leading to trapping lifetimes much shorter than the time scale of the experimental manipulations used here can also not be ruled out at this early stage.

SUMMARY AND OUTLOOK

We described the first attempt at trapping antihydrogen in a combined Penning/neutral atom trap. No evidence for antihydrogen trapping has been observed yet, but all of the necessary hardware operations for realistic trapping attempts have been successfully demonstrated. A likely explanation for our result is that the three-body production in the "normal" mixing technique yields antihydrogen that is too energetic to be trapped, but much work remains to be done before abandoning the high-rate antihydrogen production characteristic of this technique. The 2008 experimental program in ALPHA will focus on careful manipulations and mixing techniques designed to minimize the temperature of the produced antihydrogen atoms. In these endeavours, we expect to benefit both from the novel diagnostic techniques reported elsewhere in these proceedings [7] and from the ALPHA imaging silicon detector [12], expected to be installed in 2008.

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