# THE ALPHA ANTIHYDROGEN EXPERIMENT

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ALPHA is a new experiment at the CERN Antiproton Decelerator (AD). The short term goal of ALPHA is trapping of cold antihydrogen, with the long term goal of conducting precise spectroscopic comparisons of hydrogen and antihydrogen. Here we present the current status of ALPHA and the physics considerations and results leading to its design as well as recent progress towards trapping.

## 1. Introduction

Antihydrogen is the simplest atomic antimatter system, and it offers great opportunities for studies of symmetries between matter and antimatter. In 2002 the ATHENA experiment was the first to produce cold antihydrogen[1]. This result was followed by similar observations by the ATRAP collaboration[2]. Since then efforts have been focussed on understanding the formation mechanism and determining the state of the anti-

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atoms formed as well as their temperature. An important finding is that the antihydrogen formed using the technique of merged plasmas of positrons and antiprotons (which, to date, is the most efficient method of antihydrogen formation) is very warm compared to the depths of state-of-the-art atom traps[3,4]. ALPHA believes that cold and trapped antihydrogen offers the best route to conduct precision measurements on the antiatoms. ALPHA has therefore designed, built and commissioned an apparatus to do exactly that. Here we give an overview of the ALPHA experiment, and discuss some of the physics behind various design decisions, as well as some of the most recent results from ALPHA's first AD runs in 2006.

## 2. The ALPHA Apparatus

An overview of the ALPHA apparatus is shown in Figure 1. The ALPHA apparatus has been designed with the intention to trap antihydrogen atoms. Further to what is shown on the figure, ALPHA has inherited the ATHENA positron accumulator[5].

The ALPHA apparatus uses a versatile Penning-Malmberg trap for trapping and manipulation of the charged particles used for antihydrogen production. The left-hand part of the trap (see Figure 1) is enclosed by high voltage electrodes to catch the incoming antiprotons, whereas the right-hand section is used for transfer and manipulations of positrons transferred from the positron accumulator. The center of the trap is the so-called mixing trap where the antihydrogen is formed.

An antihydrogen atom can be trapped in a three dimensional magnetic minimum due to its magnetic dipole moment. If antihydrogen can be created cold enough in the magnetic trap, or be cooled once inside it, it can be trapped. Such a magnetic trap, where the transverse minimum is formed by using a multipole magnet, and the axial minimum by a pair of pinch or mirror coils (see Figure 1) will, when superimposed on the solenoid field of the Penning-Malmberg trap, have a transverse well depth $U$ (in K) according to:

$$U = \frac{\mu}{k_B}\left[\sqrt{B_W^2 + B_S^2} - B_S\right]. \tag{1}$$

Here $\mu$ is the antihydrogen magnetic moment, $k_B$ is Boltzmann's constant, $B_W$ is the multipole field at the trap wall (inner radius of the Penning-Malmberg trap electrodes) and $B_S$ the solenoid field. We note that a lower solenoid field will allow a deeper trap for the same multipole field at the wall. In the axial direction the fields add linearly, such that there are no

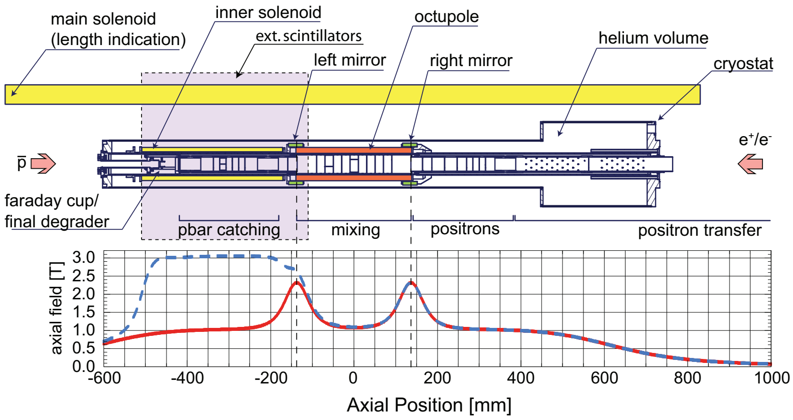


Figure 1. Overview of the ALPHA apparatus. The plot of the axial B-field shows the field with the main solenoid and the mirrors (full) and the added inner solenoid (dashed).

limitations to the trap depth by implementing a high solenoid field.

Trapping of antiprotons is significantly more efficient using a high solenoid field. The ALPHA apparatus therefore consists of a main solenoid which delivers a homogenous axial magnetic field throughout and an internal short solenoid around the antiproton catching region of the trap. This provides a low axial field in the (anti)atom trap to increase the trap depth while keeping the catching efficiency of antiprotons high.

In typical atom traps the transverse magnetic minimum is supplied by a quadrupole. However, recent measurements have demonstrated that strong transverse field components can significantly deteriorate the trapping efficiency and particle lifetime of a Penning trap[6]. Higher order multipoles will, for the same trap depth, result in much smaller transverse field components near the center of the trap. The rapid fall in field away from the wall for a higher order multipole means that extra effort has to be made to make the magnet inner coil as close to the trap vacuum as possible. ALPHA settled for an octupole design as a compromise between trap depth and particle survival[7]. The state-of-the-art ALPHA atom trap produces an effective depth of 1.13 T at $B_S$= 1 T corresponding to 0.74 K for ground state antihydrogen (eqn. (1)).

## 3. Antihydrogen Formation Alternatives

Antihydrogen is normally formed by merging two cold plasmas of antiprotons and positrons. This method has, as mentioned earlier, been shown to produce large amounts of antihydrogen before the antiprotons are in thermal equilibrium with the positrons. The antiatoms are thus at a higher temperature than ambient, as the antiproton carries most of the momentum of the antihydrogen[3,4]. Thus, even with, as expected for ALPHA, a 4 K ambient temperature, further measures are needed to create antihydrogen that is cold enough to trap.

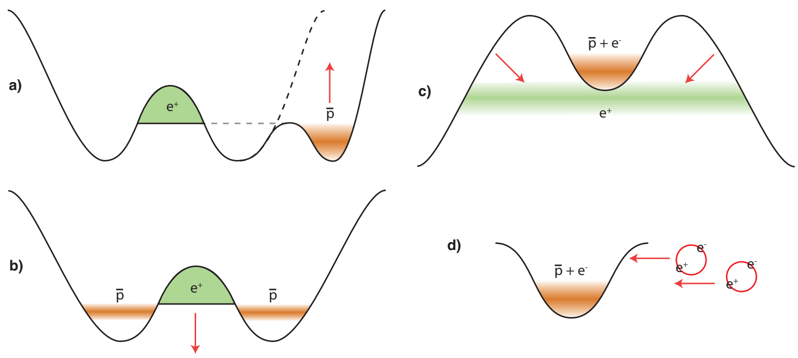


Figure 2. Alternative antihydrogen formation methods for creating antihydrogen cold enough to be trapped. See text for discussion.

The merging-scheme has the advantage of being very easy to implement, and of forming antihydrogen at impressive rates of up to 400 $s^{-1}$ [8]. ALPHA has thus chosen to first focus on variations of this scheme as the basis for methods for forming trappable antihydrogen. Figure 2 shows four approaches that are being discussed. To avoid positrons interacting with hot antiprotons, the antiprotons can be dribbled into the positron plasma, (a). However, (a) will be difficult to implement in practice, as the positron space charge typically varies from load to load with more than the 0.1 mV precision needed such that the antiprotons have low enough energy in the positron plasma. In (b) the antiprotons are injected below the positron space-charge level and the positrons are then slowly moved into contact with the antiprotons. A simple rule of thumb here is that the positron well must move slow enough that the energy change should be less than 0.1 mV ($\sim$1 K) in the time it takes an antiproton to make a bounce in the side-well in which it is trapped. For typical wells this time is $\sim$1 $\mu$s, which gives an upper limit on the rate of 100 $Vs^{-1}$. This limit will of course also depend on the formation probability, i.e. the antiproton may have to make more passes through the positron plasma in order to form an antihydrogen atom. If so, this will significantly lower the aforementioned upper limit. ALPHA plans to study this technique in 2007. Alternatively, it might be possible to hold the antiprotons in the middle and either perform a so-called inverted mixing (c) or make positronium formed nearby collide with the them (d)[9,10]. The positronium method has so far only produced low numbers of antihydrogen in a proof-of-principle experiment carried out by ATRAP[11] and the inverted-mixing technique will require recycling the positrons which will cool down into the side wells. Both techniques have the ambient temperature as the lower limit for the antihydrogen temperature, a limit method (b) does not necessarily have, as antiprotons can be injected at almost arbitrarily low energy into the positron plasma. Furthermore, in order to keep the antiprotons at the ambient temperature some electrons must be kept with them as ejecting them all is likely to lead to heating.

## 4. Recent Results

ALPHA took its first antiprotons from the CERN AD from September to November 2006 when the apparatus was fully commissioned, apart from the silicon vertex detector. The latter is to facilitate ATHENA-style antiproton annihilation imaging[3,12]. Furthermore, the first important steps towards cold, trapped antihydrogen were taken.

### 4.1. *Particle survival in octupole fields*

As mentioned earlier, ALPHA decided to use an octupole magnet to create the transverse magnetic minimum in order to avoid the limitations on charged particle trapping that a quadrupole could induce.

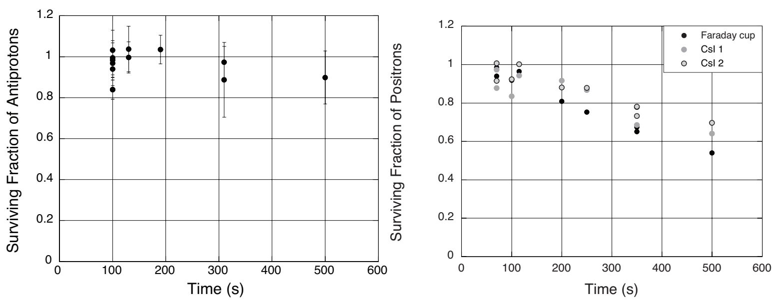


Figure 3. The ratio of the number of antiprotons (positrons) stored in the octupole field to the number stored without the field is plotted versus holding time.

Figure 3 shows the numbers of particles (antiprotons and positrons respectively) as a function of time held trapped in an octupole field of 1.2 T at the inner wall (radius 22.3 mm)[13]. In these conditions, there is no evidence for fast, so-called ballistic loss, which occurs when the particles follow the diverging field-lines induced by the multipole. This effect was observed in the earlier quadrupole measurements[6]. Furthermore, confinement lifetimes in excess of ∼100 sec were observed, which is more than sufficient for antihydrogen formation. The lifetime, and the ballistic loss, depend strongly on the radii and the lengths of the plasmas. The radii of the plasmas used here were unknown, but we note that the antiprotons are captured in an axial field of 3 T, and subsequently transferred to 1 T, causing the cloud to expand by a factor $\sqrt{3}$. The results show that our magnetic trap is compatible with antihydrogen formation using the standard schemes.

### 4.2. *Mixing in low magnetic fields*

A second cause for concern was how the antiproton positron interaction would change when taking place in a field of only 1 T. The reduced magnetic field will cause the synchrotron cooling of the positrons to slow, in addition to the expansion of the antiproton cloud mentioned above. An outstanding issue from ATHENA was concern over the spatial overlap between the positrons and the antiprotons.

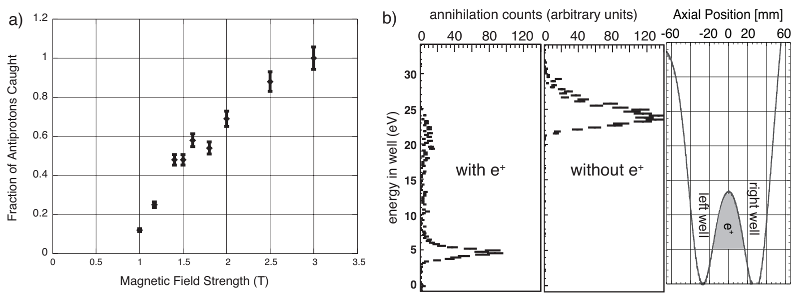


Figure 4. a) Antiproton catching efficiency vs. axial magnetic field. b) Antiproton cooling by positrons in a 1 T axial magnetic field.

Figure 4a shows, first, that it is indeed an advantage to use a 3 T axial field for antiproton catching as the efficiency is about an order of magnitude higher than at 1 T. Secondly, Figure 4b shows antiprotons being cooled by positrons in 1 T, making it likely that antihydrogen will form.

## 5. Summary and Outlook

We have presented the new ALPHA antihydrogen experiment at the CERN Antiproton Decelerator. The ALPHA experiment was successfully commissioned in 2006, where we demonstrated that the neutral (anti)atom trap is compatible with confinement of the antiprotons and positrons used for forming antihydrogen. We also demonstrated positron cooling of antiprotons at the low 1 T axial field necessary for the neutral trap.

In 2007 we plan to make the first attempt at using variations of the standard mixing techniques to produce antihydrogen cold enough to trap. In order to increase our chances of making enough antihydrogen, we are also developing the so-called rotating wall technique[14] in an attempt to sympathetically compress the antiproton plasma to significantly enhance the radial overlap of the positrons and the antiprotons when the two species are merged. Reducing the radial size of both species should also lessen the influence of the octupole magnetic field on the plasma confinement. An increased radial overlap of the two species should significantly increase the likelihood of first trapping of the antihydrogen by 2008.

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