Cold Antihydrogen Experiments and Radial Compression of Antiproton Clouds in the ALPHA Apparatus at CERN

by

Andrea Gutierrez

B.Sc., Université de Montréal, 2008
M.Sc., Université de Montréal, 2010

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

The Faculty of Graduate and Postdoctoral Studies

(Physics)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

January 2016

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Abstract

Antihydrogen is the simplest neutral antimatter atom. Precision comparisons between hydrogen and antihydrogen would provide stringent tests of CPT (charge conjugation/parity transformation/time reversal) invariance and the weak equivalence principle. In the last few years, the ALPHA collaboration has produced, and trapped antihydrogen [1][2]. Most recently, this collaboration has probed antihydrogen’s internal structure by inducing hyperfine transitions in ground state atoms [3]. In this thesis, many details of the cold antihydrogen formation, trapping and measurements of antihydrogen performed in the ALPHA apparatus are presented, with a focus on antiproton cloud compression.

Such compression is an important tool for the formation and trapping of cold antihydrogen, since it allows control of the radial size and density of the antiproton cloud. Compression of non-neutral plasmas can be achieved using a rotating time-varying azimuthal electric field, which has been called rotating wall technique.

In this work, we have observed a new mechanism for compression of a non-neutral plasma, specifically where antiprotons embedded in an electron plasma are compressed by a rotating wall drive at a frequency close to the sum of the axial bounce and rotation frequencies (in a frequency range of 50 – 750 kHz). The radius of the antiproton cloud is reduced by up to a factor of 20 with the smallest radius measured to be ∼ 0.2 mm. We have studied antiproton cloud compression as a function of the rotating wall frequency, the duration of compression, the rotating wall amplitude, the numbers of electrons and antiprotons, the magnetic field and the shape of the potential well.

The frequency range over which compression is evident is compared to the sum of the antiproton bounce frequency and the system’s rotation frequency. It is suggested that bounce resonant transport is a likely explanation for the compression of antiproton clouds in this regime.
Preface

The research presented in this thesis was carried out as a part of the ALPHA collaboration, a group of about 40 physicists from 16 different institutions around the world. The ALPHA experiment is based at CERN near Geneva, Switzerland and as a member of the ALPHA collaboration, I spent a total of nineteen months at CERN. Ten months (2010/2011) were devoted to the experimental measurements of trapped antihydrogen and the spin-flip of antihydrogen.

During the remaining nine months (2012), I worked on the commissioning of the ALPHA-2 apparatus and experiments on antiproton cloud compression.

My most significant contributions are:

Antihydrogen experiments in the ALPHA-1 apparatus:

- I specifically played a large part in preparing data, validating data runs and identifying candidate antihydrogen annihilations used as the dataset in the publications *Resonant quantum transitions in trapped antihydrogen atoms* [3], *Confinement of antihydrogen for 1,000 seconds* [2], *Discriminating between antihydrogen and mirror-trapped antiprotons in a minimum-B trap* [4], *Description and first application of a new technique to measure the gravitational mass of antihydrogen* [5] and *An experimental limit on the charge of antihydrogen* [6].

- As a part of a team, I contributed to the running and maintenance of the ALPHA-1 apparatus, collecting data and performing the online and offline antihydrogen annihilation detection analysis.

- I participated in day-to-day operations such as the maintenance of cryogenic systems (liquid helium and nitrogen), vacuum systems, shift preparation and routine shift work.
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• I participated in the optimization of techniques for trapped charged particles for the production of antihydrogen, such as radial compression (antiproton, electrons, positrons), evaporative cooling (antiprotons, electrons, positrons) and autoresonant excitation (antiprotons) (see chapters 3 and 5).

• I presented *Trapped antihydrogen* and *Resonant quantum transitions in trapped antihydrogen atoms* at the 23rd International Conference on Atomic Physics (ICAP) in Paris (2012).

**ALPHA-2 apparatus commissioning:**

• One of my major contributions was the commissioning and the assembly of the antiproton capture trap, which is intended to be used as an antiproton accumulator that provides antiprotons to the atom trap for antihydrogen studies (see section 2.3.3).

• I was in charge of the cabling and connections of the electrodes of the Penning-Malmberg trap of the antiproton trap and the atom trap (appendix B).

• I coordinated the production of new filter boards for the electrodes.

• I contributed to the setup for the high-voltage electrodes and hardware work with NIM modules for coincidence/logic/triggers to trap antiprotons.

• I participated in the wiring of the superconducting magnets for the ALPHA-2 antihydrogen trap.

• I was in charge of providing hardware pieces for the silicon detector (in collaboration with the ALPHA/TRIUMF group).

• I participated in the assembly of the silicon modules of the ALPHA-2 silicon detector using the facilities at the Liverpool Semiconductor Detector Centre with collaborators at the University of Liverpool.

**Antiproton cloud compression:**
• I was the Run Coordinator for a six-week period of beam-time and led a program to devise a method to improve the antiproton cloud properties.

• During this period of beam-time, we demonstrated cooling of the antiprotons with secondary electrons, which are produced when an antiproton deposits energy into the degrader layer. Usually, cooling is performed using electrons from an electron gun. The electron plasma cools the antiproton cloud by Coulomb collisions while the electrons cool through emission of cyclotron radiation. This new technique improved the cooling efficiency from 60% to 90%, which we believe is a result of the electron and the antiproton plasma having an almost perfect overlap inside the trap, chapter 5.

• I also identified a new regime of compression where the antiproton cloud is radially compressed in a frequency range close to the sum of the axial bounce and rotation frequencies. The antiprotons are embedded in an electron plasma, providing cooling to the antiprotons. I carried out many measurements of the process under different conditions to understand the physics behind the compression and was able to compress the antiproton cloud by up to a factor of 20 (see chapter 6).

• I numerically calculated the distributions of the antiproton axial bounce and rotational frequencies and showed that the compression occurs when the rotating wall frequency is close to the sum of those frequencies, chapter 7.

• I worked with experts in non-neutral plasma theory from UC Berkeley, who developed an ab initio theory to explain my experimental observations.

• I presented my work on antiproton cloud compression at the 6th international conference on Trapped Charged Particles and Fundamental Physics (TCP), where I was awarded best student presentation. I also presented my work at the Winter Nuclear Particle Physics Conference (WNPPC) and in a seminar at the non-neutral plasma physics group at the University of California, San Diego (UCSD).

• A peer-reviewed proceeding of TCP, titled Antiproton cloud compression in the ALPHA ap-
paratus at CERN, has been accepted for publication in the journal Hyperfine Interactions (Springer). For this publication I will be the first and corresponding author.

- I am preparing a peer-reviewed paper reporting the antiproton cloud compression measurements.

Other projects:

- I performed a simulation for a veto detector prototype. My work consisted of optimizing the geometry using three constraints: time of flight of the particles, scintillator surface and distance from the trap, see appendix C.

- I contributed to inclusion of the motion of a dipole in an inhomogeneous magnetic field (as for trapped antihydrogen and ultra cold neutrons), in collaboration with Dr. Peter Gumplinger of the GEANT4 collaboration. This physics is now included in GEANT4. I performed preliminary simulations of trapped antihydrogen and gravity interaction for a prototype apparatus, see appendix D.
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Acknowledgements

Firstly, I would like to thank my supervisor, Makoto Fujiwara, for his endless guidance and support during my PhD, and of course for giving me the opportunity to be part of this incredible journey on antihydrogen research. I would also like to thank my co-supervisor Walter Hardy for sharing his knowledge and experience. I am also grateful to the other members of ALPHA Canada, especially Art Olin and Dave Gill, who were always supportive and helped me a lot to improve my research skills and oral presentations.

I would like to thank all the members of the ALPHA Collaboration, it was amazing to spend time at CERN, work at the experiment and be part of ALPHA-1 and ALPHA-2. I am especially thankful to the people that spent night shifts with me taking data for the antiproton cloud compression: Eoin, Andrey, Phil, Ryan, Chuckman, Eli and Marcelo. I would also like to thank everybody who was interested in the antiproton cloud compression project, it was very motivating. Thanks to Joel, Jonathan, Andrey, Mike, Dirk, and Aled for the helpful discussions about the mechanism of rotating wall compression.

I would also like to thank my family for all their support and my husband, for all his help and love.
Part I

ALPHA apparatus and cold antihydrogen experiments
Chapter 1

Introduction

1.1 Antimatter

Physicist and mathematician Paul Dirac first predicted the existence of the antielectron in 1931 [7], while developing a relativistic quantum theory for the electron. The quantum theory for slow particles had already been established by Schrödinger without taking into account relativistic effects. Dirac obtained four solutions to his equation. Two corresponded to the electron (spin up and spin down), while the other two predicted the existence of a negative energy particle. The origin of such solutions can be seen at a glance in the equation for relativistic energy that carries a square root and allows a positive and a negative solutions:

\[ E = \pm \sqrt{(m^2 c^4 + \vec{p}^2 c^2)}, \] (1.1)

where \( E \) is the energy, \( m \) is the particle’s mass, \( c \) is the speed of light and \( \vec{p} \) is the particle’s momentum.

The obvious first guess was that the proton (the only positive particle known at that time) was the other particle in the solution of Dirac’s equation. But the mass difference between the electron and the proton constituted a major problem, since the Dirac equation imposed an exact symmetry between the particles. The candidacy of the proton as a possible solution was soon ruled out independently by Robert Oppenheimer and Igor Tamm [8]. They argued that it was not in agreement with the stability of the hydrogen atom since the Dirac equation also predicted the annihilation of the two particles when they were close to each other. After this rejection, Dirac introduced the new
concept of a “sea of electrons” to explain how a particle with negative energy in the sea becomes a particle with positive energy leaving a “hole” in the sea. Matter will be stable as long as the “sea of electrons” is not perturbed. This idea was replaced by the Feynman-Stueckelberg interpretation [9] in which, instead of using the concept of negative energy, antiparticles have positive energy running backwards in time. Dirac finally predicted the existence of the antielectron in a paper published in 1931 [7]:

“A hole, if there were one, would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an antielectron.”

It did not take too long for the detection of such an antiparticle. One year later, Carl Anderson detected the antielectron for the first time, while he was doing research on cosmic rays [10]. The antielectron was the first and the only antiparticle to receive its own name [10]:

“From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice and, and it is probably exactly equal to, that of the proton. [...] These particles will be called positrons.”

After the discovery of the positron, the existence of a matter-antimatter system composed of an electron and a positron, analogous to the hydrogen atom, was predicted in 1936 by Stjepan Mohorovičić and was called “electrum” [11]. This system was experimentally observed by Martin Deutsch in 1951 and became known as “positronium” [12].

The first observation of antiprotons occurred in 1955 [13]. Between the discovery of the positron and the antiproton, other particles were discovered. Among them are: the neutron (1932) [14], the muon (1937) [15], the charged pion (1947) [16, 17] and the neutral pion (1950) [18].

The solutions of Dirac’s equation for particles with spin $\frac{1}{2}$ predicted that the proton should have its matching antiparticle, called the antiproton. But to produce antiprotons, very highly energetic protons were needed.
1.2. Antihydrogen

The proposal to construct a proton accelerator needed for antiproton production was presented in 1946 and accepted in 1948 [19]. The Bevatron (Billions of eV Synchrotron) was developed and built at Lawrence Berkeley National Laboratory over several years and finally began operation in January 1954. Protons were accelerated up to energies of 6.5 GeV and the reaction during the collision with a stationary target to produce antiprotons is:

\[ p + p \rightarrow p + p + \bar{p} + p \]  \hspace{1cm} (1.2)

The Bevatron was used for both the production of antiprotons and antineutrons [21].

In 1965, the antideuteron (antiproton and antineutron nucleus) was observed at the Proton Synchrotron at CERN [22] and at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory [23].

The observation of the antiproton was of great importance, since it demonstrated that Dirac equation also applies to other particles of spin \( \frac{1}{2} \). Furthermore, the observation of the antideuteron revealed that the nuclear force is also valid for antimatter.

1.2 Antihydrogen

In 1995, antihydrogen was produced for the first time at CERN [25]. Ten atoms of antihydrogen were produced in flight from the interaction between high energy antiprotons from the Low Energy Antiproton Ring (LEAR) and a xenon jet gas target. When the antiprotons passed near the nucleus, antihydrogen was formed predominantly through the two-photon mechanism [25, 26]:

\[ \bar{p} + Z \rightarrow \bar{p} + 2\gamma + Z \rightarrow \bar{p} + e^+ + e^- + Z \rightarrow \bar{H} + e^- + Z, \]  \hspace{1cm} (1.3)

where the photon-photon interaction produced an electron-positron pair and the positron could be bound to the antiproton, resulting in antihydrogen formation [27].
1.3. Why study antihydrogen?

Later, in 1997, 101 atoms of antihydrogen were observed at Fermilab [28]. Anithydrogen was produced by the interaction of a circulating antiproton beam with a jet of molecular hydrogen gas [29]. Nevertheless, the antihydrogen atoms created in 1995 and 1997 were too energetic to be captured and studied.

In 2002, the ATHENA collaboration produced for the first time about 50,000 low-energy (a few eV) atoms of antihydrogen at CERN [30], followed by the ATRAP collaboration, who produced around 170,000 atoms of antihydrogen [31] [32]. For these measurements, antiprotons and positrons were captured in Penning traps and were made to interact to form antihydrogen.

In 2004, the ATRAP collaboration produced for the first time antihydrogen through laser controlled charge-exchange collisions [33].

In 2010, the ALPHA collaboration produced and trapped 38 cold antihydrogen atoms with energies less than \( \sim 42 \mu \text{eV} \) [1], and trapped hundreds of them later in 2010 and in 2011. The ATRAP collaboration trapped 105 atoms of antihydrogen in 2012 [34].

In 2011, ALPHA published a paper where the atoms were confined for at least 1,000 s [2]. In 2012, state transitions of the antihydrogen spin were induced by causing the atoms to interact with microwave radiation [3].

While the ALPHA and ATRAP experiments produce and confine antihydrogen atoms, the ASACUSA collaboration synthetized cold antihydrogen in a cusp trap in 2010 for the production of a spin polarized antihydrogen beam for precision spectroscopy of the ground state hyperfine splitting of antihydrogen [35]. In 2014, an antihydrogen beam was created by ASACUSA, where 80 atoms of antihydrogen were detected [36].

1.3 Why study antihydrogen?

Neutral antimatter, in the form of antihydrogen, is a promising testbed for tests of the CPT (charge conjugation/parity transformation/time reversal) invariance and the weak equivalence principle [37].
1.3. Why study antihydrogen?

In the 1950’s, explicit proofs of the CPT theorem based on the Lagrangian quantum field theory were derived by G. Lüders, W. Pauli and J.S. Bell [38–40]. The CPT theorem states that under simultaneous transformation of the charge conjugation (C), space reversal or parity (P) and time reversal (T), there is an exact symmetry of any interaction. This means that for each particle, there is an antiparticle with:

- the opposite charge,
- the opposite internal quantum numbers
- the opposite magnetic moment
- the same lifetime
- the same (inertial) mass

CPT invariance has been tested in many sectors, by the comparison between matter and antimatter properties. Among some of the CPT invariance tests are shown in table 1.1. Until now, all the measurements performed are consistent with CPT symmetry.

<table>
<thead>
<tr>
<th>Type of measurement</th>
<th>Quantity measured</th>
<th>Value measured</th>
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<tr>
<td>$e^-$ and $e^+$ mass [41]</td>
<td>$</td>
<td>m_{e^+} - m_{e^-}</td>
</tr>
<tr>
<td>$e^-$ and $e^+$ charge [42]</td>
<td>$</td>
<td>q_{e^+} + q_{e^-}</td>
</tr>
<tr>
<td>$e^-$ and $e^+$ gyromagnetic ratio [43]</td>
<td>$(g_{e^+} - g_{e^-})/g_{\text{average}}$</td>
<td>$(-0.5 \pm 2.1) \times 10^{-12}$</td>
</tr>
<tr>
<td>$p$ and $\bar{p}$ magnetic moment [44]</td>
<td>$(\mu_p - \mu_{\bar{p}})/\mu_{\text{average}}$</td>
<td>$(0 \pm 5) \times 10^{-6}$</td>
</tr>
<tr>
<td>$p$ and $\bar{p}$ mass [45, 46]</td>
<td>$</td>
<td>m_p - m_{\bar{p}}</td>
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<tr>
<td>$p$ and $\bar{p}$ charge [45, 46]</td>
<td>$</td>
<td>q_p - q_{\bar{p}}</td>
</tr>
<tr>
<td>$K^0$ and $\bar{K}^{0}$ mass [47]</td>
<td>$</td>
<td>m_{K^0} - m_{\bar{K}^0}</td>
</tr>
<tr>
<td>$K^0$ and $\bar{K}^{0}$ lifetime [47]</td>
<td>$(\Gamma_{K^0} - \Gamma_{\bar{K}^0})/\Gamma_{\text{average}}$</td>
<td>$(8 \pm 8) \times 10^{-18}$</td>
</tr>
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Table 1.1: Measurements that test CPT invariance. For a more extensive list, see reference [48].

Antihydrogen is the simplest antimatter atomic system, analogous to the hydrogen atom, but composed of an antiproton with an orbiting positron. Its matter partner, hydrogen, is the best understood atom in physics and has been studied to a very high precision. CPT symmetry implies that the eigenenergies of antihydrogen and hydrogen are the same. The measurements of the electronic (positronic) transitions of antihydrogen is a promising measure that would test the CPT invariance.
1.3. Why study antihydrogen?

The most precise measurements performed on hydrogen that are suitable for a comparison between hydrogen and antihydrogen are:

- The 1S–2S electronic transition is one of the best candidate for a high precision measurement in antihydrogen since its natural width is very narrow (1.3 Hz) and it has been measured to 4.2 parts in $10^{15}$ in hydrogen [49]. Future experiments of antihydrogen, including 1S–2S spectroscopy, are discussed in section 3.5.

- The ground state of the hyperfine transition is known to 1.4 parts in $10^{12}$ in hydrogen [50]. Measurements of the hyperfine transition of antihydrogen are discussed in section 3.4.

The Standard Model is a very successful Quantum Field theory that explains the experimental observations of Particles Physics on a microscopy scale. On the other hand, it seems that it is incomplete since it fails to explain the matter-antimatter inbalance, the nature of dark matter and the working of gravity on a microscopic scale. The CPT theorem states that for all Quantum Field theories that incorporate Lorentz invariance, locality and unitarity (of which the Standard Model is one), CPT invariance holds exactly [38, 51, 52]. A detection of CPT violation, even the tiniest amount, would imply that one or more of these conditions do not hold, which in turn would mean that our understanding of the Nature must be reformulated at the most fundamental level.

The CPT theorem does not provide any information about the gravitational acceleration of antihydrogen (antimatter) on the Earth (matter). By CPT invariance, the free fall of antihydrogen on an antimatter Earth (“anti-Earth”), should be the same as hydrogen on the Earth. Also, Einstein’s weak equivalence principle is a foundation stone of general relativity and testing it is of great interest. According to the weak equivalence principle, any object (matter or antimatter) should fall to the Earth at the same rate. Even though antimatter was discovered decades ago, a test with neutral antimatter is more suitable for a direct measurement on the gravity interaction between matter and antimatter. The reason is that the motion of charged (antimatter) particles can be easily distorted by electric fields, among other disruptions [53]. The ALPHA collaboration recently reported a limit on the ratio of the gravitational mass to the inertial mass of antihydrogen [5].
1.4 Thesis overview

During my PhD, I was part of the first experiments on trapped antihydrogen and was also involved in the transition between the ALPHA-1 and the ALPHA-2 apparatus. The ALPHA-1 apparatus was used to trap and make the first measurements on antihydrogen by flipping the spin of the positron. In 2012, the ALPHA collaboration disassembled ALPHA-1 and the new ALPHA-2 apparatus was installed. This thesis is separated into two parts: part I is about cold antihydrogen experiments in ALPHA-1, while part II is about antiproton cloud compression in the antiproton trap of ALPHA-2.

During part I, in chapter 2, I describe the ALPHA-1 and ALPHA-2 apparatus, along with the similarities and differences between them. Furthermore, I explain how charged particles and neutral particles can be trapped in the apparatus and how they are detected. Chapter 3 is dedicated to experiments with antihydrogen. Here, I describe the techniques used by ALPHA to produce and trap antihydrogen. I also present the experimental measurements on trapped antihydrogen, its confinement for 1,000 s and the first experimental measurements on the internal structure of antihydrogen.

During part II, in chapter 4, I first discuss the motivation for compressing antiproton clouds in ALPHA. Then, I give a theoretical overview of the confinement of non-neutral plasmas in a Penning trap and its properties. I describe the rotating wall mechanism, which is used to radially compress non-neutral plasmas. This includes an overview of the theoretical knowledge, which it must be stressed, is as yet incomplete. Then I discuss the way compression is routinely performed in ALPHA for the production of antihydrogen. In chapter 5 I present the experimental set up and procedure used for the measurements of antiproton cloud compression in ALPHA-2. The results for these measurements are presented in chapter 6. The compression process was studied under different conditions (time, frequency, voltage, magnetic field, particle number, etc.) to understand the physics behind the compression. In chapter 7 I discuss possible compression mechanisms that can be responsible for the antiproton cloud compression. Bounce resonant transport seems to be a good candidate and I performed numerical calculations of the axial bounce frequency of the antiprotons and the rotation frequency of the system to compare the sum of these frequencies to the range of frequencies where compression was observed.
Chapter 2

ALPHA Apparatus

2.1 The Antiproton Decelerator experimental hall

The ALPHA apparatus is located at CERN in the Antiproton Decelerator (AD) hall. The AD currently supplies antiprotons to six experiments aiming to study the properties of antimatter. These experiments are:

- **ACE** (Antiproton Cell Experiment): The goal of the experiment is to study the effectiveness and suitability of an antiproton beam for treating cancer [54].

- **AEGIS** (Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy): The goal of the experiment is to produce an antihydrogen beam to make a direct measurement of the Earth’s gravitational acceleration with the use of a moiré deflectometer [55].

- **ALPHA** (Antihydrogen Laser PHysics Apparatus) : The goal of the experiment is to produce, trap and study the properties of antihydrogen such as the 1S-2S transition [56]. ALPHA is a successor of the ATHENA experiment.

- **ASACUSA** (Atomic Spectroscopy And Collisions Using Slow Antiprotons): The goals of the experiment are to produce an antihydrogen beam to study the hyperfine structure of the atom, produce and study antiprotonic helium (where one electron of the helium atom is replaced by an antiproton) and finally, to study the interaction of antiproton beams with matter [57].

- **ATRAP** (Antihydrogen TRAP): The goal of the experiment is to produce, trap and study properties of antihydrogen [58].
2.2. ALPHA-1 and ALPHA-2

- **BASE** (Baryon Antibaryon Symmetry Experiment): The goal of the experiment is to trap antiprotons and measure their magnetic moment [59].

The six experiments are located in the AD hall as shown in figure 2.1. Note that GBAR experiment (Gravitational Behaviour of Antihydrogen at Rest) is under construction and it is not shown in figure 2.1.

![Figure 2.1: Schematic of the AD hall. Image modified from [60]. Antiproton deceleration and cooling is explained in section 2.4.1.](image)

**2.2 ALPHA-1 and ALPHA-2**

The ALPHA experiment is a successor of the ATHENA experiment [61], which produced low energy antihydrogen in 2002, but without trapping it [30]. The ALPHA-1 apparatus was constructed in 2005 and replaced in late 2011 by the ALPHA-2 apparatus. Figure 2.2 illustrates the key components of the ALPHA-1 apparatus, a charged particle trap and an antihydrogen trap, which are
surrounded by the three-layer silicon detector.

![Diagram of ALPHA-1 trapping region](image)

Figure 2.2: ALPHA-1 trapping region. The annihilation detector is the silicon tracking detector which surrounds the magnetic trap and the Penning-Malmberg trap. The 1 Tesla external solenoid is not shown here. Image from [62].

ALPHA-1 and ALPHA-2 have similar characteristics:

- They include Penning-Malmberg traps, which are composed of cylindrical electrodes for axial confinement and an uniform, axial magnetic field radial confinement of charged particles (antiprotons, electrons and positrons).

- The Penning-Malmberg traps are placed inside of an ultra-high vacuum space with a pressure as low as \(10^{-13}\) mbar. The ultra-high vacuum space is surrounded by a liquid helium cryostat so that the walls of the trap can reach temperatures near 4 K.

- Both apparatuses also possess a magnetic atom trap superimposed on the Penning-Malmberg trap. The trap is composed of a transverse octupole and several axial mirror coils. Ground state antihydrogen with energies up to \(\sim 43\, \mu\text{eV}\) (0.5 K) can be confined in the magnetic trap.

- Antihydrogen annihilation is detected by a three-layer cylindrical silicon detector surrounding the apparatus. The vertex of the annihilation can be determined in time and in space.
2.2. ALPHA-1 and ALPHA-2

- ALPHA-2 inherited the ALPHA-1 positron accumulator, which provides positrons to produce antihydrogen. The positron accumulator is briefly described in section 2.5.

During the operation of the ALPHA-1 apparatus, the ALPHA collaboration mastered new techniques to optimize antiproton and positron plasma parameters to produce trappable antihydrogen. Among those techniques are:

- The rotating wall mechanism, which compresses antiproton clouds and positron plasmas resulting in denser groups of particles [63]. For more details, see section 4.3.

- Evaporative cooling, which is used to cool particles to temperatures below those otherwise achievable [64]. For more details, see section 3.2.1.

- The autoresonant injection of antiprotons, used to inject antiprotons into the positron plasma to create antihydrogen [65]. For more details, see section 3.2.2.

Antihydrogen was successfully trapped by ALPHA in the ALPHA-1 apparatus in 2010 [1] and the first experiments on the internal structure of antihydrogen were performed in 2011 [3].

To achieve the ultimate goal of the ALPHA collaboration, precision laser spectroscopy on antihydrogen, laser access is needed. Therefore, despite the fruitful performance of the ALPHA-1 apparatus, it was decided to build a new apparatus (ALPHA-2) to allow laser access, as well other improvements.

The commissioning of the ALPHA-2 apparatus began in 2012. Partial operation initiated in June 2012 and first antihydrogen trapping measurements were performed during 2014. I personally worked on the antiproton capture trap of ALPHA-2 (section 2.3.3) and performed the measurements on antiproton cloud compression for this thesis in late 2012 (chapter 6).

Figure 2.3 and figure 2.4 are photographs of the ALPHA-1 and the ALPHA-2 apparatuses, respectively. In this chapter, we will present the ALPHA-1 and the ALPHA-2 apparatus and how they work, including the details of their similarities and differences.
2.2. ALPHA-1 and ALPHA-2

Figure 2.3: Photograph of the ALPHA-1 apparatus. The grey cylindrical volume is the 1 T external solenoid. The silicon detector and the particle/atom traps are inside it. The antiprotons from the AD are injected from the left. A part of the positron accumulator can be seen on the right hand side of the picture.

Figure 2.4: Photograph of the ALPHA-2 apparatus. The "Carlsberg" grey cylindrical volume is the 1 T external solenoid, the silicon detector and the atom trap with laser access are placed inside it. The green cylindrical volume at the left hand side is the 3 T external solenoid of the antiproton capture trap. The antiprotons arrive from the left side and the positron accumulator is on the right hand side of the apparatus (not shown here). The light blue rectangular pads are the antiproton scintillators.
2.3 Penning-Malmberg traps

Both Penning traps and Penning-Malmberg traps (sometimes called cylindrical Penning traps) consist of a uniform, axial magnetic field for the radial confinement of charged particles and an electric field for the axial confinement. The difference between them is that the original Penning trap had hyperbolic electrodes, creating a quadratic electric potential, while the Penning-Malmberg trap has hollow cylindrical electrodes creating an electric potential with anharmonic contributions. The motion of charged particles in a Penning trap can be analytically described, but the trap presents some limitations since it does not allow an easy access to the trap volume. The Penning-Malmberg trap is much more versatile, since it is possible to stack the hollow cylindrical electrodes. As a result, differently charged particles can be held in the trap, segmented electrodes can provide variable axial electric fields, and there is access at the end of the electrode stack to place diagnostic devices. Even though Penning-Malmberg traps have non-harmonic contributions, the theoretical motion of charged particles in a Penning trap can be considered to be a first approximation of the equations of motion in a Penning-Malmberg trap.

2.3.1 Charged particle motion in a Penning trap/Malmberg-Penning trap

In this section, we discuss the motion of single particles. See section [4.2] for plasmas, for which space charge and collective effects are important.

The classic Penning trap consists of an axial, uniform magnetic field:

\[ \vec{B} = B\hat{z}, \]  \hspace{1cm} (2.1)

and a quadratic electric potential:

\[ \phi(x, y, z) = \frac{V_0}{2d^2} \left( z^2 - \frac{1}{2} x^2 - \frac{1}{2} y^2 \right), \]  \hspace{1cm} (2.2)
where $V_0$ is the applied potential and $d$ is a characteristic trap length [66].

The motion of charged particles in such a trap can be derived from the Lorentz force equation:

$$\frac{m}{dt^2} \vec{r} = q \left( -\nabla \phi + \frac{dr}{dt} \times \vec{B} \right), \quad (2.3)$$

where $\vec{r} = (x, y, z)$. In Cartesian coordinates, the equations of motion can be written as [66]:

$$\frac{d^2 x}{dt^2} - \omega_c \frac{dy}{dt} - \frac{1}{2} \omega_z^2 x = 0, \quad (2.4)$$

$$\frac{d^2 y}{dt^2} + \omega_c \frac{dx}{dt} - \frac{1}{2} \omega_z^2 y = 0, \quad (2.5)$$

and

$$\frac{d^2 z}{dt^2} + \omega_z^2 z = 0, \quad (2.6)$$

where

$$\omega_c = \frac{qB_z}{m} \quad (2.7)$$

is the cyclotron frequency and

$$\omega_z = \sqrt{\frac{qV_0}{md^2}} \quad (2.8)$$

is the axial frequency. From the $\hat{z}$ equation of motion, we can observe that the charged particle undergoes simple harmonic motion. The $\hat{x}$ and $\hat{y}$ equations of motion are coupled, and by making a complex substitution $u = x + iy$, we obtain [66]:

$$\frac{d^2 u}{dt^2} + i\omega_c \frac{du}{dt} - \frac{1}{2} \omega_z^2 u = 0. \quad (2.9)$$

Equation (2.9) has a solution of the form $u = \exp(-i\omega_\pm t)$ with

$$\omega_\pm = \frac{1}{2} \left( \omega_c \pm \sqrt{\omega_c^2 - 2\omega_z^2} \right). \quad (2.10)$$
2.3. Penning-Malmberg traps

<table>
<thead>
<tr>
<th>Particle</th>
<th>$\omega_c/2\pi$</th>
<th>$\omega_z/2\pi$</th>
<th>$\omega_m/2\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron/positron</td>
<td>84 GHz</td>
<td>12 MHz</td>
<td>1 kHz</td>
</tr>
<tr>
<td>Antiproton</td>
<td>46 MHz</td>
<td>300 kHz</td>
<td>1 kHz</td>
</tr>
</tbody>
</table>

Table 2.1: Frequencies of charged particles in the ALPHA-2 antiproton trap in a typical potential well in a 3 T magnetic field.

$\omega_c^2 > 2\omega_z^2$ is required for a confined oscillatory motion in the $\hat{x}$ and $\hat{y}$ directions. The high frequency solution is the modified cyclotron frequency and it is usually known as $\omega'_c$ with $\omega'_c \equiv \omega_+ = \omega_c - \omega_m$, where $\omega_m \equiv \omega_-$. The low frequency solution is the magnetron frequency and can be expressed as $\omega_m \equiv \omega_- = \omega_z^2 / 2\omega'_c$. The three oscillation frequencies of charged particles in a Penning trap are:

$$\omega'_c \approx \omega_c = \frac{qB_z}{m}, \quad (2.11)$$

$$\omega_z = \sqrt{\frac{qV_0}{md^2}}, \quad (2.12)$$

and

$$\omega_m = \frac{\omega_z^2}{2\omega'_c}. \quad (2.13)$$

These oscillation frequencies follow the hierarchy:

$$\omega_c \gg \omega_z \gg \omega_m, \quad (2.14)$$

and figure 2.5 shows an example of the motion of a charged particle in a Penning trap. Typical oscillation frequencies of antiprotons, electrons and positrons in the ALPHA experiment are calculated in table 2.1. The magnetron frequency is the same for all these particles since it does not depend on the mass of the particles.
2.3. Penning-Malmberg traps

Figure 2.5: The charged particle motion in a Penning trap is the superposition of the three oscillatory modes: cyclotron, axial and magnetron oscillation. Image from [67].

2.3.2 ALPHA-1 Penning-Malmberg trap

The ALPHA-1 Penning-Malmberg trap is composed of a stack of thirty-five electrodes immersed in a 1 T solenoidal magnetic field directed along the trap axis. The stack of electrodes is illustrated in figure 2.6. The cylindrical electrodes are made from aluminium and are gold-plated to avoid oxidization. The electrodes have different radii and lengths for specific purposes and they are isolated from each other by synthetic ruby spheres or ceramic spacers (in the case of high voltage electrodes). By applying appropriate voltages to the electrodes, it is possible to create an electric potential that axially confines the charged particles.

The ALPHA-1 trap can be divided into 3 sections:

- **Antiproton trap:** Left hand side section, where the antiprotons are captured from the AD using high voltage electrodes and sympathetically cooled by an electron plasma (see section 2.4). A six-segmented electrode provides the rotating wall field to radially compress the antiproton cloud (see section 4.3). An additional internal solenoid surrounding this region can be energized to give a total magnetic field of 3 T.

- **Positron trap:** The right hand side section is used to prepare positrons plasmas after capturing them from the positron accumulator (see section 2.5). One segmented electrode is used to
2.3. Penning-Malmberg traps

radially compress the positron plasmas.

- **Mixing trap:** The central section is composed of thirteen electrodes where four of them are specially filtered using low noise amplifiers. Antihydrogen production is performed in this section of the trap. The electrodes of the mixing trap are designed to have a larger inner diameter and very small thickness to allow antihydrogen to have the maximum radial motion inside the magnetic trap without annihilating (see section 2.8.1).

The inner diameter of the electrodes of the antiproton trap and the positron trap is 36.6 mm and the inner diameter of the electrodes in the mixing trap is 44.6 mm. Voltages are applied to the electrodes through a circuit board with a passive RC-filter for each electrode. The filter has a low-pass connection for DC voltages, which is the normal operation of the electrodes, and a high-pass connection for fast pulses, which is used for the segmented electrodes (rotating wall electrodes) or electrodes where fast pulses are required (e.g. electrodes with pulses for electron ejection). Normal amplifiers can sustain voltages in a ± 140 V range to a precision of 4 mV, while the specially filtered amplifiers have low-noise voltages in a ± 72 V range within 2 mV. High-voltages (up to ~5 kV) are applied directly to the electrodes without filters.
2.3. Penning-Malmberg traps

Figure 2.6: Diagram of the ALPHA-1 electrode stack. Image from [67]
2.3.3 ALPHA-2 Penning-Malmberg traps

The ALPHA-2 apparatus possesses two disconnected Penning-Malmberg traps. The antiproton capture trap is separated from the mixing trap, so that independent operation can be carried out. The antiproton capture trap is intended to be used as an accumulator of antiprotons, which will make higher numbers of antiprotons available to the mixing trap. Another advantage for the separation of the antiproton capture trap and the mixing trap is that the antiproton degrader will not obstruct the path for laser access.

**ALPHA-2 antiproton capture trap**

The ALPHA-2 Penning-Malmberg antiproton capture trap is composed of a stack of twenty electrodes immersed in a 3 T solenoidal magnetic field, directed along the trap axis. Figure 2.7 illustrates the electrode stack. Two high-voltage electrodes are used to trap antiprotons from the AD (see section 2.4.2) and two segmented electrodes near each end can be used to compress the antiproton clouds. The ideal use of the catching trap is to constantly capture antiprotons and accumulate them at the end of the trap. Then, optimal amounts of antiprotons can be transferred to the mixing trap to mix them with positrons to produce antihydrogen. Therefore, antiprotons would be available ‘on demand’.

The inner diameter of each electrode is 29.6 mm. The electrodes filters and connections are the same as for ALPHA-1 (section 2.3.2). I personally contributed to the cabling and connection of the electrodes. For more details about this work, see appendix B.

**ALPHA-2 mixing trap**

The ALPHA-2 Penning-Malmberg mixing trap is composed of a stack of twenty-seven electrodes immersed in a 1 T solenoidal magnetic field directed along the trap axis. Figure 2.8 illustrates the electrode stack. The trap is similar to the one of ALPHA-1, with three different sections:
2.4. Antiproton production, capture and cooling

As discussed in section 1.1, the antiproton was not observed until 1955, more than twenty years after the discovery of the positron. The reason for such a long wait was that a proton beam of very high energy was needed to produce an antiproton by creating a proton-antiproton pair. As a threshold, the incident proton must carry at least 6 times its mass in energy. The production and the detection of the first antiproton was carried out in the Bevatron at the Lawrence Berkeley National Laboratory.

**Antiproton trap:** Left hand section for antiproton capture, where antiprotons are re-captured from the antiproton trap. It is composed of a stack of seven electrodes with an inner diameter of 29.6 mm, including a rotating wall electrode. An internal solenoid can be energized to provide a maximum axial field of 2 T. This trap section can have an overall axial magnetic field of 3 T.

**Positron trap:** Placed at the right hand side, this trap is similar to the antiproton trap at the opposite end. It is used to capture positrons from the positron accumulator and can also have an overall axial magnetic field of 3 T.

**Mixing trap:** It is the core of the trap, with a total of thirteen electrodes. The inner diameter is larger (44.6 mm), the same as in the ALPHA-1 apparatus.

![Diagram of the ALPHA-2 electrode stack of the antiproton capture trap. The high voltage (HV) electrodes are in red and the six-segmented rotating wall (RW) electrodes are in blue.](image-url)
2.4. Antiproton production, capture and cooling

Laboratory, where protons were accelerated up to energies of 6.5 GeV [13]. The experiment was mainly undertaken by Owen Chamberlain and Emilio Segrè, who shared the Nobel Prize in 1959 for this discovery.

Collision experiments between a proton and an antiproton beam were performed from the 80’s, when the W and Z bosons were discovered at CERN [68, 69] and the top quark was discovered in the Tevatron at Fermilab [70].

Nowadays, antiproton beams are decelerated and stored to make low energy measurements of the properties of antimatter.

2.4.1 The Antiproton Decelerator (AD)

The Antiproton Decelerator (AD) is a unique machine designed to decelerate and cool antiprotons from the giga-electronvolt to the mega-electronvolt energy range [71] and is a successor of LEAR (Low Energy Antiproton Ring) [72]. A pulse of $10^{13}$ protons with a momentum of 26 GeV/c is received from the Proton Synchrotron (PS) at CERN. Before entering the AD, the pulse of protons collides with a target consisting of a thin iridium rod embedded in graphite to create antiprotons [73]. Antiprotons are produced through a proton-proton collision reaction where a proton-antiproton pair is created:

$$ p + p \rightarrow p + p + p + \bar{p}. $$

(2.15)
About $5 \times 10^7$ antiprotons are created through this reaction and about $3 \times 10^7$ antiprotons with a momentum of 3.5 GeV/c are injected into the AD after being focussed and selected with a magnetic horn [74].

The AD decelerates and cools antiprotons using a cycle of $\sim 100$ s, where it alternates deceleration and cooling of the beam [74]. Figure 2.9 shows a typical AD cycle. Radio-frequency (rf) deceleration is applied when the antiproton pulse passes through a rf cavity. Deceleration causes spreading of the beam momentum and an increase in divergence (in accelerator physics terms, an increase of the emittance of the beam). To counteract this effect, two techniques of cooling are employed: stochastic cooling and electrons cooling.

![Figure 2.9: AD cycle during deceleration and cooling [74].](image)

Stochastic cooling is applied to antiprotons with momentum of 3.5 GeV/c and 2 GeV/c. Stochastic cooling is a feedback system that corrects the orbital motion of the particles [75]. A "pick-up" detects the motion of the particles and produces a correction derived from the deviation of the
2.4. Antiproton production, capture and cooling

particles from the ideal trajectories. After a short time, the particles pass through the kicker and an electric field is applied to correct the position and momentum of the particle. The beam needs to circulate many times to concentrate the particles around the chosen orbit. Simon van der Meer shared the 1984 Nobel prize with Carlo Rubbia. Simon van der Meer contributed to the discovery of the W and Z bosons by inventing the technique of stochastic cooling to accumulate intense beams of antiprotons, while Carlo Rubbia led the UA1 experiment that detected the W and Z bosons [68, 69].

Electron cooling is performed by injecting a dense electron beam along the antiproton beam with the same average velocity [76]. The antiproton beam is cooled by the electron beam by Coulomb collisions on a short section of the ring. The electrons are then extracted from the AD ring.

After cooling and deceleration, the antiproton beam is extracted to the experiment. The beam is a \(~200\) ns long bunch, has about \(3 \times 10^7\) particles and a kinetic energy of 5.3 MeV (momentum of 100 MeV/c). The cycle is repeated and the experiments receive a bunch of antiprotons every 100 s.

2.4.2 Antiproton capture and cooling

Antiprotons are extracted from the AD into the experiment with a kinetic energy of 5.3 MeV (see section 2.4.1). Since we are only able to trap antiprotons having an energy less than \(~5\) keV or less, very thin layers of material (typically aluminium) are placed before the trap entrance to cause the antiprotons to lose energy in the material before the capture. This process is called degrading and the layers are called a “degrader”. About \(3 \times 10^7\) antiprotons are extracted from the AD, but only about 0.5% survive the degrading process with an energy less than 5 keV.

In principle, the antiproton capture and cooling mechanism is the same in ALPHA-1 and ALPHA-2 but there are some differences such as the thickness and the degrader material used. In ALPHA-1, the degrader is a 12.5 \(\mu\)m thick stainless steel foil and a 218 \(\mu\)m thick aluminum foil, while in ALPHA-2, there are layers of aluminium and beryllium. A part from the thickness, the degrader material must be compatible with the vacuum requirements and be strong enough to hold at least 1 atm of pressure. More details about antiproton capture in ALPHA-2 is found in section 5.1.1.
After antiprotons traverse the degrader, they are captured in the Penning-Malmberg trap. Figure 2.10 illustrates the antiproton capture procedure. The capture is performed by erecting a high voltage (5 keV) electrode (E13) a few seconds before the extraction of the antiprotons from the AD. E13 is 23 cm away from the degrader and only antiprotons with an energy less than 5 keV are reflected back towards the degrader. A second high voltage electrode (E01), which is placed next to the degrader, is triggered to trap the antiprotons between E01 and E13. The electrode E01 is triggered at a time called the “closing time”, which is the time between the beam extraction signal from the AD and switching the voltage.

Figure 2.10: Schematic illustration of the antiproton capture. The black curve is the resulting potential of the voltage applied to the electrodes. The stack of electrodes in the capture region are shown at the top of the drawing. The two high-voltage electrodes are in yellow and the rotating wall electrode is in indigo. The stack of degraders is represented as one layer next to the first electrode (E01). a) The antiprotons (in red) travel from the AD to be degraded before entering into the capture region while the voltage in E13 is already raised. b) A fraction of the antiprotons traverse the material and only the particles with an energy below 5 keV are reflected by the potential at E13. c) E01 is erected to trap the remaining antiprotons.
2.4. Antiproton production, capture and cooling

We typically load electrons from an electron gun (see section 2.6) before the antiproton capture procedure. The electrons are used to sympathetically cool the antiprotons through Coulomb collisions [77], since the electrons are quickly cooled in a strong magnetic field through cyclotron radiation. The electrons cool exponentially with a time constant of $\sim 0.43$ s in a 3 T magnetic field [63, 78]. Figure 2.11 shows the antiproton cooling schematically. The antiprotons and electrons are usually allowed to interact for 80 s. A large fraction of antiprotons are cooled and migrate to the low energy well. After the interaction time, one high voltage electrode is changed to a lower voltage so hot antiprotons are able to escape.

![Figure 2.11](image)

Figure 2.11: Schematic illustration of antiproton cooling. The black curve is the confining potential. a) The electrons (in blue) are loaded in advance and the antiprotons (in red) are captured by the high voltage potential as already shown in figure 2.10. b) The antiprotons and electrons are allowed to interact (usually about 80 s) and as a result, a large fraction of the antiprotons are cooled. c) The high voltage electrode on the left hand side is switched to a lower voltage so remaining hot antiprotons are allowed to escape (red arrow).

The antiproton cooling is a non-exponential process which accelerates as the antiprotons cool [77]. The electron plasma is limited in how fast it can dissipate the energy from the antiprotons, which depends on the ratio of the numbers of electrons to antiprotons. A low number of electrons per
antiprotons limits the cooling process by an increase of the electron plasma temperature, according to the demonstration in Ref. [77]. We have observed that the number of cooled antiprotons also depends on the interaction time. The efficiency of antiproton cooling as a function of the interaction time is shown in figure 2.12. The efficiency of antiproton cooling is the ratio of the number of cooled antiprotons (antiprotons that do not escape after high voltage electrode is switched to a lower voltage) to the number of captured antiprotons. We observed that at least several tens of seconds is needed to obtain a cooling efficiency higher than 50%.

![Figure 2.12: Antiproton cooling efficiency as a function of the cooling time. The cooling time is the time for which antiprotons and electrons are allowed to interact.](image)

The antiproton cooling efficiency depends on the cooling time but also on the radial overlap between the antiproton cloud and the electron plasma. If the electron plasma is radially smaller than the antiproton cloud, the cooling is less efficient because a fraction of the antiprotons can not interact with the electrons. It is possible to use the rotating wall technique to compress or expand the radius of the electron plasma to match the radius of the antiproton cloud (see the rotating wall technique in section 4.3). Figure 2.13 shows the effect on the antiproton cooling efficiency, when varying the electron plasma radius before the antiproton capture, as well as the resulting antiproton radius. The cooling efficiency increases as the electron plasma radius is increased. It is estimated that the initial radius of the antiproton cloud is $\sim 4$ mm [63].
2.4. Antiproton production, capture and cooling

Figure 2.13: Top: Antiproton cloud radius as a function of the radius of the electron plasma used to cool antiprotons. Symbols correspond to trials with different total number of electrons ($1 \times 10^8$ – $1.65 \times 10^8$ electrons). Open symbols represent radii measured directly from MCP images and radii from red solid symbols are calculated from central intensity from the image on the MCP. For these plasmas, it is not possible to accurately measure the radius so it is assumed that the electron plasma radial profiles are self similar and infer the plasma radius from the peak density. The inset figure shows this approach. Bottom: Antiproton cooling efficiency as a function of the electron plasma radius. The cooling time is 30 s. Image from [63].
2.5. Positron Accumulator

In ALPHA-2, instead of using electrons from the electron gun, we used the secondary electrons produced when the antiprotons pass through the degrader. Section 5.1.2 has more details about this procedure.

2.5 Positron Accumulator

The ALPHA-2 positron accumulator is the same as the one used in ALPHA-1 and ATHENA. A new 1.42 GBq $^{22}$Na radioactive source was installed in 2013 and the source region was rebuilt, but the core remains the same.

Positrons are spontaneously generated in $\beta^+$ radioactive decay, in which a positron is emitted. ALPHA uses a $^{22}$Na source which has a half-life of 2.6 years and has a positron yield of 90.4%. The $^{22}$Na decay reactions in which the positrons are produced are:

\[
^{22}_{11}\text{Na} \rightarrow ^{22}_{11}\text{Ne}^* + e^+ + \nu_e
\]

\[
^{22}_{11}\text{Ne}^* \rightarrow ^{22}_{11}\text{Ne} + \gamma
\]

Shortly after the $^{22}$Na decay, a 1.27 MeV $\gamma$ is released from the $^{22}$Ne as it relaxes to the ground state.

The positron accumulator is a Surko-type positron accumulator and the techniques used to accumulate positrons are pioneered by the positron research group at the University of California, San Diego [79]. See Ref. [80] for a comprehensive review of Surko-type positron accumulators and their applications. Figure 2.14 shows a schematic of the positron accumulator.

The positron accumulation is described in detail in Ref. [81], and here we summarize its stages:

1. The emitted positrons are directed into a cold neon layer (called the “moderator”), where the positrons thermalize and diffuse through the material.

2. About 0.4% of the positrons escape the moderator with a kinetic energy of about 50 eV and are guided by a magnetic field into the positron trapping region. There, a 0.15 T axial,
2.5. **Positron Accumulator**

Figure 2.14: On top, positron accumulator schematic. The source is positioned at the left and the positrons are accumulated as a plasma in the right side (green ellipse). The positrons are eventually extracted to the right, where they are trapped in the mixing trap for antihydrogen production. On the bottom, on-axis trapping electric potential as a function of the position, showing the pressure. It shows the cooling stages for the positrons. Image adapted from [67].

- A uniform magnetic field provides radial confinement and a Penning-Malmberg trap provides axial confinement.

3. The positrons lose energy by electronic excitation of a nitrogen buffer gas. The gas inlet is placed at the source side of the accumulator, where the electrodes have the smallest diameter. The diameter increases the further from the source, creating a pressure gradient. The positrons are cooled and trapped in the region with the lowest pressure. The rotating wall technique is applied to radially confine the positron plasma. This mode of accumulation lasts for about 200 s and about $1 \times 10^8$ positrons are accumulated.

4. After the accumulation, two high-rate cryo-pumps are used to remove the nitrogen gas and improve the vacuum from $1 \times 10^{-5}$ to $1 \times 10^{-9}$ mbar in about 40 s. Then, a valve between the accumulator and the atom trap is opened and the positrons are transferred and recaptured in the Penning-Malmberg trap of the atom trap. Up to 80% of the positrons survive this procedure.
2.6 Movable stick

The stick is composed of different devices that can be used according to requirements of the experiment. The components are:

- **Electron source:** Electrons are used in ALPHA to cool antiprotons because of their short cooling time (about 0.4 s in 3 T) in a strong magnetic field through cyclotron radiation [78]. Electrons are produced by thermionic emission from a barium-oxide filament, which is placed inside an electron gun [82]. The resulting electron beam is guided by the magnetic field to the antiproton capture trap, where electrons are trapped by the axial potentials.

- **Micro-Channel Plate (MCP) detector system:** This consists of an assembly of a phosphor screen, an MCP and a mirror, which are used to record a transverse image of the particles clouds/plasmas. For more details, refer to section 2.7.2.

- **Microwave horn:** In ALPHA-1, the horn antenna injects microwave radiation to the centre of the trap. It was used to perform microwave experiments on antihydrogen. For more details on the measurements, refer to section 3.4.

- **Microwave mirror:** Another way to inject microwaves is to place a horn outside the apparatus in front of a window and to direct the microwaves inside the trap through the microwave mirror. This technique was used to measure the magnetic field by determining the cyclotron frequency of an electron plasma.

- **Pass-through:** A cylindrical electrode allowing the passage of particles to the atom trap.

The movable stick is the same in ALPHA-1 and in ALPHA-2 antiproton capture trap. Figure 2.15 shows the exterior of the movable stick in the ALPHA-2 antiproton capture trap. The stick is placed at one side of the antiproton capture trap and can be moved along its vertical axis. The atom trap has another movable stick, but it is not shown here.
2.7 Charged particle detection and diagnostic devices

ALPHA uses various types of charged particle detectors. They can measure the number of particles and parameters of the plasmas such as the density and the transverse size. Some can also be used to measure the temperature of charged particles.

2.7.1 Faraday Cup

The Faraday cup (FC) consists of a thin layer of conducting material. When the electrons or positrons are dumped to the FC, the charge of the particles induces a voltage and with a suitable amplifier, the voltage can be measured. Since the capacitance of the conductor can be measured, the amount of charge collected can be calculated, giving the number of particles. At least a few hundred thousand particles is needed to get a measurement above the noise level.

Figure 2.16 shows an example of the resulting traces from the FC. A background, probably coming from an electrical coupling with the other electrodes, is subtracted. The resulting peak gives the electron number.
2.7. Charged particle detection and diagnostic devices

Figure 2.16: Example of the FC traces. The measured FC trace is in yellow and the background trace is in green. The trace giving the electron number is in red ($\sim 5 \times 10^6$ electrons).

The antiproton capture trap in ALPHA-2 has a Faraday cup placed next to the first electrode. This FC is also used as a degrader (discussed in section 5.1.1). The FC is a 165 $\mu$m thick beryllium layer.

The antiproton number is not measured with the FC because antiprotons ionize and annihilate in the conductor producing a large number of secondary particles, which carry away charge. Hence the measurement is not reliable and plastic scintillators are used instead to detect radiation from antiproton annihilations (see section 2.7.3).

2.7.2 MCP/phosphor/CCD detector assembly

The microchannel plate (MCP) detector system is a two dimensional sensor that amplifies the detected signal with high efficiency and high speed [83]. It consists of a plate of a semiconducting material with an hexagonal array of miniature electron multipliers placed parallel to each other. Since the channels’ axes have a small tilt (usually about 8 degrees) with the direction of incident particle, when the particle strikes into the front surface of the MCP, it impacts the inner surface of one of the microchannels. Such impact creates a cascade of secondary electrons which are accelerated to the rear surface of the MCP. The cascade is proportional to the incident number of particles
2.7. Charged particle detection and diagnostic devices

and is directed onto a phosphor screen. The cascade of electrons excites the phosphor atoms, which deexcites by emitting light. The light is redirected into a charged coupled device (CCD) camera by a 45° mirror [85], which produces an image of the charge distribution. A schematic is shown in figure 2.17.

![Figure 2.17: Schematic of the MCP, phosphor screen, 45° mirror and CCD assembly. The incident particle can be an antiproton, electron or positron. Objects are not drawn to scale.](image)

The MCP/phosphor/CCD assembly is used in ALPHA to obtain information about the density and the radial size of the antiproton, positron and electron plasmas. In ALPHA, this detector assembly is placed in the movable stick (see 2.6).

The MCP in ALPHA is a E050VP47 device manufactured by El-Mul Technologies [84]. The diameter of each channel is 10 μm with 12 μm centre-to-centre spacing. The active diameter of the MCP is 43.5 mm. A metallic coating deposited on the front and at the rear surfaces of the MCP allows electrical contact, where the particles are accelerated by the potential difference (typically hundreds...
of volts). A minimum gain of $1 \times 10^4$ is achieved at a bias voltage of 1.2 kV.

### 2.7.3 Scintillators

Antiprotons are dumped into a material (typically the degrader layer) so their annihilation can be detected. Each annihilation produces an average of three charged pions [86], which can be detected with plastic scintillators. When charged particles pass through plastic scintillators, they electronically excite the atoms/molecules, which release light when they relax. The scintillators are coupled to a photomultiplier tube (PMT). The light is guided, then collected by a photocathode, where a primary electron is emitted due to the photoelectric effect. The primary electron is focused into the electron multiplier section and accelerated through a series of dynodes creating secondary electron emission. The final cascade is converted into an electronic signal.

In ALPHA, 40 cm wide by 60 cm high scintillator pads are placed vertically, normal to the floor, which minimizes their sensitivity to the cosmic rays. They are assembled by pairs and there is one pair on each side of the trap, about 60 cm from the trap and centred at the axial position of the degrader. Figure 2.18 shows a photograph of the setup. If both of the scintillators in a pair detect a signal passing a voltage threshold in a defined time window (i.e. in “coincidence”), it is considered a “count”. Since the scintillators cover a relatively small solid angle, a GEANT4 simulation is used to translate the “counts” into the total number of dumped antiprotons. Taking the geometry into account, the detection efficiency for antiproton annihilation on the degrader is $\sim 20\%$. The background rate from cosmic rays is $40 \text{s}^{-1}$.

### 2.7.4 Plasma temperature diagnostics

The temperatures of the antiproton and positron plasmas are very important since they affect the antihydrogen production and trapping rate.

Since the trapped plasma/cloud is assumed to be in thermal equilibrium, the kinetic energy distribution parallel to the axial magnetic field is expected to follow a one-dimensional Maxwell-Boltzmann
2.7. Charged particle detection and diagnostic devices

Figure 2.18: Picture of the ALPHA-2 apparatus. Red lines indicates the position of a pair of scintillators/PMT assemblies at one side of the antiproton capture trap. The scintillator assembly is placed at about 60 cm from the trap. Another pair of detectors is symmetrically placed at the other side of the apparatus (not shown in the picture). The annihilation of the antiprotons occurs at the degrader, placed inside the trap (approximated position is indicated by the yellow rectangle).
distribution \[87\]:

\[ f(E_\parallel) \propto \exp \left( -\frac{E_\parallel}{k_B T} \right), \]  

(2.17)

where \( E_\parallel \) is the parallel energy, \( k_B \) is Boltzmann’s constant and \( T \) is the temperature. By slowly lowering the confining axial well potential at one side, it is possible to measure the parallel energy distribution of the particles. As particles escape from the well, they are detected. By knowing the relation between time and the escaping potential, it is possible to build up the parallel energy distribution \( f(E_\parallel) \) and to extract the temperature using equation \[2.17\]:

\[ \frac{\ln f(E_\parallel)}{dE_\parallel} \approx -\frac{1}{k_B T}. \]  

(2.18)

In ALPHA we are able to measure the temperature of the antiprotons using the scintillators (see section \[2.7.3\]) and the temperature of the positrons using the MCP/Phosphor assembly (see section \[2.7.2\]).

Figure \[2.19\] shows examples of temperature measurements for antiprotons. The temperature is extracted by fitting a straight line on a semi-log plot. The non-exponential behaviour of low energy particles escaping from the well is due to the space charge of the plasma that changes the height of the potential. Corrections for this effect are discussed in Ref. \[88\].

### 2.8 Atom traps

In ALPHA, Penning-Malmberg traps are used to confine antiprotons, electrons and positrons. When neutral antihydrogen is synthesized, a neutral atom trap is superimposed on the Penning-Malmberg trap and is used to confine the antihydrogen atoms.

In this section, we will discuss how antihydrogen is confined in a magnetic trap. We will also present the ALPHA-1 atom trap, where antihydrogen was trapped for the first time, as well as the ALPHA-2 atom trap, where laser spectroscopy of antihydrogen will be performed.
2.8. Atom traps

Figure 2.19: Integrated number of antiproton loss as a function of the well depth. The well depth is ramped down, so time flows from right to left. Each set of points represents one measurement. The calculated temperatures are: 1040 K (A), 325 K (B), 57 K (C), 23 K (D), 19 K (E) and 9 K (F). Image from [64].

2.8.1 Antihydrogen motion in a magnetic field minimum trap

Antihydrogen atoms can be trapped by using the interaction of the atom’s magnetic dipole moment with an inhomogenous magnetic field. The antihydrogen atom has an intrinsic magnetic dipole moment $\vec{\mu}$ due to the spins of the antiproton and the positron and the orbital motion of the positron. Since the magnetic dipole moment is, to first approximation, inversely proportional to the mass and $m_e/m_p = 5.4 \times 10^{-4}$, the antihydrogen magnetic dipole moment can be approximated as the positron’s dipole magnetic moment. If the antihydrogen atom is in its ground state, the orbital angular momentum is zero, hence only the positron’s spin angular momentum contributes to the atom’s magnetic dipole moment.

The magnetic potential energy of the antihydrogen magnetic dipole in an inhomogenous magnetic field can be written as

$$ U = -\vec{\mu} \cdot \vec{B}, \quad (2.19) $$
2.8. Atom traps

where $\vec{\mu}$ is the magnetic moment of antihydrogen and $\vec{B}$ is the magnetic field.

Assuming that the rate of change of the direction of the magnetic field at the particle’s position is slow compared to the Larmor frequency (precession of the magnetic moment of the atom around the external magnetic field), the spin follows adiabatically the direction of $\vec{B}$. In a strong magnetic field, the spins of the antiproton and the positron are essentially uncoupled and, there are two stable configurations, where $\vec{\mu}$ and $\vec{B}$ are parallel or antiparallel to each other. For an atom in the ground state, the two possible magnetic potential energies are

$$U = \pm \mu_B B,$$  \hspace{1cm} (2.20)

where $\mu_B$ is the Bohr magnetron. These two magnetic potential energies correspond to two cases:

- **Low field seeking atom**: The magnetic dipole moment of the particle is antiparallel to the magnetic field. Such particles are attracted to regions with a low magnetic field strength.

- **High field seeking atom**: The magnetic dipole moment of the particle is parallel to the magnetic field. These particles are attracted to regions with a high magnetic field strength.

To create a static trap, an extremum (maximum or minimum) magnetic field is required. It is only possible to trap low field seeking particles by constructing a three dimensional static magnetic field minimum. High field seeking particles cannot be trapped because it is impossible to create a static magnetic field maximum in free space [89].

For stable trapping, the kinetic energy of the atom must be lower than the depth of the magnetic potential well and, as already mentioned, the magnetic dipole moment must move adiabatically in the magnetic field. In a region where the magnetic field is too small, the spin cannot follow the changing direction of the magnetic field and can flip its orientation relative to the magnetic field, escaping from the trap. This loss of particles from the trap is called Majorana losses [90]. Magnetic traps are usually constructed so that the minimum magnetic field is large enough to prevent such losses.
The well depth is proportional to the difference between the minimum magnetic field magnitude and the maximum at the trap boundary and can be expressed as a potential energy,

\[ k_B T = \mu (B - B_0), \]  

(2.21)

where for ground state of antihydrogen, \( \mu = \mu_B \).

### 2.8.2 ALPHA-1 atom trap

The ALPHA-1 atom trap consists of three superconducting magnets and one external solenoid. Two mirror coils provide axial confinement, while an octupole coil provides radial confinement of antihydrogen. The external solenoid (1 T) provides radial confinement for antiprotons and positrons before synthesizing antihydrogen and provides the minimum magnetic field of the atom trap.

The two mirror coils are co-axially positioned at each side of the trap at about 28 cm apart. When the two mirror coils are energized, they create an axial magnetic field minimum, as shown in figure 2.20. The coils operate at a current of 600 A, each producing a maximum longitudinal field of 1.2 T.

![Figure 2.20](image)

Figure 2.20: On-axis magnetic field produced by the two mirror coils of the ALPHA-1 atom trap, superimposed on 1 T external solenoid. Image from [67].

A multipolar field produces the radial confinement well to trap antihydrogen. The simplest magnetic
2.8. Atom traps

Trap is the Ioffe-Pritchard, which uses a quadrupole magnetic field [91]. In this experiment, where the antiproton and positron plasmas must remain radially confined, the order of the multipolar field was carefully chosen because a transverse magnetic field breaks the Penning-Malmberg trap cylindrical symmetry [92]. The octupole coil was chosen because its magnetic field close to the axis is lower than a quadrupole or a sextupole magnetic field, as shown in figure 2.21. This characteristic minimizes the transverse-field effects on charged particles, and storage of antiproton and positron plasmas is possible without significant loss of the particles [93]. When trapping antihydrogen, it is very important to maximize the well depth so antihydrogen atoms do not annihilate on the inner surface of the electrode. Higher order multipoles have a steep gradient near the trap boundary, so that a significant amount of trap depth can be lost in the material of the vacuum system and the electrodes. For this reason, and the difficulties in manufacture, multipoles of higher order than an octupole were not used. To increase the well depth, the electrodes in this region of the apparatus (as shown in fig. 2.6) have larger inner radius (22.2 mm) and are very thin (0.5 mm).

![Transverse magnetic field as a function of radius for a quadrupole, a sextuple and an octupole. We can observe by looking at the vertical line that the octupole produces the shallowest trap depth. The vertical line represents the radius of the inner electrode. Image from [67].](image)

**Figure 2.21:** Transverse magnetic field as a function of radius for a quadrupole, a sextuple and an octupole. We can observe by looking at the vertical line that the octupole produces the shallowest trap depth. The vertical line represents the radius of the inner electrode. Image from [67].

Figure 2.22 shows a picture of the first layer of the octupole windings. There is a total of eight
2.8. Atom traps

layers, which are needed to generate a strong magnetic field. A serpentine pattern was used to wind the octupole, rather than a racetrack pattern, because this cancels out the axial fields by azimuthally staggering each layer by 45° with respect to each other [94]. The octupole is operated with a current of 900 A producing 1.55 T at the inner radius of the electrodes. The mirror coils and the octupole are wound directly onto the vacuum vessel wall as shown in figure 2.22, where they are in direct contact with a liquid helium bath at a temperature of 4.2 K. The contact of the vacuum vessel wall with the liquid helium also acts as a cryopump, which allows the volume in the trap chamber to reach very low pressures (see section 2.11).

Figure 2.22: Photograph of the first layer of the octupole windings for ALPHA-1. Image from [56]

The minimum well depth is given by the difference between the radial magnetic field magnitude at the electrode wall and minimum magnetic field magnitude at the centre of the well (since our mirror coils can provide stronger fields than the octupole). The former is the sum in quadrature of the octupole’s magnetic field at the electrode wall $B_w$ and the axial solenoidal field $B_z$, which are orthogonal to each other. The latter is just the axial solenoidal field and the mirror coils. The
difference between the magnetic field magnitude is written as

\[ \Delta B = \sqrt{B_z^2 + B_w^2} - B_z. \] (2.22)

To maximize the probability of trapping antihydrogen, the well depth needs to be as large as possible. For that reason, antihydrogen production takes place in the 1 T region of the trap.

The trap depth is usually given in units of kelvin, which can be converted to kinetic energy by multiplying by the Boltzmann constant \( k_B \). For the currents given above, the trap depth is about 0.5 K, so that antihydrogen with a kinetic energy equal to or less than about 0.5 K \( \times k_B = 44 \mu\text{eV} \) is trapped, while antihydrogen with higher energies will eventually escape from the trap.

Figure 2.23 shows the total 3-D magnetic field minimum antihydrogen trap of ALPHA-1, where the mirror coil, the octupole magnet and the external solenoid have been superimposed.

![Magnetic field strength of the ALPHA-1 antihydrogen trap](image)

Figure 2.23: The magnetic field strength of the ALPHA-1 antihydrogen trap. The octupole, two axial mirror coils and external solenoid are superimposed.
2.8. Atom traps

Quench protection

The magnets are made from niobium-titanium (NbTi) wires embedded in a copper matrix. NbTi is a type II superconductor alloy, with a critical temperature of 9.2 K [95]. The copper matrix gives mechanical stability and in the event of a quench (that is, loss of superconducting state), the copper provides a path for the large currents. If the superconducting wires alone carry the current during a quench, Joule heating (heat generated by the passage of an electric current through a conductor) would lead to too high temperatures, damaging the coils.

A quench protection system (QPS) is required to protect the magnets. The QPS safely extracts the current when a quench is identified. A quench occurs when a region of the superconducting material becomes resistive and heats other parts of the superconductor above the critical temperature, creating a chain reaction. This situation can be avoided by monitoring the voltage across several regions of the magnet using a system controlled by a Field Programmable Gate Array (FPGA). If an abnormally high voltage, indicating a quench, is detected, a high current insulated-gate bipolar transistor (IGBT) is used to safely extract the current through a resistor network, where the energy is dissipated as heat.

This system was designed so it could quickly shutdown the magnetic trap to detect antihydrogen. A quick shutdown reduces the background due to noise counts and cosmic rays. The magnets have extremely low inductances, which allows the current to be removed in a very short time. The magnetic fields decay with a time constant of 9 ms, as shown in figure 2.24. Antihydrogen detection is performed in a 30 ms time window from the beginning of the shutdown.

2.8.3 ALPHA-2 atom trap

The ALPHA-2 atom trap is composed of nine superconducting magnets. The octupole and the mirror coils have the same design as the magnets in ALPHA-1, and they operate at the same currents and produce the same magnetic fields.
2.8. Atom traps

Figure 2.24: Current decay of the octupole and mirror coils as a function of time. 0 ms is the time when the magnets begin to be ramped down. Image from [67].

- **One octuple**: As in ALPHA-1, an octupole magnetic field is used to provide radial confinement of antihydrogen atoms. The octupole produces a magnetic field of 1.55 T at a current of 900 A.

- **Five mirror coils** provide the axial confinement of antihydrogen atoms. The mirror coils can be independently energized, so different axial lengths and well depths can be obtained during the experiments. Each mirror coil can be energized up to 600 A, producing a maximum axial field of 1.2 T.

- **External solenoid**: Provides the minimum magnetic field of the trap, while keeping the charged particles (antiprotons and positrons) radially confined during antihydrogen production. The nominal magnetic field is 1 T. The solenoid is new for ALPHA-2 and is designed to be capable of quickly changing its field.

- **Two solenoids at each end of the trap**: These solenoids are energized at a current of 250 A to give a field of 2 T during the manipulation of charged particles, to improve the radial confinement, and reduce the cooling time. They are de-energized before synthesizing antihydrogen.
The ALPHA-2 magnetic trap is more versatile, allowing the length of the well to be changed and the field profile to be fine-tuned. The magnetic trap has the same quench protection system, providing a safe mechanism to de-energize the superconducting magnets during a quench, as already described in section 2.8.2.

2.9 Laser access in ALPHA-2

ALPHA-2 has 8 windows for optical access to the antihydrogen trap. There are 4 on each side of the trap and have a direct path to the centre of the trap. The laser accesses will be used for experiments on 1S–2S two photon spectroscopy, Lyman-α spectroscopy among other experiments. A cavity to enhance the laser power is built inside the apparatus. More details about future experiments on antihydrogen are described in section 3.5.

2.10 Antihydrogen detection

In this section, we present the ALPHA-1 silicon tracking detector which was used during the experiments with trapped antihydrogen during 2010 and 2011. The detection principle remains the same for the ALPHA-1 and ALPHA-2 silicon tracking detectors but the geometry of the ALPHA-2 detector is slightly different, occupying a larger volume and including more silicon modules. We first discuss antiproton annihilation, which is the main process to be detected when studying antihydrogen, and then we discuss how to discriminate antihydrogen from cosmic rays.

2.10.1 Antiproton annihilation

Antiprotons are slowed in matter just like protons, following the Bethe-Block formula but with a smaller energy transfer to electrons (more details in appendix A). When an antiproton stops in matter and comes close to a nucleus, it annihilates. The simplest way to understand the annihilation of an antiproton with a proton or a neutron is the rearrangement of the quarks. Figure 2.25 shows
2.10. Antihydrogen detection

an example of the quarks’ rearrangement into three pions when the antiproton annihilates with a proton.

![Diagram of antiproton annihilation](image)

Figure 2.25: Example of the simplest picture to understand antiproton annihilation.

Proton-antiproton annihilation (at rest), usually results in the production of a combination of pions ($\pi^+, \pi^-, \pi^0$), ranging from two to eight in number, with an average of five pions. An average of three charged pions and two neutral pions are produced and the multiplicity of pions is shown in figure 2.26 [100–102].

The pions are created directly or through the decay of mesonic resonances. When five pions are produced, each one has a kinetic energy of about 236 MeV [96]. For an isolated proton-antiproton annihilation at rest, these pions will directly escape at different angles set by momentum conservation. If the annihilation occurs in a nucleus, a pion could enter the nucleus and be absorbed [97], have a charge-exchange process [98] or cause the fragmentation of the nucleus itself [99]. Because of these different possible reactions, proton-antiproton and neutron-antiproton annihilation are not easy to distinguish. Pions, able to escape from the nucleus, will fly away from the annihilation point.

The lifetime of pions is short. The lifetime of charged pions is $2.6 \times 10^{-8}$ s, while the lifetime of neutral pions is $8.4 \times 10^{-17}$ s [103]. The lifetime of charged pions is long enough to pass through the detector, but neutral pions will decay into gamma rays, which most often produce electron-positron pairs [102].
2.10. Antihydrogen detection

In ALPHA, when antihydrogen is released from the magnetic trap, it annihilates on the surface of the electrodes. It could also annihilate with background gases inside the trap. In antihydrogen annihilation, the positron can annihilate with an electron by producing two or three photons, while the antiproton annihilation is more complicated. The electrodes are made from gold-plated aluminium, so an antiproton annihilation with a heavy nucleus must be considered, as well as the fact that the electrodes may be covered by frozen gas molecules.

2.10.2 ALPHA-1 silicon tracking detector

The detector is composed of 60 double sided silicon microstrip modules arranged in three concentric layers co-axially placed around the antihydrogen trapping region, between the cryostat and the external solenoid.

Each module, called a hybrid, consists of a semiconductor microstrip detector and the front end electronics. One module is composed of two 6 cm × 23 cm silicon wafers, one on the front and one on the rear of a Printed Circuit-Board (PCB). Each side reads out 256 signal strips, which are placed
2.10. Antihydrogen detection

orthogonally to the other side, giving positional information when a particle deposits energy.

The detector is symmetrically divided into two axial sections, as shown in figure 2.27. Each section consists of 30 modules, arranged into three concentric layers around the trap. The total axial length of the detector is 46 cm, providing a solid angle coverage of \( \sim 72\% \) of tracks originated at the axial centre of the trap, travelling in a straight line and interacting at least one with the active area of each layer [104].

![Figure 2.27: ALPHA-2 silicon tracking detector assembly at the Liverpool semiconductor detector centre at the University of Liverpool in July 2012 [105].](image)

When a charged particle passes through the silicon area, the signals from the orthogonally positioned strips give information about the position of the particle. If the signal is larger than a threshold, the point of intersection of the two signals is called a "hit". As already mentioned, an antiproton annihilation produces on average about three charged pions and two neutral pions. Between the surface of the electrodes and the detector layers, there are several materials that could scatter and absorb the particles. The pions resulting from the annihilation are so-called minimum ionizing particles (MIP), meaning that the mean energy loss rate is close to the minimum and most of the MIPs can at least travel through the apparatus before being stopped.

The passage of the charged particles produced from the annihilation triggers a hit on each layer of the detector. Given this information and the geometry of the detector inside the apparatus, the annihilation vertex is reconstructed. The detector is surrounded by a 1 T external solenoid that bends the path of the charged pions. For this reason, the trajectories of the particles are reconstructed using
2.10. Antihydrogen detection

helices instead of straight lines. Figure 2.28 illustrates an example of an antiproton annihilation inside the apparatus. For a detailed description of hardware and software used in antihydrogen detection, see Ref. [102]. Using Monte Carlo simulations, the resolution of the reconstructed vertex position is estimated to be $(0.67 \pm 0.04)$ cm in the axial direction, $(0.68 \pm 0.04)$ cm in the radial direction and $(0.82 \pm 0.04)$ cm in the azimuthal direction at the trap wall.

![Figure 2.28: Schematic of the cross section at the axial centre of the ALPHA-1 apparatus. The objects are labelled: a) electrodes, b) trap vacuum wall, c) octupole magnet winding, d) liquid helium reservoir, e) inner isolation vacuum wall, f) outer isolation vacuum wall, g) silicon detector and h) external solenoid magnet. The yellow star is the reconstructed vertex of an antiproton that annihilated into three pions (two charged and one neutral). The red curves are the reconstructed trajectories of the particles that pass through the detector producing hits (red points on the silicon layers). The neutral pion quickly decayed into two photons, one of them is absorbed on the octupole magnet winding and the other produced an electron-positron pair. Image from [110].](image)

In addition to silicon modules, the ATHENA experiment used a detector with CsI crystals for the
2.10. Antihydrogen detection

detection of photons from positron annihilation [30, 106]. Because of the material between the trap and the detector, the total efficiency for the detection of two simultaneous photons was about 5% [107]. The ALPHA experiment has more material between the trap and the detector (e.g. superconducting coils and cryostat) and it was deemed impractical to try to detect the photons, due the gamma absorption in the materials.

Figure 2.29: Schematic cross section of the three layer silicon detector. Red tracks are the reconstructed trajectories of the particles from the hits in the detector (red dots). The blue diamond is the reconstructed vertex and the black circle at the center is the electrode wall. a) Antiproton annihilation and b) cosmic ray. Image from [1].

The main background when detecting antihydrogen comes from cosmic rays. Fortunately the topology of a cosmic ray’s passage through the detector is usually very different from that of an antiproton annihilation. Figure 2.29 shows an example of track reconstruction for an antiproton annihilation and a cosmic ray.

To discriminate annihilations from cosmic rays, three variables are used:

1. **Number of charged particle tracks**: The majority of the cosmic ray events register two tracks from the passage of the charged particle through the detector, one on the upper half of the detector and the other on the bottom side of the detector. About 46% of the reconstructed antiproton annihilation events have at least three tracks from three charged pions (in addition to some neutral pions).
2.10. Antihydrogen detection

2. **Combined linear fit residual:** Because of their high energies, cosmic rays are expected to follow straight line trajectories, but are sometimes bent by the magnetic fields or scattered on materials. However, antiproton annihilations are not expected to have so many co-linear tracks. For this reason, the combined linear fit residual

\[
\delta = \min \left\{ \sum_{i \in N_{\text{hits}}} d_{L,i}^2 \right\},
\]

where \(d_{L,i}\) is the residual between the fitted line and the \(i\)th hit in the set of \(N_{\text{hits}}\) is calculated. \(\delta\) is calculated for every pair of tracks and the combination providing the smallest value for \(\delta\) is chosen. Cosmic rays trajectories will have a \(\delta\) close to zero, compared to antiproton annihilation trajectories.

3. **Vertex radius:** When released from the trap, antihydrogen will almost certainly annihilate on the wall of the electrodes. The reconstructed vertex is then constrained to be inside a given volume, chosen to be slightly larger than the electrode radius to allow for the finite reconstruction resolution.

The discriminating variables are optimized from two sets of data. One set is the background cosmic ray data when the magnetic trap is energized and there are no particles in the apparatus. The second set of data is from the annihilation signal of antihydrogen when antiprotons and positrons are mixed. The optimization was performed using a blind analysis approach, so the data from trapped antihydrogen was not used for this propose. This eliminates the possibility of the algorithm being improperly biased. Figure 2.30 shows the results of the optimization for the two sets of data.

After the optimization, the ALPHA-1 detector background rate is \((47 \pm 2) \times 10^{-3}\) events/s and \((64.4 \pm 0.1)\%\) of the antiproton annihilation events are accepted. The overall annihilation event efficiency is \((58 \pm 7)\%\), when combined with the \((90 \pm 10)\%\) trigger efficiency [110].
2.10. Antihydrogen detection

Figure 2.30: Measured antiproton annihilation signal and background distributions for the discriminating variables before and after applying the cuts. a) Distribution of the number of charged particle tracks, b) vertex radius of the reconstructed events, and the combined linear residuals for c) events with two charged tracks and d) events with three tracks and more. Note that in d), the background distribution is multiplied by a factor of 20 to allow comparison. The shaded areas represent the regions rejected by the cuts. Image from [110].
2.10.3 ALPHA-2 silicon tracking detector

The ALPHA-2 silicon tracking detector is an upgrade of the ALPHA-1 detector. The 60 double-sided hybrid modules from ALPHA-1 were reused and reassembled with the addition of 12 extra double-sided hybrid modules. There is then a total of 72 modules. Additionally, the radii of the layers were enlarged to accommodate the trap and cryostat of ALPHA-2. Table 2.2 shows the number of modules and radius of each layer, while figure 2.31 compares the ALPHA-1 and the ALPHA-2 module configuration. The silicon modules of the ALPHA-2 detector are staggered, which improves the solid angle by 5% [104].

<table>
<thead>
<tr>
<th>Layer position</th>
<th>ALPHA-1 number of modules</th>
<th>ALPHA-2 number of modules</th>
<th>ALPHA-1 radius [cm]</th>
<th>ALPHA-2 radius [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner</td>
<td>16</td>
<td>20</td>
<td>7.5</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.45</td>
</tr>
<tr>
<td>Middle</td>
<td>20</td>
<td>24</td>
<td>9.55</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11.35</td>
</tr>
<tr>
<td>Outer</td>
<td>24</td>
<td>28</td>
<td>10.8</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11.4</td>
<td>13.25</td>
</tr>
</tbody>
</table>

Table 2.2: ALPHA-1 and ALPHA-2 different module configuration and radii of each layer.

2.11 Cryostat and vacuum

When filled with liquid helium, the cryostat keeps the apparatus at cryogenic temperatures, and the magnets of the atom trap in the superconducting state. The cryostat has a volume filled with liquid helium, located between the ultra-high vacuum (UHV) volume and the outer vacuum chamber (OVC) of the apparatus. Superconducting magnets are placed inside this volume and are wound directly to the outer surface of the UHV vessel wall containing the electrode stack (see section 2.8.2). Liquid helium (temperature of 4.2 K) covers the magnets. The electrodes are adjacent to the cryostat vacuum pipe but are in high vacuum. They are cooled to about 8 K. The pressure inside the trap is estimated, from the antiproton annihilation rate, to be in the range of $10^{-13}$ mbar to $10^{-14}$ mbar [67]. Such low pressures are only attainable at cryogenic temperatures where the cold surfaces of the UHV volume act as a cryopump, freezing background gases. Low pressure is very important.
Figure 2.31: On the top, transverse section of the ALPHA-1 silicon detector. On the bottom, transverse section of the ALPHA-2 silicon detector. Image from [104].
when manipulating antimatter, since collisions with any background atoms or molecules will cause annihilation. A heat shield and the OVC insulate the cryostat from room temperature. The silicon detector is placed around the OVC, at room temperature. Figure 2.32 shows a cross sectional schematic of the ALPHA-2 apparatus.

Figure 2.32: Cross sectional schematic of ALPHA-2. 1) Antiproton capture trap, 2) transfer line with two external solenoid to transfer antiprotons to the antihydrogen trap, 3) antihydrogen trap and 4) cryostat tower with the liquid helium inlet and transfer line with one external solenoid to transfer positrons from the positron accumulator (not shown) to the antihydrogen trap.
Chapter 3

Trapped antihydrogen experiments

One of the ultimate goals of the ALPHA collaboration is to perform precision laser spectroscopy of antihydrogen and to compare the resulting spectrum with that of hydrogen. ALPHA has made major technological advances to tailor antiproton and positron plasmas, and to merge them together to produce trapped antihydrogen. The ALPHA collaboration successfully trapped antihydrogen during 2010 – 2011 in the ALPHA-1 apparatus.

In this chapter, we first discuss how antihydrogen can be produced. We discuss evaporative cooling, a technique that is used by ALPHA to reduce the plasma temperatures to produce trappable antihydrogen. We also describe the autoresonant injection, a technique used for controlled injection of antiprotons into the positron plasma. The rotating wall technique, used to achieve small plasma radii, will be presented in the second part of this thesis. Each of these techniques is important for optimizing the plasma parameters prior to synthesizing antihydrogen.

Following this, we discuss how antihydrogen trapping experiments are performed and we will show the results of the measurements from 2010 and 2011. We also present measurements of the antihydrogen lifetime inside the magnetic trap and the first demonstration of changing the spin of ground state antihydrogen, which was induced by resonant microwave radiation.

At the end of this chapter, we discuss future experiments on antihydrogen that may be carried out in the ALPHA-2 apparatus.
3.1 Antihydrogen formation

Antihydrogen is the bound state of an antiproton and a positron and the antimatter analogue of the hydrogen atom.

As already mentioned in section 1.2, relativistic antihydrogen was produced by the interaction of antiprotons with a jet gas target. In ALPHA, the formation of low energy antihydrogen is required since it needs to be confined in a shallow magnetic trap, as discussed in section 2.8. The formation of low energy antihydrogen can be achieved via several different mechanisms, which are detailed below. More detailed descriptions can be found in Ref. [111].

**Spontaneous radiative recombination**

This is the simplest process, in which a photon carries away the excess energy required to form a bound state:

\[
\bar{p} + e^+ \rightarrow \bar{H} + h\nu, \tag{3.1}
\]

where \( h \) is Planck’s constant and \( \nu \) is the frequency of the photon [112]. This process is the inverse of photo-ionization.

**Laser-stimulated recombination**

The rate of the above interaction can be enhanced by stimulating the capture by irradiating the system with \( k \) photons of energy \( h\nu \)

\[
\bar{p} + e^+ + k h\nu \rightarrow \bar{H} + (k + 1)h\nu. \tag{3.2}
\]

This process could potentially enhance production into a particular quantum state [113], but it is yet to be experimentally demonstrated [114].

**Three-body recombination**

This is expected to be the most efficient process in experiments such as ALPHA, that use dense
3.2 Antihydrogen production in ALPHA

positron plasmas (∼ 10^7 cm⁻³) at low temperature [115]. Experimental evidence, including measurements of the state distribution [31], the lack of stimulated recombination [114] and the high production rate strongly support this.

The reaction is

\[ \bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+. \]  

(3.3)

Essentially, two positrons scatter near the antiproton, and one loses enough energy to become bound to the antiproton, while the other carries away the binding energy.

**Charge exchange**

Charge exchange consists of the collision between a positronium (Ps), the bound state of an electron and a positron, with an antiproton:

\[ \bar{p} + Ps \rightarrow \bar{H} + e^-. \]  

(3.4)

Here the antiproton exchanges with the electron of the positronium. One of the advantages of this process is that the final state of the antihydrogen can be selected to some extent by using positronium in defined atomic states [116]. The ATRAP experiment [117], the AEGIS collaboration [118] and the GBAR collaboration [119] will make use of this process to form antihydrogen.

**Pulsed field recombination**

In this proposal, the Coulomb potential of the antiproton is modified to trap a positron in a bound state by using a pulsed electric field [120]. This has not been demonstrated experimentally.

### 3.2 Antihydrogen production in ALPHA

As already mentioned, antihydrogen formation in ALPHA is thought to occur via three body recombination (TBR). The evidence for this includes measurements that states in which the atoms are formed are weakly bound [31] and the rate of formation is much higher than the rate that is expected for radiative recombination at the measured positron temperature [122]. The rate of antihydrogen formation depends strongly on the positron plasma temperature, density and the magnetic field. In
3.2. Antihydrogen production in ALPHA

the case of a infinitely large steady-state plasma, the rate is \[37\]

\[
\Gamma_{TBR} = 8 \times 10^{-12} C \left( \frac{4.2 \text{ K}}{T} \right)^{9/2} \left( \frac{n_e}{\text{cm}^{-3}} \right)^2 \text{s}^{-1},
\]

(3.5)

where \(n_e\) is the positron plasma density, and \(C\) is a numerical constant, which depends on the magnetic field (see table 3.1). The rate also varies with temperature as \(T^{-9/2}\). The scaling with \(T\) has been studied both theoretically \([121]\) and experimentally \([122]\). In Ref. \([122]\), a scaling of \(T^{-1.1 \pm 0.5}\) was obtained, which is in strong disagreement with equation 3.5. However, in experiments, the conditions of an infinite plasma in steady state conditions do not hold, which is expected to affect the scaling. The recombination process is still not entirely understood, and it is still being studied. For a recent review, see Ref. \([111]\).

<table>
<thead>
<tr>
<th>Magnetic field</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>B → 0</td>
<td>(\sim 0.76)</td>
</tr>
<tr>
<td>B = 1 T</td>
<td>(\sim 0.1)</td>
</tr>
<tr>
<td>B → ∞</td>
<td>(\sim 0.07)</td>
</tr>
</tbody>
</table>

Table 3.1: The value of the constant \(C\) as a function of the magnetic field, which decreases as the magnetic field increases. Values extracted from \([123–125]\).

However, it is clear that to optimize for the highest rate of low energy antihydrogen formation, it is very important to have cold and dense positron plasmas. For this purpose, evaporative cooling is used to cool the positron plasmas (see section 3.2.1) and the rotating wall technique is used to radially compress them (see section 3.3).

3.2.1 Evaporative cooling technique

Evaporative cooling was first applied to neutral atoms in 1986 \([126]\) and famously used to form Bose-Einstein condensates of dilute alkali gases in 1995 \([127, 128]\). It consists of lowering the depth of the trapping potential, and sometimes using a radio frequency to remove the most energetic atoms \([126]\). The remaining atoms in the trap can re-thermalize to a lower average temperature, and the process continues until the desired temperature is reached. Using this technique, temperatures as low as 450 pK have been reached \([129]\). Evaporative cooling was also used on highly charged
3.2. Antihydrogen production in ALPHA

ions in an electron beam ion trap at high temperatures [130]. The ALPHA collaboration applied the evaporative cooling to cold clouds of antiprotons [64] and electron and positron plasmas [1] for the first time.

Since charged particles in a Penning-Malmberg trap are strongly bound to the magnetic field, evaporative cooling relies on letting the most energetic particles escape in the axial direction by reducing the depth of the confining potential. Figure 3.1 shows an example of the electric potential used to achieve evaporative cooling in Ref. [64]. The left hand side of the potential is lowered from 1.5 V to 10 mV relative to the potential minimum. The escaping antiprotons followed the magnetic field lines and annihilate on the degrader. The antiprotons remaining inside the well thermalize for 10 s and afterwards the temperature was inferred from measuring the Maxwell-Boltzmann distribution of the particles escaping from the trap (see section 2.7.4).

![Figure 3.1: Example of potential wells used during evaporative cooling where the most energetic antiprotons escape to the left. Image from [64].](image)

The results of these experiments are shown in figure 3.2a, where temperatures as low as \((9 \pm 4)\) K (10 mV well depth) were reached. The limitation of this procedure is that the technique relies on losing the particles; for example, at the lowest temperature, only \(\sim 6\%\) of the initial 45,000 antiprotons remain. This is shown in figure 3.2b). At the lowest temperature, the radius of the cloud...
3.2. Antihydrogen production in ALPHA

has expanded from 0.6 mm before evaporative cooling to 3 mm afterwards.

Figure 3.2: a) Temperature as a function of the on-axis well depth after performing the evaporative cooling technique. b) Fraction of antiprotons remaining as a function of the on-axis well depth. Images from [64].

3.2.2 Autoresonant injection technique

Autoresonant excitation is used in ALPHA to inject antiprotons into positron plasmas to form antihydrogen [65]. It was one of the key techniques that led to the observation of trapped antihydrogen [1].

A trapped antiproton plasma can be thought of as an oscillator and autoresonant injection is based on the excitation of the motion by a swept-frequency drive. In the relevant experimental parameters, the system behaves as a non-linear oscillator, with frequency of small-amplitude oscillation \( \omega_0 \) and with a monotonic relation between its amplitude and frequency. When the perturbation is chirped downwards in frequency, the energy of the system increases so that the oscillation frequency matches the driving frequency, then the oscillator follows the drive and becomes “locked”. To inject the antiprotons, the frequency chirp is continued until the antiprotons have just enough energy to enter the positron plasma. There, there is an abrupt change in the frequency of the oscillation and the antiprotons lose resonance with the drive. Therefore, the antiprotons have close to the minimal energy required to enter the positron plasma. This is shown in figure [3.3]

Figure [3.4] shows the axial energy distribution for several final drive frequencies measured in a
Figure 3.3: On the top, the voltages applied to the electrodes to create the nested well for positrons and antiprotons. On the bottom, the black curve is the on-axis potential (nested well). The blue shading represents the approximate space charge of the positron plasma, which is nested within a surrounding well with antiprotons. Before the autoresonant drive is applied, the antiprotons are located at the top of the left peak of the nested well. The red curve illustrates the axial motion of the antiprotons when applying the autoresonant chirp generator. Antiprotons lose autoresonance after traversing the positron well.
3.2. Antihydrogen production in ALPHA

series of experiments. One can see how the energy of the antiprotons can be chosen by selecting the final drive frequency. There is an inverse relationship between the amplitude and the oscillator frequency, shown in figure 3.4.

Figure 3.4: a) Axial energy distribution of 15,000 antiprotons driven to different final frequencies. Frequencies in a) are normalized to $\omega_0/2\pi = 410$ kHz. b) Measurements of the axial energy of antiprotons as a function of the final drive frequency (open squares). Calculations of the axial energy as a function of the drive frequency is shown for the vacuum potential (solid blue line), for a potential with 15,000 antiprotons (green dashed line) and for a potential with 50,000 antiprotons (red dotted-dashed line). Image from [65].

Further studies and simulations were performed to improve the rate of trapped antihydrogen [131]. Once the antiprotons are in the positron plasma, formation of antihydrogen can take place, a process that is called mixing and is presented in the following section.

The autoresonant injection of antiprotons has been proven to be very effective when producing trappable antihydrogen since antiprotons are injected into the positron plasma with little excess longitudinal energy. Other techniques to inject antiprotons into the positron plasmas use antiprotons at higher energies (several eV). The antiprotons are released into the nested well from a higher potential so they can interact with the positrons [30, 31].
3.2.3 Mixing

The superconducting magnets of the atom trap are energized, before mixing the antiprotons and positrons. The particles are confined in a nested well, where the positrons are nested in a central well within a surrounding well with antiprotons, as already shown in figure 3.3 [132].

The antiprotons are injected into the positron plasma with a frequency sweep of 350 to 200 kHz over 1 ms. After injection, the particles are allowed to interact for 1 s to form antihydrogen through three-body recombination (see section 3.2). During mixing, hot antihydrogen, not trapped in the magnetic trap, annihilates on the walls of the electrodes and is detected by the silicon tracking detector. Figure 3.5 shows the $x - y$ and $z - \phi$ projection vertex distribution of the annihilations recorded during this time. The annihilation vertices form a ring centred on the radius of the electrodes, uniform in $\phi$, and centred axially on the position of the positron plasma.

![Figure 3.5: Colour-density maps of antiproton annihilation vertices measured during antihydrogen formation. On the left is the $x - y$ projection and the white circle is the inner surface of the electrode. On the right is the $z - \phi$ projection. Image from [67].](image-url)
3.3 Antihydrogen trapping

Experiments on antihydrogen trapping were performed during 2010 and 2011. The first measurements were reported in *Nature* in 2010, where 38 antihydrogen atoms were detected after being trapped for 172 ms in the ALPHA-1 apparatus [1]. This data set consisted of 335 attempts. In each attempt, the antiprotons and the positrons were prepared and mixed to form antihydrogen. The steps that were followed in each attempt to trap antihydrogen were:

1. Antiprotons and positrons were captured from the antiproton beam and accumulator, respectively. The rotating wall is applied to achieved the desired plasma densities (see section 3.3.1).
2. Antiprotons and positrons were placed at the centre of the magnetic atom trap in a nested well.
3. The superconducting magnets of the magnetic atom trap were energized to their maximum field over 25 s.
4. EVC was performed to positrons and antiprotons.
5. Antiprotons were injected into the positron plasma by applying an autoresonant drive (section 3.2.2).
6. Antiprotons and positrons were allowed to interact for 1 s (section 3.2.3).
7. The electrodes were grounded, allowing remaining charged particles to axially escape from the Penning-Malmberg trap.
8. Four axial electric field pluses were applied to remove any “mirror-trapped” antiprotons (section 3.3.2).
9. 172 ms after mixing, a static electric field was raised to deflect any remaining antiprotons, and the superconducting magnets of the atom trap were quickly de-energized.
10. Any trapped antihydrogen released annihilated on the electrodes of the apparatus. Antihydrogen annihilations were detected during a time window 30 ms long.
3.3. Antihydrogen trapping

The interpretation of trapped antihydrogen results will be presented in section 3.3.3. The summary of all of the measurements during 2010/2011 will be reported, as well as experiments where antihydrogen was confined for longer times. At the end of this section, we will show the experiments on the resonant quantum transitions of antihydrogen and present a discussion of possible future experiments.

3.3.1 Plasma preparation

Each trapping attempt begins by catching and cooling antiprotons from the AD (section 2.4). For each attempt about $3 \times 10^4$ antiprotons are caught and cooled. The antiproton cloud is radially compressed using the rotating wall (see section 4.3) to a radius of about 0.8 mm and a density of about $6.5 \times 10^6$ cm$^{-3}$. Evaporative cooling (EVC) is used on antiprotons to achieve a temperature of about 200 K (see section 3.2.1).

A positron plasma containing about $2 \times 10^6$ positrons is transferred to the mixing trap from the positron accumulator (section 2.5). The rotating wall technique and the EVC technique are performed and the resulting positron plasma has a radius of about 0.9 mm, a density of about $5.5 \times 10^7$ cm$^{-3}$ and a temperature of about 40 K.

3.3.2 Mirror trapped antiproton background

As discussed in section 2.8, antihydrogen can be trapped in an inhomogeneous magnetic field. However, bare antiprotons can be also "mirror trapped" by the magnetic atom trap. Mirror trapped antiprotons have been extensively studied since they produce one of the main backgrounds when trapping and detecting antihydrogen [4]. When antihydrogen is released from the trap to annihilate and be detected, the silicon detector is sensitive to the charged particles produced in the antiproton annihilation but not to the gamma rays produced in the positron annihilation. For this reason, it is crucial to have a way to discriminate between the annihilation of a bare antiproton from antihydrogen.
3.3. Antihydrogen trapping

Charged particles can be mirror trapped because they possess a magnetic moment that originates in their motion. From the first adiabatic invariant \([133]\), we can state that the magnetic dipole moment of a gyrating particle is constant. The magnetic moment is given by

\[
\mu = \frac{1}{2}mv_\perp^2 = \text{constant}, \tag{3.6}
\]

where \(\mu\) is the magnetic moment, \(B\) is the external magnetic field and \(\frac{1}{2}mv_\perp^2\) is kinetic energy of the particle perpendicular to \(B\). If the magnetic field changes spatially or temporally, the perpendicular component of the kinetic energy of the particle must change to maintain a constant magnetic moment. Additionally, the total energy of the particle is

\[
E_{\text{tot}} = \frac{1}{2}mv_\parallel^2 + \frac{1}{2}mv_\perp^2 + q\phi, \tag{3.7}
\]

where \(q\phi\) is the electrostatic potential energy in the trap. The total energy of the particle is conserved. In the absence of an electric field, when the particle moves from a low magnetic field to a higher magnetic field, \(v_\perp\) must also increase to compensate the change in the magnetic field. As a consequence, \(v_\parallel\) must decrease. If the magnetic field is high enough, \(v_\parallel\) goes to zero and the particle is then reflected from the region of high magnetic field.

To avoid a mirror-trapped antiproton background during the trapping experiments, four pulses of axial electric field (up to 500 V/m) are applied so that mirror trapped antiprotons can escape from the trap. We can always postulate that there could be antiprotons with higher magnetic moments that would remain trapped despite the pulses.

Fortunately, information about the different dynamics of antihydrogen and antiprotons can be used to distinguish them. After they are released from the magnetic trap, the silicon detector provides the position and timing of the annihilations. During the magnet shutdown, a bias electric field is applied, which will deflect the trajectory of antiprotons, depending on the direction of the electric field, while the trajectory of neutral antihydrogen remains unchanged. This technique is intended to help discriminate mirror trapped antiprotons from antihydrogen. Additionally, we can compare the
3.3. Antihydrogen trapping

spatial and temporal distributions to simulations.

In order to validate this technique, mirror trapped antiprotons were deliberately created and detected during the magnetic trap shutdown for bias electric fields of about 500 V/m in strength that pushed antiprotons either to the right side of the apparatus (right bias) or to the left side of the apparatus (left bias). Figure 3.6 shows the experimental data and simulations for mirror trapped antiprotons when using no bias, left bias and right bias. The simulations match the experimental data well: we observe that when a bias is applied, trapped antiprotons are well localized around a given axial position.

![Simulation and experimental data of mirror trapped antiprotons](image)

Figure 3.6: Simulated $t$ and $z$ coordinates of released mirror trapped antiprotons for no bias (green scattered dots), left bias (blue scattered dots) and right bias (red scattered dots). Solid points are the experimental data of mirror trapped antiprotons. $t = 0$ is the time when the magnetic trap is shut down.

3.3.3 38 trapped antihydrogen atoms

The report of the first trapping of antihydrogen atoms was published in *Nature* by the ALPHA collaboration in 2010 [1]. 38 antihydrogen atoms were detected after being trapped for 172 ms.

After trapping the antihydrogen atoms, they are released from the trap, and the annihilation vertex is reconstructed from the data gathered by the silicon detector. Figure 3.7 shows the annihilation vertex events as a function of time and axial position, $z$, where 0 ms is the time when the superconducting magnets of the atom trap are shutdown. Simulations are also shown, for antihydrogen (a) and for mirror trapped antiprotons (b). One can see that the data match the simulations of antihydrogen well.
3.3. Antihydrogen trapping

and not the one for mirror trapped antiprotons. Additionally, the data taken with different electric fields are all similar, indicating that the events are not due to charged particles.

Figure 3.7: a) Simulated $t$ and $z$ coordinates of released antihydrogen after the trap shutdown (grey scattered dots). b) Simulated $t$ and $z$ coordinates of released mirror trapped antiprotons for no bias (green scattered dots), left bias (blue scattered dots) and right bias (red scattered dots). Annihilation events of antihydrogen trapping experiments are plotted for no bias (green circles), left bias (blue triangles) and right bias (red triangles). One annihilation event was also detected during the heated positrons experiments (violet star).

Furthermore, control experiments were performed where antihydrogen formation was suppressed by heating the positrons to a temperature of about 1,100 K. The goal of these experiments was to rule out any other source of background during antihydrogen trapping. The control experiments are expected to suppress antihydrogen formation, so that no antihydrogen should be detected. Tableef{tab:antihydrogen} shows the results for the experiments with trapped antihydrogen and for the experiment with heated positrons. Only one event was detected during the heated positron experiments in 246 attempts (a rate of 0.0041 events per attempt) and 38 events in 335 attempts were detected during trapped antihydrogen experiments (rate of 0.11 events per attempt).
3.3. Antihydrogen trapping

<table>
<thead>
<tr>
<th>Type of measurement</th>
<th>Bias electric field</th>
<th>Number of attempts</th>
<th>Annihilation events</th>
<th>Estimated background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antihydrogen trapping</td>
<td>None</td>
<td>137</td>
<td>15</td>
<td>0.19</td>
</tr>
<tr>
<td>Antihydrogen trapping</td>
<td>Left</td>
<td>101</td>
<td>11</td>
<td>0.14</td>
</tr>
<tr>
<td>Antihydrogen trapping</td>
<td>Right</td>
<td>97</td>
<td>12</td>
<td>0.14</td>
</tr>
<tr>
<td>Heated positrons</td>
<td>None</td>
<td>132</td>
<td>1</td>
<td>0.19</td>
</tr>
<tr>
<td>Heated positrons</td>
<td>Left</td>
<td>60</td>
<td>0</td>
<td>0.08</td>
</tr>
<tr>
<td>Heated positrons</td>
<td>Right</td>
<td>54</td>
<td>0</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 3.2: Number of annihilation events for antihydrogen trapping and heated positrons (antihydrogen formation suppression) experiments for different bias electric fields.

3.3.4 Antihydrogen confinement for 1,000 s

The confinement time of 172 ms was the shortest time possible to hold antihydrogen in our magnetic trap and still perform the manipulations to clear the charged particles. The short time assures the highest probability to detect antihydrogen atoms before they might be lost through annihilation with background gases, collisional energy transfer or any other loss mechanisms. One of the motivations to study the confinement time is to investigate the specific capabilities of the ALPHA trap to hold antihydrogen for a long time. It is known that magnetically trapped atoms can be confined for up to 1 s in room temperature traps [134] and up to 10 – 30 min in cryogenic temperature traps [135–137]. Another motivation to confine antihydrogen for long times is to allow formation ground state antihydrogen, since ground state antihydrogen will be necessary for precision spectroscopy. As already mentioned before, antihydrogen is created through three-body recombination, which results in antihydrogen formed in excited states. The de-excitation of antihydrogen to its ground state takes place via radiative and collisional processes. It was calculated that after 0.5 s, 99% of trapped antihydrogen will be in the ground state [2]. Finally, the transition rate for spectroscopic measurements is expected to be low, so a long interaction time will be needed to obtain a signal.

Table 3.3 shows the results of the confinement measurements. Confinement measurements were performed up to 2,000 s, where only one antihydrogen annihilation was detected in three attempts. We observed trapping times longer than 1 s, implying that a sample of ground-state antihydrogen was obtained for the first time [2].
3.3. Antihydrogen trapping

<table>
<thead>
<tr>
<th>Holding time [s]</th>
<th>Number of attempts</th>
<th>Annihilation events</th>
<th>Estimated background</th>
<th>Statistical significance (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>119</td>
<td>76</td>
<td>0.17</td>
<td>≫ 20</td>
</tr>
<tr>
<td>10.4</td>
<td>6</td>
<td>6</td>
<td>0.01</td>
<td>8</td>
</tr>
<tr>
<td>50.4</td>
<td>13</td>
<td>4</td>
<td>0.02</td>
<td>5.7</td>
</tr>
<tr>
<td>180</td>
<td>32</td>
<td>14</td>
<td>0.05</td>
<td>11</td>
</tr>
<tr>
<td>600</td>
<td>12</td>
<td>4</td>
<td>0.02</td>
<td>5.8</td>
</tr>
<tr>
<td>1,000</td>
<td>16</td>
<td>7</td>
<td>0.02</td>
<td>8</td>
</tr>
<tr>
<td>2,000</td>
<td>3</td>
<td>1</td>
<td>0.004</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Table 3.3: Number of annihilation events for different times of confinement and the respective estimated background.

The rate of events per attempt appears to decrease from $0.64 \pm 0.07$ (0.4 s holding time) to $0.44 \pm 0.16$ (1,000 s holding time). However, we do not have sufficient statistics to extract quantitative information on the trapping lifetime of antihydrogen.

The trapping rate at short times has been improved from the one in section 3.3.3 after evaporative cooling and autoresonant injection were further optimized. Nonetheless, there are several possible mechanisms which could lead to loss of trapped antihydrogen over time. These are mostly due to the presence of background gases (expected to be composed of He and H₂) inside the trap [138]. Here is an overview of the possible mechanisms for antihydrogen loss [2]:

- **Destruction**: Collisions of antihydrogen with neutral atoms can cause the antihydrogen to annihilate. This happens when the antiproton gets close to a nucleus, or when exotic bound states are created with background gas atoms.

- **Heating**: During an elastic collision between antihydrogen (< 0.5 K) and background gases (~ 10 K), the antihydrogen can gain energy and be expelled from the trap.

- **Quasi-trapped orbits**: This mechanism is well known for magnetically trapped neutrons [139]. Antihydrogen atoms with a kinetic energy higher that the trap depth can be temporarily confined since the depth of the magnetic trap is anisotropic. The mirror coils can produce a deeper axial trap than the octupole produces in the transverse direction.
3.3. Antihydrogen trapping

3.3.5 Summary of trapped antihydrogen measurements

During the 2010 experimental run, we observed 320 annihilation events compatible with antihydrogen. Those events were gathered in experiments performed for different bias electric fields and for different holding times ranging from 172 ms up to 2000 s. Each experimental attempt was performed as already described in section 3.3 but with small variations in the plasma preparation that resulted in more efficient antihydrogen trapping.

During 2011, we detected an additional 275 atoms: 65 of these events were associated with microwave experiments (see section 3.4). A summary $t - z$ plot of the detected antihydrogen events is presented in figure 3.8.

![Figure 3.8](image.png)

Figure 3.8: Top panel: simulated $t$ and $z$ coordinates of released antihydrogen after the trap shutdown (grey scattered dots). Bottom panel: simulated $t$ and $z$ coordinates of released mirror trapped antiprotons for no bias (green scattered dots), left bias (blue scattered dots) and right bias (red scattered dots). The black solid points are the combined trapped antihydrogen data sets from 2010 and 2011. $t = 0$ is the time when the magnetic trap is shut down.
Figure 3.9 shows distributions of vertex variables of the 595 trapped antihydrogen events. We observe that the majority of trapped antihydrogen has either 2 or 3 tracks. The vertex radius distribution (figure 3.9b) has a peak at 2 cm < R < 2.5 cm, which is compatible with the electrodes’ inner radius (2.2 cm). The linear residual distribution (figure 3.9c) are compatible with the results of the blind analysis shown in figure 2.30. We observe in figure 3.9d that the vertices are concentrated at the centre of the trap between -15 cm < z < 15 cm, the length of the trap as defined by the mirror coils. Figure 3.9e shows the distribution of the time of detection. The vast majority of events have t < 30 ms, as predicted by the simulations (figure 3.8). Figure 3.9f shows the distribution of the vertex azimuthal angle, which should not have a direction preference, as we observe.

3.4 Resonant quantum transitions in antihydrogen

3.4.1 Hyperfine structure of the ground state

In this section, we discuss the hyperfine structure of (anti)hydrogen atoms, with or without an applied magnetic field. The antihydrogen atom is composed of a positron orbiting a antiproton. The positron and the antiproton each have spin one-half and can be oriented either "up" or "down". To study the ground state of the atom, we will use more convenient and simpler basis states, where the single arrow refers to the positron spin and the double arrow refers to the antiproton spin:

\[ |↑⇑⟩ \] (3.8a)

\[ |↑⇓⟩ \] (3.8b)

\[ |↓⇑⟩ \] (3.8c)
3.4. Resonant quantum transitions in antihydrogen

Figure 3.9: Distributions of vertex variables for trapped antihydrogen: a) distribution of number of tracks, b) distribution of vertex radius, c) distribution of linear residual, d) distribution of vertex axial position, e) distribution of time of detection, at $t = 0$ s the magnetic trap is turned off, f) distribution of vertex azimuthal angle. For detailed information on the cuts performed, see section 2.10.2; for a comparison with blind analysis, see figure 2.30.
3.4. Resonant quantum transitions in antihydrogen

The spin-spin coupling between the positron and the antiproton is responsible for the “hyperfine structure” in the energy levels \[140\]. Spin-orbit coupling causes “fine structure”, but does not apply to the ground state, where the orbital angular momentum of the positron should be zero. In the absence of an external magnetic field, there are four ground states composed of a triplet:

\[
\begin{align*}
|\uparrow\uparrow\rangle \\
\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle + |\downarrow\downarrow\rangle \\
|\downarrow\downarrow\rangle
\end{align*}
\]

with total spin 1, \[3.9\]

and a singlet

\[
\frac{1}{\sqrt{2}}|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle,
\]

with total spin 0. \[3.10\]

For matter hydrogen, the energy difference between the triplet and singlet state is

\[\Delta E \approx 5.88 \times 10^{-6}\text{eV},\]

which corresponds to the zero-field hyperfine splitting frequency \[141,142\]:

\[f_H = 1,420,405,751.7667 \pm 0.001\;\text{Hz},\]

which is known to very high precision. This frequency is in the microwave range and corresponds to the famous "21-centimeter line" of hydrogen, which is of great importance in astronomy and cosmology, because of the ubiquity of hydrogen in the universe \[143\].

In this presentation, we use the well established formalism for hydrogen to describe the types of measurements that will be made. The object of the ALPHA experiments is to see to what accuracy this formalism describes antihydrogen.
3.4. Resonant quantum transitions in antihydrogen

In the presence of a magnetic field, we need to consider the interaction of the positron and the antiproton spins with the magnetic field. The change in the energy of the state due to an external magnetic field is known as “Zeeman effect” \[140\]. The hyperfine states in a magnetic field are \[144\]:

\[
|a\rangle = \cos(\theta_n) |\uparrow\downarrow\rangle - \sin(\theta_n) |\downarrow\uparrow\rangle, \tag{3.13}
\]

\[
|b\rangle = |\uparrow\uparrow\rangle, \tag{3.14}
\]

\[
|c\rangle = \cos(\theta_n) |\downarrow\uparrow\rangle + \sin(\theta_n) |\uparrow\downarrow\rangle, \tag{3.15}
\]

\[
|d\rangle = |\downarrow\downarrow\rangle, \tag{3.16}
\]

where \(n\) is the principal quantum number and the mixing angles are \[37\]

\[
\tan(2\theta_n) \simeq \frac{51 \text{ mT}}{n^3 B}. \tag{3.17}
\]

The corresponding energies of the hyperfine states for the ground state of (anti)hydrogen are written as

\[
E_a = -A \left( 1 + 2 \sqrt{1 + (\mu_e - \mu_p)^2 B^2/4A^2} \right), \tag{3.18}
\]

\[
E_b = A - (\mu_e + \mu_p) B, \tag{3.19}
\]

\[
E_c = A \left( -1 + 2 \sqrt{1 + (\mu_e - \mu_p)^2 B^2/4A^2} \right), \tag{3.20}
\]

\[
E_d = A + (\mu_e + \mu_p) B, \tag{3.21}
\]

where \(\mu_e\) and \(\mu_p\) are the (anti)electron and the (anti)proton magnetic moments respectively, \(A = h f_H/4\) and \(B\) is the external magnetic field \[140\].

For a magnetic field of \(\sim 1\) T, which is the case applicable to ALPHA, and for antihydrogen in ground
3.4. Resonant quantum transitions in antihydrogen

state, \( \cos(\theta_1) \sim 1 \), while \( \sin(\theta_1) \sim 0 \). The spins of the positron and the antiproton are essentially uncoupled and behave as if they were alone in the external magnetic field. For antihydrogen, the states are approximated to:

\[
|a\rangle = |\uparrow\downarrow\rangle, \tag{3.22}
\]
\[
|b\rangle = |\uparrow\uparrow\rangle, \tag{3.23}
\]
\[
|c\rangle = |\downarrow\uparrow\rangle, \tag{3.24}
\]
\[
|d\rangle = |\downarrow\downarrow\rangle, \tag{3.25}
\]

where the single arrow is the positron spin and the double arrow is the antiproton spin.

As already discussed in section 2.8.1, an antihydrogen atom confined in the magnetic trap if its magnetic dipole moment is antiparallel to the magnetic field. Since \( \mu_e/\mu_p \approx m_p/m_e \), so \( \mu_e \gg \mu_p \). For this reason, states \( |c\rangle \) and \( |d\rangle \) correspond to the "low-field seeking" states (trappable states). On the other hand, antihydrogen atoms in "high-field seeking" states (\( |a\rangle \) and \( |b\rangle \)) are expelled from the trap. Figure 3.10 shows the Zeeman splitting of the ground state of (anti)hydrogen as a function of the external magnetic field. This diagram is known as the Breit-Rabi diagram.

By applying resonant microwaves to the atoms, it is possible to induce a transition between the hyperfine splitting states. The radiation is resonant if the photon energy equals the energy difference between the states. Two vertical arrows representing the transitions for spin flip from trappable states to untrappable states have been drawn in figure 3.10. These transitions involve flipping the spin of the positron, and can be represented as:

\[
|d\rangle = |\downarrow\downarrow\rangle \rightarrow |a\rangle = |\uparrow\downarrow\rangle, \tag{3.26}
\]
\[
|c\rangle = |\downarrow\uparrow\rangle \rightarrow |b\rangle = |\uparrow\uparrow\rangle. \tag{3.27}
\]
3.4. Resonant quantum transitions in antihydrogen

Figure 3.10: The Breit-Rabi diagram showing the hyperfine structure of the energy levels of the (anti)hydrogen atom in an external magnetic field. The vertical dashed line intercepts the 1 T magnetic field that is used during the experiment in ALPHA-1. The two black arrows join the states used during the experiment in section 3.4.4 The arrows have been offset horizontally for clarity.
The approximate corresponding frequencies at the minimum on-axis magnetic field in ALPHA-1 ($B_{\text{min}}$) are

\[ f_{ad} = 28.72 \text{ GHz} \quad (3.28) \]

and

\[ f_{bc} = 27.30 \text{ GHz}. \quad (3.29) \]

If $f_{ad}$ and $f_{bc}$ are precisely measured under the same conditions, the difference between the two frequencies $f_{ad} - f_{bc}$ gives the zero-field hyperfine splitting frequency $f_H$.

### 3.4.2 Microwave injection and transition probability

The spin-flip measurements relies on the fact that resonant microwaves can induce a transition from a trappable state into an untrappable state. An antihydrogen atom in untrappable state is expelled from the trap and the annihilation can be detected by the silicon detector.

During the antiproton beam time of 2011, ALPHA performed measurements of the spin flip transition. The time-varying magnetic field was produced by an Agilent 8257D PSG synthesizer and with a maximum output power of about 700 mW. The radiation entered the vacuum system via a waveguide and was injected into the trap by a horn antenna, which was placed on the movable stick of the apparatus, described in section 2.6 and illustrated in figure 3.11.

The spin-flip transition as a function of frequency in the ALPHA-1 trap was calculated using Monte Carlo simulations [3, 145], the results of which are shown in figure 3.12. The shape of the line has a sharp peak with a long tail on the high-frequency side. The abrupt low-frequency edges are due to the minimum magnetic field in the center of trap. The long high-frequency tails are associated with the inhomogeneity of the magnetic field of the antihydrogen trap. One can see that transition $|c\rangle \rightarrow |b\rangle$ also has a small probability to occur at the same frequencies as the transition $|d\rangle \rightarrow |a\rangle$. 
3.4. Resonant quantum transitions in antihydrogen

Figure 3.11: Schematic of the ALPHA-1 apparatus. A microwave horn at the right hand side of the apparatus illustrates the microwave injection. Image from [3].

Figure 3.12: Transition probability as a function of the frequency in the ALPHA-1 trap. The frequency difference between the two transitions is the zero-field hyperfine splitting frequency. If frequencies are applied near the $|d\rangle \rightarrow |a\rangle$ transitions, there is a small probability that $|c\rangle \rightarrow |b\rangle$ is also induced, since they overlap. Image from [3].
3.4.3 Static magnetic field measured with the electron cyclotron resonance

The static magnetic field in the ALPHA-1 trap was measured using a novel method, where the cyclotron motion of an electron plasma was excited using microwave radiation [146, 147]. The resulting temperature increase was detected by monitoring the frequency of the plasma’s quadrupole mode.

To carry out a measurement, a series of 4 µs long microwave pulses are injected into the trap, where the electron plasma is confined. The microwave frequency is changed for each pulse so that a scan near the cyclotron frequency of the plasma is made. When the microwave frequency matches the cyclotron frequency, the electron plasma temperature increases. The change of temperature is determined by measuring the frequency of the plasma’s quadrupole mode, which depends on the plasma’s aspect ratio and temperature [149]. Figure 3.13a shows the quadrupole frequency measurement as a function of time for a single scan. The multiple peaks correspond to the excitation of the cyclotron motion, when applying the microwave pulse, which results on the increase of the plasma temperature and, therefore in the quadrupole mode frequency of the plasma. The plasma is then allowed to cool through cyclotron radiation over 30 s. The cyclotron frequency of the plasma is determined by examining the height of the step in the quadrupole frequency as a function of the microwave frequency (figure 3.13b). The microwaves are on resonance with the cyclotron frequency at the maximum of this curve.

After identifying the cyclotron frequency of the electron plasma, the static magnetic field can be deduced from the equation:

\[
B = \frac{2\pi m f_c}{q},
\]

(3.30)

where \(f_c\) is the cyclotron frequency, \(q\) is the elementary charge, and \(m\) is the mass of the electron.

This technique was used to calibrate the magnetic fields used during the spin-flip measurements. Figure 3.14 shows an example of calibration.
3.4. Resonant quantum transitions in antihydrogen

Figure 3.13: a) Quadrupole mode frequency as a function of time. A microwave pulse of 4 µs is applied every 30 s. The microwave frequency is scanned near the cyclotron frequency. b) Change in the quadrupole mode frequency as a function of the applied microwave frequency gives the cyclotron frequency of the plasma. Image from [147].

Figure 3.14: Example of calibration of the external solenoid using the cyclotron frequency. Image from [150].

Lakeshore Current Field Calibration

\[ f_c = 0.6536 \text{[GHz/A]} I + 0.0736 \text{[GHz]} \]

\[ B = 0.0233 \text{[T/A]} I + 0.0026 \text{[T]} \]
3.4. Resonant quantum transitions in antihydrogen

3.4.4 Experimental procedure

The microwave radiation is reflected from metallic structures in the apparatus. The amount of power that is transmitted to the trapping volume depends on the microwave frequency in a very complicated way because of multiple reflections of the microwaves within the electrode stack. It is important to ensure that as much microwave power as possible is delivered to the atoms. This dependance was determined by measuring the reflected power as a function of frequency. Two frequencies that were separated by the ground state hyperfine splitting (equation 3.12), and that also have good transmission were selected as resonant frequencies to be used in the experiments. The magnetic field that should tune the atoms’ transitions can be calculated by inverting equations 3.18, 3.19, 3.20 and 3.21. The magnetic field was set to this value by varying the current in the external solenoid and measuring the cyclotron frequency. This field is referred to as $B_{\text{min}}$, and the corresponding selected resonant frequencies $f_{\text{res}}(ad, bc)$.

To avoid changing the power delivered to the atoms because of the frequency-dependent transmission, the magnetic field was instead changed by 3.6 mT to change between on-resonance and off-resonance. This corresponds to a 100 MHz detuning of the transitions. In further experiments we decided to change the microwave frequency by 100 MHz to bring the radiations back into resonance with atoms. This gives a total of six combinations of experimental parameters, as shown in table 3.4.

<table>
<thead>
<tr>
<th>Series number</th>
<th>Microwave frequency</th>
<th>Magnetic field</th>
<th>Type of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series 1</td>
<td>$f_{\text{res}}(ad, bc)$</td>
<td>$B_{\text{min}}$</td>
<td>On-resonance</td>
</tr>
<tr>
<td>Series 2</td>
<td>$f_{\text{res}}(ad, bc)$</td>
<td>$B_{\text{min}} + 3.6$ mT</td>
<td>Off-resonance</td>
</tr>
<tr>
<td>Series 3</td>
<td>$f_{\text{res}}(ad, bc) + 100$ MHz</td>
<td>$B_{\text{min}} + 3.6$ mT</td>
<td>On-resonance</td>
</tr>
<tr>
<td>Series 4</td>
<td>$f_{\text{res}}(ad, bc)$</td>
<td>$B_{\text{min}} + 3.6$ mT</td>
<td>Off-resonance</td>
</tr>
<tr>
<td>Series 5</td>
<td>Power off</td>
<td>$B_{\text{min}}$</td>
<td>No-microwaves</td>
</tr>
<tr>
<td>Series 6</td>
<td>Power off</td>
<td>$B_{\text{min}} + 3.6$ mT</td>
<td>No-microwaves</td>
</tr>
</tbody>
</table>

Table 3.4: Table showing a total of six combinations of experimental parameters.

All the measurements have the same experimental procedure:
3.4. Resonant quantum transitions in antihydrogen

- **Antihydrogen production**
  The antiproton and positron plasma preparation and antihydrogen formation (1 s mixing) is the same as the trapped antihydrogen measurements discussed at the beginning of this chapter (section 3.3).

- **60 s of atom confinement**
  In this period of time, the magnetic field could be changed from \( B_{\text{min}} \) to \( B_{\text{min}} + 3.6 \text{ mT} \), to choose between on-resonance and off-resonance. The magnetic field was then allowed to stabilize.

  This period of time was also used as a background and as we discussed in section 3.3.4, to ensure antihydrogen had de-excited to the ground state.

- **180 s of microwave irradiation**
  During this period of time microwaves were injected.

  We do not know a priori in which hyperfine state trapped antihydrogen is; it could be either in \(|d\rangle\) or \(|c\rangle\). For this reason, we apply microwaves resonant with both of the positron spin flip transitions \(|d\rangle \rightarrow |a\rangle\) and \(|c\rangle \rightarrow |b\rangle\), one at a time. A frequency sweep from \((f_{bc} - 5 \text{ MHz})\) to \((f_{bc} + 10 \text{ MHz})\) is applied for 15 s, then a frequency sweep from \((f_{ad} - 5 \text{ MHz})\) to \((f_{ad} + 10 \text{ MHz})\) is applied for another 15 s. This cycle is repeated six times, for a total time of 180 s. Figure 3.15 shows the cycle of microwave injection. The frequencies are resonant with the minimum on-axis magnetic field \(B_{\text{min}}\) or \(B_{\text{min}} + 3.6 \text{ mT}\).

  Since the magnetic field is highly inhomogenous away from the central axis, a transition will likely occur only when the antihydrogen passes through the magnetic field minimum. 180 s should be enough time for antihydrogen to pass through the center of the trap. During the 180 s time window, we expect to see antihydrogen annihilations when an atom passes through either of the transitions \(|d\rangle \rightarrow |a\rangle\) or \(|c\rangle \rightarrow |b\rangle\).

  As will be discussed later in section 3.4.7 during this detection time window, we use the **appearance mode** analysis.
• **The magnetic trap shut down**

The magnetic trap is turned off in the same way as other experiments described in [3.3]. In this time window, we use **disappearance mode** analysis (see section [3.4.6]), and detect antihydrogen that remained in the trap after the microwave irradiation.

![Figure 3.15: Microwave injection cycle. During the first 15 s, microwaves resonant to $f_{bc}$ are applied, then from $15 < t < 30$ s, microwaves resonant to $f_{ad}$ are applied. This 30 s cycle is repeated six times for a total time of 180 s.](image)

3.4.5 **Description of measurements**

As we mentioned before, we performed 6 different types of measurements (see table [3.4]).

Figure [3.16] shows the injected frequency range along with the transition probability as a function of frequency for the two different on-resonance measurements. These measurements are called Series 1 (when using $B_{min}$) and Series 3 (when using $B_{min} + 3.6$ mT).

Off-resonance measurements were performed in alternation with every attempt of Series 1 and Series 3. Series 2 was alternated with every attempt of Series 1. Likewise, off-resonance measurements, Series 4, was alternated with every attempt of Series 3. Series 2 and Series 4 are identical.

Figure [3.17] illustrates the off-resonance measurements.
3.4. Resonant quantum transitions in antihydrogen

Figure 3.16: Top: the Series 1 probability transition as a function of the frequency when the minimum on-axis magnetic field is $B_{\text{min}}$. Bottom: the Series 3 probability transition as a function of the frequency when the minimum on-axis magnetic field is $B_{\text{min}} + 3.6$ mT (resonance shifted by 100 MHz compared to series 1). Both series are on-resonance measurements. The two yellow bins in each plot represent the frequency ranges that are applied. Image from [3].
3.4. Resonant quantum transitions in antihydrogen

Figure 3.17: Series 2 and 4. Probability as a function of the frequency when the minimum on-axis magnetic field is $B_{\text{min}} + 3.6$ mT. Yellow bins represent the ranges of the frequencies applied, which are 100 MHz lower than the transition resonance frequency. We observe that the upper frequency sweep overlaps with the tail of the $|c\rangle \rightarrow |b\rangle$ transition, meaning that there is a small but non-zero probability to induce this transition.

3.4.6 Results of disappearance mode analysis

In the disappearance mode analysis, we detect any antihydrogen atoms that remain after the microwave irradiation. The detection occurs during the 30 ms time window, using the standard antihydrogen event analysis (see section 2.10). Table 3.5 shows the number of antihydrogen events detected for each series, along with the rate per run. The different experiments are grouped in table 3.6. The rates of detection in the on-resonance measurements are clearly smaller than the rates of the off-resonance measurements. This indicates that during microwave injection, antihydrogen atoms are transferred to untrappable states and have escaped from the trap before the disappearance mode analysis.

If we compare the off-resonance rates with the no-microwaves measurements, we observe that off-resonance microwaves appear to reduce the rate of detection. There are two possible explanations for this. Recall that there is a small probability to induce $|c\rangle \rightarrow |b\rangle$ when injecting off-resonant
microwaves, as illustrated in figure [3.17]. Additionally, the microwaves induce currents in the electrodes, resulting in heating. Cryogenically absorbed gas can evaporate, resulting in a poorer vacuum, and a reduced antihydrogen lifetime. During the microwave injection, our temperature sensors placed on the electrodes outside the trapping region, measured temperatures changed as high as 3 K.

<table>
<thead>
<tr>
<th>Series number</th>
<th>Microwave frequency</th>
<th>Magnetic field</th>
<th>Type of measurement</th>
<th>Number of attempts</th>
<th>Number of events</th>
<th>Rate (events/attempt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$f_{res}(ad, bc)$</td>
<td>$B_{min}$</td>
<td>On-resonance</td>
<td>79</td>
<td>1</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>2</td>
<td>$f_{res}(ad, bc)$</td>
<td>$B_{min} +3.6$ mT</td>
<td>Off-resonance</td>
<td>88</td>
<td>16</td>
<td>0.18 ± 0.05</td>
</tr>
<tr>
<td>3</td>
<td>$f_{res}(ad, bc)$</td>
<td>$B_{min} +3.6$ mT</td>
<td>On-resonance</td>
<td>24</td>
<td>1</td>
<td>0.04 ± 0.04</td>
</tr>
<tr>
<td>4</td>
<td>$f_{res}(ad, bc)$</td>
<td>$B_{min} +3.6$ mT</td>
<td>Off-resonance</td>
<td>22</td>
<td>7</td>
<td>0.32 ± 0.12</td>
</tr>
<tr>
<td>5</td>
<td>Power off</td>
<td>$B_{min}$</td>
<td>No-microwaves</td>
<td>52</td>
<td>17</td>
<td>0.33 ± 0.08</td>
</tr>
<tr>
<td>6</td>
<td>Power off</td>
<td>$B_{min} +3.6$ mT</td>
<td>No-microwaves</td>
<td>48</td>
<td>23</td>
<td>0.48 ± 0.10</td>
</tr>
</tbody>
</table>

Table 3.5: Results of disappearance mode for on-resonance, off-resonance and no-microwave measurements. Results are from [3].

<table>
<thead>
<tr>
<th>Type of measurement</th>
<th>Number of attempts</th>
<th>Number of events</th>
<th>Rate (events/attempt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-resonance (Series 1+3)</td>
<td>103</td>
<td>2</td>
<td>0.02 ± 0.01</td>
</tr>
<tr>
<td>Off-resonance (Series 2+4)</td>
<td>110</td>
<td>23</td>
<td>0.21 ± 0.04</td>
</tr>
<tr>
<td>No-microwaves (Series 5+6)</td>
<td>100</td>
<td>40</td>
<td>0.40 ± 0.06</td>
</tr>
</tbody>
</table>

Table 3.6: Summary of flip-spin transition measurements.

### 3.4.7 Results of appearance mode analysis

In the appearance mode analysis, we look for events during the 180 s long microwave injection window, during which antihydrogen atoms could be ejected from the trap. Because of the long observation time, the cosmic background becomes higher than the expected signal. We expect to get about 8 cosmic events in 180 s compared to the expected antihydrogen event number (about 0.5
detected event per attempt). To improve the signal-to-noise ration, an alternative criteria for annihilation event identification was introduced, using a technique known as a bagged decision tree classifier, in the random forest approach [3][151-153]. This reduces the cosmic rate to \((1.7 \pm 0.3) \text{ mHz}\) from \((47 \pm 2) \text{ mHz}\). This method is ten times more effective in the rejection of cosmic rays, while accepting 75\% of antihydrogen events compared to the standard analysis.

Figure 3.18 shows the number of events selected from the alternative criteria as a function of time in the 180 s appearance mode window. The expected cosmic background per bin per run is \(0.026 \pm 0.005\) events.

Clearly, the on-resonance measurements have a higher number of events than the off-resonance and no-microwave measurements. The events are mostly detected during the first microwave sweep \(0 < t < 30\) s, implying that the first sweep has enough time and power to induce the transitions. In fact, 14 out of 37 events in the first 30 s occur in the first second of one of the frequency sweeps.

After 30 s, the on-resonance measurements look similar to off-resonance and no-microwave measurements. In the off-resonance measurements, there is an excess of events during \(15 < t < 30\) s, indicating that \(|c\rangle \rightarrow |b\rangle\) transitions might be induced when applying the sweep around \(f_{ad}\).

Figure 3.19 shows the antihydrogen event counts as a function of the axial position. One can see that the on-resonance events occur for \(|z| < 6\) cm, similar to the events produced in the numerical simulations. Antihydrogen annihilations with background gases are more scattered in space, since annihilations are not concentrated at the magnetic field minimum.

Taking these pieces of evidence together, we can conclude that we have observed quantum transitions in trapped antihydrogen atoms. We have localized the transition frequencies at the trap minimum to approximately 100 MHz, which corresponds to a relative precision of \(4 \times 10^{-3}\).

### 3.5 Future experiments on antihydrogen

With the ALPHA-2 apparatus fully commissioned and ready to take measurements, a new era of antihydrogen research is around the corner. Soon, the ALPHA collaboration will be able to make
Figure 3.18: Antihydrogen event counts as a function of time. Microwave radiation is injected at $t = 0$ s for 180 s (see section 3.4.4). The errors bars are due to statistics. Image from [3].
3.5. Future experiments on antihydrogen

Figure 3.19: Antihydrogen event counts as a function of the axial position for $0 < t < 30$ s. The grey histogram is the result of numerical simulations, where spin-flip transitions are induced. The dashed black curve histogram is the result of numerical simulations, where antihydrogen annihilates with background gases. Image from [3].
laser spectroscopy measurements. Here we will discuss several future measurements that can be performed in antihydrogen:

- **1S–2S two photon spectroscopy**
  The 1S–2S electronic transition is known to a precision of $4.2 \times 10^{-15}$ in hydrogen, one of the most precise measurements in physics [49]. This spectroscopic measurement in antihydrogen will allow a comparison between hydrogen and antihydrogen. The transition is forbidden for single photons, so two photons each with wavelength 243 nm must be absorbed to induce the transition. Using two counter-propagating photons allows the doppler effect to be cancelled to the first order. Also, the fact that single-photon decay is forbidden means that the transition has a natural line width of only 1.3 Hz, which is why such high-precision measurements can be made. However, the line will be broadened by the Zeeman effect and time of flight broadening [154]. One of the biggest challenges is to perform spectroscopy in a large trap volume with very few antihydrogen atoms (about 1 atom per attempt). The ALPHA-2 apparatus is designed to allow laser access and the trap has an optical resonant cavity that increases the laser power in the trapping volume.

- **1S–2P one photon spectroscopy and cooling**
  Also called Lyman-α transition, this transition has a line width of 99.7 MHz [156], and is suitable for laser cooling of trapped antihydrogen in the ground state [156]. This transition requires radiation at a wavelength of 121.56 nm, which is in the vacuum ultraviolet (VUV) and its production is very challenging. Doppler cooling of magnetically trapped hydrogen was first reported in 1993 [155] and no other similar experiments have been reported since then. Within the ALPHA collaboration, a pulsed Lyman-α laser has been developed [157, 158]. The VUV light was generated using a four-wave mixing process in a mixture of krypton and argon, where two wavelengths are mixed to obtain the Lyman-α wavelength [158]. Based on calculations it has been estimated that antihydrogen can be cooled to temperatures as low as 20 mK, using the available power levels [159].
3.5. Future experiments on antihydrogen

- **Positrons cooled sympathetically with laser cooled atoms**
  One way to increase the rate of trapped antihydrogen is to further cool the constituent particles. In particular, the temperature of the positron plasma greatly influences both the rate of antihydrogen production and its final temperature (see section 3.2). Sympathetic cooling of positrons using laser cooled $^9$Be$^+$ ions was demonstrated in 2002 [160, 161]. This technique has been studied computationally in the context of antihydrogen experiments and, it was found that the positron temperature could be reduced by about one order of magnitude [162]. It was also found that antihydrogen formation in the presence of $^9$Be$^+$ ions is not affected [162].

- **Adiabatic expansion cooling of antihydrogen**
  Adiabatic expansion cooling consists of adiabatically changing the shape of the magnetic well, which will perform work on the atoms and cool them. With the new ALPHA-2 atom trap, the length of the magnetic trap can be effectively expanded in the axial direction [163].

- **Nuclear magnetic resonance (NMR) transitions**
  When antihydrogen is in a trappable state ($|c\rangle$ or $|d\rangle$), the spin of the antiprotons can also be flipped. Such transitions are called NMR transitions. The transition frequency passes through a broad maximum at a magnetic field of 0.65 T, which makes the NMR transition much less sensitive to the magnetic field inhomogeneity [164]. At 0.65 T, the frequency corresponding to the $|c\rangle \rightarrow |d\rangle$ transition is about 655 MHz with a corresponding wavelength of about 46 cm. Since the wavelength is larger than the diameter of the electrodes, the radiation will not propagate down the electrode stack and a coaxial transmission line and a built-in resonator will be required [165].

- **Electric charge of antihydrogen**
  Using the experimental data from 2010 and 2011, ALPHA derived an experimental limit on the charge of antihydrogen. It was found that the charge of antihydrogen is $Q/e = (1.3 \pm 1.1 \pm 0.4) \times 10^{-8}$, where $e$ is the unit charge and the errors are from statistical and systematic effects [6]. It has been proposed that by applying randomly oscillating electric
fields to a sample of trapped antihydrogen, it should be possible to increase the precision of the measurement of the antihydrogen charge by several orders of magnitude [166, 167].

- **Gravity**

  Using again the experimental data from 2010 and 2011, ALPHA reported directly measured limits on the ratio of the gravitational mass \( M_g \) to the inertial mass of antihydrogen \( M \), \( F = \frac{M_g}{M} \). Ratios above \( F = 75 \) (statistics alone) and \( F = 110 \) (including worst-case systematic effects for gravity) and \( F = -65 \) (combined statistical and systematic effects) were ruled out [5]. It was found with simulations that, by cooling antihydrogen to \( \sim 30 \) mK, and by increasing the magnetic trap shut down time to \( \sim 300 \) ms, it could be possible to measure \( F \) to the level \( F = \pm 1 \) [5].
Part II

Antiproton cloud radial compression
Chapter 4

Non-neutral plasma confinement and radial compression in a Penning-Malmberg trap

In section 4.1, we discuss the motivation for antiproton cloud compression in antihydrogen experiments. Later, we give a theoretical overview of the confinement of non-neutral plasmas in a Penning-Malmberg trap (section 4.2). We also discuss the rotating wall mechanism, which consists of a rotating, time-varying, azimuthal, electric field and is used to radially compress non-neutral plasmas (section 4.3). ALPHA has been routinely using the rotating wall mechanism to compress antiprotons clouds and electron and positrons plasmas since 2008 [63]. In section 4.4, we describe how ALPHA sympathetically compresses the antiproton clouds with an electron plasma, which differs from the measurements found in this thesis, where the electron plasma is not directly compressed (chapter 6).

4.1 Motivation for the compression of antiproton clouds

When working with charged particles in Penning-Malmberg traps, it is necessary to counteract the slow expansion and loss of the plasma due to the imperfections in static fields and the presence of background gases (more details in section 4.3). Radial compression with the rotating wall mechanism has proven to be a very efficient way to increase the lifetime of particles inside a trap [168].
4.1. Motivation for the compression of antiproton clouds

During antihydrogen experiments, it is important to be able to control the radial size of the antiproton clouds and positron plasmas, and to avoid expansion and loss during preparation of the plasma for mixing.

As already mentioned in section 2.8.2, the presence of the octupole field, which is needed to trap the neutral antihydrogen, breaks the cylindrical symmetry of the Penning-Malmberg trap. Such disturbance causes the diffusion and expansion of confined non-neutral plasmas, but which can be counteracted with the rotating wall. Furthermore, the presence of the transverse magnetic field will cause the loss of particles beyond a critical radius since charged particles closely follow the magnetic field lines [169]. Radially small clouds of antiprotons are less sensitive to this perturbation.

Yet another reason to reduce the radial size of antiprotons clouds is to achieve good overlap between the antiproton cloud and the positron plasma during the formation of antihydrogen. As already mentioned in section 3.2, the rate of antihydrogen formation strongly depends on the positron plasma density. For this reason, the positron plasmas are typically small (∼ 0.9 mm) and when mixed with the antiprotons, a similar radial size for the antiproton cloud is needed to increase the probability of interaction between the two species.

A low kinetic energy is a requirement for trapping antihydrogen, since only antihydrogen atoms with energies less than 44 µeV (0.5 K) are confined in the trap, as already seen in section 2.8.2. Perhaps most importantly, the kinetic energy of antihydrogen formed from antiprotons and positrons depends on the azimuthal velocity of the former, $v_\theta$, which is expressed as:

$$v_\theta = \omega_{\text{rot}} r,$$

where $\omega_{\text{rot}}$ is the rotation frequency and $r$ is the radius of the cloud. If the antiproton cloud is compressed, the radius is reduced, and therefore the azimuthal velocity too. Since the electric field produced by the antiprotons is negligible, the azimuthal velocity is determined by the radial position of the plasma, and smaller antiproton clouds are almost always better.
4.2 Non-neutral plasma confinement in a Penning-Malmberg trap

A non-neutral plasma is a many-body collection of charged particles, in which the total charge is noticeably different from zero. The name, non-neutral plasma, was first used in the publication of Davidson’s monograph, *Theory of Nonneutral plasmas* (1974) [170]. Non-neutral plasmas share some of their properties with electrically neutral plasmas, such as plasma waves, instabilities, and Debye shielding [171]. On the other hand, such non-neutral plasmas are characterized by intense self-electric fields that play an important, and sometimes dominant, role in the plasma dynamics [172]. Non-neutral plasmas can be confined in Penning traps by static electric and magnetic fields and also be in a state of global thermal equilibrium, unlike neutral and quasi-neutral plasmas [172]. Examples of such plasmas are pure electron plasmas, positron plasmas, pure ion plasmas of one or more species and in our case, antiproton-electron plasmas.

4.2.1 Non-neutral plasma fundamental properties

The non-neutral plasma properties discussed in this section follow that of Ref. [133, 171]. Even though non-neutral plasmas are not charge neutral, they can be called plasmas because they have many collective properties common to neutral plasmas, as discussed above.

The plasma frequency is the most fundamental time-scale in plasma physics:

\[ \omega_p = \sqrt{\frac{ne^2}{\epsilon_0 m}} \]  

(4.2)

where \( n \) is the number density, \( e \) is the elementary charge, \( m \) the mass of the particle and \( \epsilon_0 \) is the vacuum permittivity. For a given density, electron plasmas have the fastest plasma frequencies because of the dependance of \( \omega_p \) on the mass of the particle. The plasma frequency corresponds to the typical oscillation frequency in response to the displacement of a small charge in the plasma. The plasma period \( \tau_p = 1/\omega_p \) is also of great importance, since plasma oscillation can only be clearly observed over time periods longer than \( \tau_p \). Similarly, plasmas can only be observed over
a length longer than the distance traveled by the plasma particle $\tau_p v$, where $v$ is the speed of the particle. This distance is called the Debye length:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T}{n e^2}},$$

(4.3)

where $T$ is the temperature, $k_B$ is Boltzmann constant and $n$ is the density of the plasma. $\lambda_D$ is independent of mass, so is generally comparable for all plasma species.

To be considered a plasma, the Debye length must be smaller than the overall dimensions of the system $L$:

$$\frac{\lambda_D}{L} \ll 1.$$  

(4.4)

A single charged particle inside a non-neutral plasma will attract other particles with opposite charge, or repel other particles with same charge. Plasma particles act collectively to cancel or shield the field of an extra charge introduced into the plasma. This phenomena is called Debye shielding [171]. Particles are shielded from external view and the particle’s Coulomb field falls off exponentially as $e^{-r/\lambda_D}/r$, instead of $1/r^2$, as for an isolated charge.

### 4.2.2 Plasma rotation frequency

The rotation frequency of the plasma is analogous to the magnetron frequency of a single charged particle (see section 2.3.1). Here, the non-neutral plasma self-electric field produced by the ‘self-charge’ or ‘space charge’ creates an $\vec{E} \times \vec{B}$ circular drift about the symmetry axis of the trap.

Many of the plasmas used in ALPHA are typically long and have small radii, and we can approximate them as infinite cylinders. Using the Lorentz force equations of motion, and Gauss’ law to find the radial electric field inside a infinite cylinder, we can calculate the rotation frequency [173].

Since $\vec{E}$ is perpendicular to $\vec{B}$ (i.e. $\vec{B} = B\hat{z}$ and $\vec{E} = E\hat{r}$), only the perpendicular equation of motion
4.2. Non-neutral plasma confinement in a Penning-Malmberg trap

is modified:

\[
m\frac{d\vec{v}(t)}{dt} = q(\vec{E} + \vec{v} \times \vec{B}). \tag{4.5}\]

A constant azimuthal velocity,

\[
\vec{v}_\theta = \frac{\vec{E} \times \vec{B}}{B^2} \tag{4.6}
\]

is a solution of equation 4.5, where \( \vec{v}_\theta = \omega_{\text{rot}} \hat{\theta} \).

From Gauss’ law, one can find that inside an infinite charged cylinder, the radial electric field is

\[
E_r = \frac{enr}{2\epsilon_0}. \tag{4.7}
\]

It will be shown in section 4.2.4 that the density is almost constant. The magnitude of the plasma azimuthal velocity can then be written as:

\[
v_\theta = \frac{enr}{2\epsilon_0 B_z} = \omega_{\text{rot}} r. \tag{4.8}
\]

The plasma rotation frequency \( \omega_{\text{rot}} \) is independent of the species’ charge, mass and radial coordinate, so that non-neutral plasmas are characterized by global rigid-rotation [174].

4.2.3 Theory of confinement

Confinement in a Penning-Malmberg trap is underpinned by the conservation of the total canonical angular momentum of the plasma [172]. As already mentioned in section 2.3, axial confinement is provided by the electrostatic field and radial confinement by the axial magnetic field. It can be shown that due to the \((\vec{E} \times \vec{B})\) forces, the plasma revolves about the magnetic field axis. The
canonical angular momentum is expressed as [172]:

\[
P_\theta = \sum_{j=1}^{N} mv_{\theta j} r_j - \sum_{j=1}^{N} |e|A_\theta(r_j)r_j,
\]

(4.9)

where \(m\) is the mass of the particles, \(v_{\theta j}\) is the azimuthal velocity, \(r_j\) is the distance from the axis of symmetry (radius) of the \(j^{th}\) particle, \(N\) is the total number of particles, \(|e|\) is the absolute value of the elementary electric charge and \(A_\theta\) is the azimuthal component of the vector potential. The first right-hand term of equation 4.9 is the total mechanical angular momentum and the second right-hand term comes from the rotation of the charged particles in the magnetic field. The vector potential of a uniform, axial magnetic field is \(A_\theta(r_j) = \frac{B r_j}{2}\), where \(\vec{B} = B \hat{z}\) and \(\vec{A} = A_\theta(r)\hat{\theta}\). Here \((r, \theta, z)\) denote a cylindrical coordinate system with the \(z\) axis coincident with the axis of symmetry of the trap. Equation 4.9 becomes:

\[
P_\theta = \sum_{j=1}^{N} mv_{\theta j} r_j - \sum_{j=1}^{N} \frac{|e|B}{2} r_j^2.
\]

(4.10)

For a strong magnetic field, the second term dominates, and the canonical angular momentum can be approximated as

\[
P_\theta \approx -\sum_{j=1}^{N} \frac{|e|B}{2} r_j^2.
\]

(4.11)

Since we are dealing with particles carrying a single sign of charge, the charge and the other constants can be excluded from the sum:

\[
P_\theta \approx -\frac{|e|B}{2} \sum_{j=1}^{N} r_j^2 \approx -\frac{|e|B}{2} < r^2 > N,
\]

(4.12)

where \(< r^2 >\) is the mean-square radius of the plasma.

Given the conservation of the total canonical angular momentum, we conclude that the mean-square
radius of the plasma must be approximately constant, hence the particles are largely confined. This is an important feature of non-neutral plasmas, distinct from neutral plasmas whose confinement has proven very difficult. In section 4.3 we show how increasing the canonical angular momentum results on plasma radial compression.

4.2.4 Global thermal equilibrium

Electron plasmas can evolve to a state of global thermal equilibrium after a long confinement time \[175\]. Plasma particles reach such global thermal equilibrium by Coulomb collisions with each other and, assuming conservation of the total energy and total canonical angular momentum, the thermal distribution of the plasma can be described by a one-particle distribution:

\[
    f(h, p_\theta) = n_0 \left( \frac{m}{2\pi k_B T} \right)^{3/2} \exp \left[ -\frac{1}{k_B T} (h + \omega p_\theta) \right],
\]

(4.13)

where \( h \) is the one-particle energy and \( p_\theta \) is the one-particle canonical angular momentum. Here

\[
    h = \frac{1}{2} m v^2 + e \phi(r, z),
\]

(4.14)

\[
    p_\theta = m v_\theta r + \frac{e B}{2} r^2
\]

(4.15)

and \( \phi(r, z) \) is the electric potential.

By substituting equations (4.14) and (4.15) into equation (4.13) the thermal distribution can be expressed as:

\[
    f(r, v) = n(r, z) \left( \frac{m}{2\pi k_B T} \right)^{3/2} \exp \left[ -\frac{m}{2k_B T} (v + \omega \theta)^2 \right],
\]

(4.16)

where

\[
    n(r, z) = n_0 \exp \left[ -\frac{1}{k_B T} [e \phi_R(r, z) + e \phi_p(r, z)] \right].
\]

(4.17)

\( \phi_R(r, z) \) is the effective trap potential in the rotating frame and \( \phi_p(r, z) \) is the plasma space-charge...
potential. Equation 4.16 is a Maxwellian velocity distribution rotating as a rigid body at a uniform rotation frequency $\omega$ (also called $\omega_{\text{rot}}$). For simplicity, we use $\Phi(r, z) = \phi_R(r, z) + \phi_p(r, z)$. The Maxwell-Boltzmann distribution becomes

$$n(r, z) = n_0 \exp \left[ \frac{e\Phi(r, z)}{k_B T} \right]. \tag{4.18}$$

The plasma density largely depends on the plasma’s space charge potential, so it is possible to find these two quantities by self-consistently solving Poisson’s equation:

$$\nabla^2 \Phi(r, z) = -\frac{en(r, z)}{\epsilon_0}. \tag{4.19}$$

Figure 4.1 shows measurements of the density and the rotating frequency over time as the plasmas reach a global thermal equilibrium state.

Figure 4.1: Experimental density and rotation frequency evolving over time to global thermal equilibrium as a function of radius. After 10 s, global thermal equilibrium is reached and the rotation frequency becomes almost constant as a function of radius, as for rotation of a rigid body. Image from [175].
Global thermal equilibrium solver

A global thermal equilibrium solver [176], developed by Prof. F. Robicheaux of Purdue University and extensively used by the ALPHA collaboration, has been used for the analysis of the experimental results of this thesis.

On providing the number of particles, peak intensity, temperature, electrode configuration and voltages, the algorithm outputs the charge density and potential in the trap. The calculation is initialized using an initial guess of the charge density to solve Poisson’s equation. After the electric potential is calculated, it is used to find a new charge density. The algorithm is repeated until both solutions (density and potential) converge to stable values. Figure 4.2 shows examples of the density as a function of radius calculated by self-consistently solving Poisson’s equation and the Maxwell-Boltzmann distribution and table 4.1 shows their plasma parameters. It has been demonstrated that, provided $\lambda_D \ll L$, the plasma density (equation 4.17) is nearly constant until the radius is within a few $\lambda_D$ of the edge and then falls off to zero. From figure 4.2, one can see that colder plasmas have a flatter density and almost abruptly falls off to zero, while for hotter plasmas, the density falls off more gradually.

<table>
<thead>
<tr>
<th>Number of electrons</th>
<th>Peak density [cm$^{-3}$]</th>
<th>Temperature [K]</th>
<th>$\lambda_{debye}$ [mm]</th>
<th>$L_z$ [mm]</th>
<th>$\omega_{rot}$ [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20\times 10^6</td>
<td>5\times 10^6</td>
<td>100</td>
<td>~0.3</td>
<td>~19</td>
<td>~2</td>
</tr>
<tr>
<td>20\times 10^6</td>
<td>1\times 10^8</td>
<td>100</td>
<td>~0.1</td>
<td>~37</td>
<td>~48</td>
</tr>
<tr>
<td>20\times 10^6</td>
<td>5\times 10^6</td>
<td>2000</td>
<td>~1</td>
<td>~19</td>
<td>~2</td>
</tr>
<tr>
<td>20\times 10^6</td>
<td>1\times 10^8</td>
<td>2000</td>
<td>~0.3</td>
<td>~35</td>
<td>~47</td>
</tr>
</tbody>
</table>

Table 4.1: Electron plasma parameters as calculated by a global thermal equilibrium solver [176]. Number of electrons and plasma temperature are input parameters, while the remaining parameters are output from the solver.

It is possible to force the solver to use a specific radial profile density. After each iteration, the density solution is normalized to the desired radial profile. In this case, the solution obtained will not in general correspond to global thermal equilibrium.
4.2. Non-neutral plasma confinement in a Penning-Malmberg trap

Figure 4.2: Calculated density as a function of radius for $20 \times 10^6$ electrons for different peak densities $n_0$ and different temperatures. Densities are normalized by their peak.

4.2.5 Antiproton-electron plasmas

Understanding antiproton-electron plasmas is very important when synthesizing antihydrogen. Electrons provide a source of cooling for the antiprotons while applying the rotating wall, and while performing manipulations before the production of antihydrogen (see section 2.4.2). For these reasons, electrons are important for the antiproton experiments performed in ALPHA.

In ALPHA, we usually refer to trapped electrons as an electron plasma. We typically use about $20 \times 10^6$ electrons in a plasma having $\sim 30$ mm length and $\lambda_D \sim 0.3$ mm. The self-electric field (space charge) of the electron plasma is large enough to create an $\vec{E} \times \vec{B}$ rotation, as explained in section 4.2.2. If a second species (antiprotons) is added to the electron plasma, the antiprotons will rotate under the influence of the electron plasma’s space charge. The number of antiprotons is small compared to the number of electrons (about $1.5 \times 10^5$ antiprotons) and thus has a negligible space charge. Also, the Debye length is large for a pure antiproton cloud. For these reasons, we refer to trapped antiprotons as an antiproton cloud, rather than a plasma.
Centrifugal separation

Centrifugal separation can be important for multi-species plasmas in a global thermal equilibrium state at low temperatures [177] and has been observed for species having different charge-to-mass ratios, for example, for laser cooled Be$^+$-ion [178-180] and Be$^+$-positron [181] systems.

ALPHA observed centrifugal separation between antiprotons and electrons in 2010 [182]. Figure 4.3 shows an example of centrifugal separation at $\sim 100$ K, for different magnetic fields. Centrifugal separation was also reported by the ATRAP experiment [183].

![Figure 4.3: Example of centrifugal separation of an antiproton-electron plasma in a (a) 1 T and (b) 3 Tesla magnetic field. Image from [182]](image)

Even though the centrifugal separation dynamics can be important when using antiproton-electron plasmas and synthesizing antihydrogen, it will not be discussed here since we do not observe it in the measurements of this thesis. The reason for this is that the temperatures of the antiproton-electron plasmas, about 500 K, are not low enough.

4.3 Rotating wall mechanism

In a perfect trap, plasmas can be confined for an indefinite time via conservation of the canonical momentum of the plasma [184]. However, in a real trap, asymmetries in the static fields and the
presence of background gases exert a drag on the plasma [184] and, as a consequence, there is a slow expansion and loss of particles [185–187]. Fortunately, non-neutral plasmas can be radially compressed using a time-varying rotating electric field, called a “rotating wall”.

The rotating wall was first developed by the non-neutral plasma group at the University of California in San Diego in 1997 to radially compress magnesium ion plasmas [168], see also work at TRIUMF in Ref. [188]. Later, compression of electron plasmas was achieved [189]. Heating when using the rotating wall was observed and to counteract these effects, cooling gases such as SF$_6$, CF$_4$ or CO$_2$ were added to positron plasmas [190].

A large amount of experimental and theoretical work has improved our understanding of the mechanism of the rotating wall. However, a complete microscopic theory remains a future goal. Fortunately, a macroscopic, phenomenological description provides a useful explanation of the most important features. In this theory, the rotating wall balances or exceeds the drag on the plasma by applying positive torque to the plasma [184]. From the equations of Theory of Confinement (section 4.2.3), we can see how applying a positive torque can reduce the radial size of the plasma.

Equation 4.12 shows the relation between the canonical angular momentum and the mean-square radius of the plasma. If the rotating wall applies a positive torque to the plasma:

$$\tau = \frac{dP_\theta}{dt} > 0$$  \hspace{1cm} (4.20)

then,

$$\tau \approx -\frac{|e|B}{2} \frac{d\langle r^2 \rangle}{dt} N > 0,$$  \hspace{1cm} (4.21)

which implies a decrease in the radius of the plasma:

$$\frac{d\langle r^2 \rangle}{dt} < 0.$$  \hspace{1cm} (4.22)

A positive torque will increase the canonical angular momentum while decreasing its magnitude (the canonical angular momentum is negative). Therefore $\langle r^2 \rangle$ will decrease and the plasma will
4.3. Rotating wall mechanism

compress.

One of the mechanisms to apply torque to the plasma is via excitation of plasma modes. It has been studied that it is possible to achieve plasma compression by exciting Trivelpiece-Gould modes (TG modes) [191-193]. TG modes are surface waves that rotate in the azimuthal direction. When they damp, the angular momentum associated with the wave is transferred to the bulk of the plasma. If the rotating wall continuously excites the TG modes, this results in a torque. Modes that rotate faster than the plasma are found to provide a positive torque, resulting in the compression of the plasma. On the other hand, modes rotating slower than the plasma provide a negative torque and expansion of the plasma is observed [193]. The degree of compression depends on the efficiency of coupling of the external torque to the plasma [194]. It was experimentally observed that an electron plasma compresses near the predicted and observed TG mode frequencies of the electron plasma (see figure 4.4) [191].

Figure 4.4: Measured compression rate of an electron plasma as a function of the rotating wall frequency $f_s$. The calculated and measured frequencies of different modes (labelled by $(m_\theta, m_z, m_r)$) are shown on the bottom. Image from [193].
Compression has been observed in several different regimes and there is not a single explanation that covers them all. Here is an overview of several compression regimes:

- **Weak drive**: For weak rotating wall excitations, it was shown that electric fields transfer torque to the plasma by exciting Trivelpiece-Gould plasma modes \([191]\). The Trivelpiece-Gould modes carry angular momentum that can be transferred to the particles by a wave-particle coupling \([189]\) as discussed above, also see section 7.1.3.

- **Strong drive**: When a larger amplitude rotating electric field coupled with a source of cooling is used, compression over a broad range of frequencies, without the need to couple the plasma to a specific mode, is observed \([195-197]\).

- **Sideband cooling**: The sideband cooling mechanism in the single particle regime relies on the coupling of the cyclotron or axial motion with the magnetron motion of the particle produced by the rotating electric field. For example, the excitation of the cyclotron mode leads to a decrease of the radius of the magnetron mode, which results in the “axialization” of particles (i.e. the particle radially moves towards the axis), see section 7.1.6.

- **Bounce resonant transport**: The resonance on the bounce transport (axial and rotation motion) of particles (plasma or single particle regime) can result in compression (see section 7.1.7).

- **Sympathetic compression**: With two species of particles, compressing one species with the rotating wall can cause the other species to follow via Coulomb collisions \([63]\). ALPHA performs this type of compression, by applying a rotating wall to an antiproton-electron plasma, to compress the electron plasma that sympathetically compresses the antiproton cloud (see section 4.4).

The rotating electric field is produced by an electrode divided into azimuthally isolated segments and by applying to each segment a sinusoidal potential \(V_{\omega_j}\) of frequency \(\omega_{RW}\) and phase \(\theta_j = 2\pi j/k\),
where $k$ is the number of segments. The potential is then:

$$V_{\omega j} = A_\omega \cos[m_\theta(\theta_j - \omega_{RW}t)]$$

(4.23)

where $m_\theta = 1$ corresponds to the dipole mode and $m_\theta = 2$ to the quadrupole mode. Figure 4.5 illustrates a six-segmented rotating wall setup, where a sinusoidal waveform voltage generator is connected to each segmented electrode with a phase shift of 60°.

Figure 4.5: Schematic representing a transverse section of the rotating wall. A sinusoidal potential is applied to a six-segmented electrode with a phase difference of 60° between each segment. The red circle illustrates the plasma, and the blue arrow the direction of rotation.

In ALPHA, the amplitude of the rotating wall can vary between 0 V to 10 V. Figure 4.6 shows the rotating wall potential for various phases. In ALPHA, the generator is AC coupled to the electrode, so when applying the rotating wall, the potential of the segmented electrode is added to an overall bias potential.
4.4 Sympathetic compression of antiproton clouds

In 2008, ALPHA published a paper with the first detailed measurement of radial compression of antiproton clouds in the ALPHA1 apparatus [63]. This paper summarizes the procedure for the antiproton cloud radial compression that was used in the experiments to trap antihydrogen. A rotating wall drive with a frequency in the $10 \text{ MHz}$ range is applied to the antiproton-electron plasma. Such a drive radially compresses the electrons plasma that is co-located with the antiproton cloud. When the electrons move towards the centre of the trap, it is thought that the electrons transfer angular momentum to the antiprotons by Coulomb collisions and, as a consequence, the antiproton cloud also becomes radially smaller. Such compression is called "sympathetic compression". Antiproton clouds were compressed to a radius as small as $0.29 \text{ mm}$ in a $3 \text{ T}$ magnetic field when applying the rotating wall at $\omega_{RW}/2\pi = 20 \sim 25 \text{ MHz}$ [63].

Sympathetic compression differs from the direct compression studied in this thesis (chapter 6) by the fact that for the sympathetic compression, the rotating wall acts directly on the electron plasma (in the $10 \text{ MHz}$ range). This was demonstrated by applying the rotating wall drive in the absence of

Figure 4.6: Rotating wall radial potential when applying a $1 \text{ V}$ sinusoidal potential to the 6 segmented electrode. Each image illustrates the potential at different phases: a) $0^\circ$, b) $60^\circ$, c) $120^\circ$, d) $180^\circ$, e) $240^\circ$ and f) $300^\circ$. 

4.4 Sympathetic compression of antiproton clouds
antiprotons and observing that the electron plasma compresses.

The electron plasma used during sympathetic compression typically has a radius of about 0.8 mm and its rotation frequency and axial bounce frequency is in the 10 MHz range. As stated in Ref. [63], the electron plasma is unchanged when applying the rotating wall at \( \omega_{RW}/2\pi = 400 \text{ kHz} \). This frequency is in the same range as the antiproton axial bounce frequency.

Figure 4.7 shows some typical examples of compression after applying the rotating wall for 1 s, 20 s and 60 s. The bare antiproton MCP images are obtained by ejecting the electrons just before dumping the particles to the MCP. One can see that the electron plasma clearly compresses when applying the rotating wall and the antiproton clouds’ radial sizes follow that of the electron plasma. There are about 11,000 antiprotons captured and cooled and the smallest radius measured at this frequency is 0.42 mm.

Figure 4.8 shows the electron plasma radius and the antiproton cloud density as a function of the rotating wall compression time. These measurements were performed for both slow and fast electron plasma compression. Fast compression is achieved by increasing the rotating wall voltage by a factor of 5 with respect to the slow compression. One can observe in figure 4.8a that during fast compression, the electron plasma takes as little as 5 s to reach a minimum size, compared to the slow compression, which takes at least 45 s. However, the antiproton cloud only compresses when the slow electron plasma compression is used (see fig. 4.8b). It is thought that during fast compression, the antiprotons are “left behind” in a region of low electron density, because the antiproton-electron collision rate is too low to keep the two species coupled.

Figure 4.9 shows the electron plasma radius as a function of the antiproton cloud radius for different compression times. The measurements were performed using slow compression. The radii of both species get proportionally smaller as the compression time increases, showing that the electron plasma radius and the antiproton cloud radius compress at similar rates.

The smallest antiproton cloud radius achieved was 0.29 mm, using frequencies of about 20 – 25 MHz. These measurements use frequencies that directly compress the electron plasma, which is a different approach from the one in chapter 6 where for the frequencies applied, the rotating wall does not act
4.4. Sympathetic compression of antiproton clouds

Figure 4.7: Example of the radial compression of an antiproton-electron plasma for $\omega_{RW}/2\pi \sim 10$ MHz. The center figures are MCP images at different times. It is observed that electron plasma is radially compressed. The outer columns show their resulting radial profiles, where the red lines are generalized Gaussians [i.e. $\exp(-|r/r_0|^k)$ where $k \approx 2$] fitting the radial profiles. Image from [63].
4.4. Sympathetic compression of antiproton clouds

Figure 4.8: (a) Electron plasma radius as a function of compression time for slow and fast compression. The electron plasmas is radially compressed for both kinds of compression to a similar radius. (b) Antiproton cloud density as a function of time of compression for slow and fast compression. It is observed that the antiproton cloud is not radially compressed in fast compression. Image from [63].
4.4. Sympathetic compression of antiproton clouds

Figure 4.9: Electron plasma radius as a function of antiproton cloud radius. Measurements are performed for different times of compression (slow compression) and it is suggested that both radii are proportionally compressed. Image from [63].

directly on the electron plasmas.

4.4.1 Antiproton cloud compression by the ASACUSA collaboration

In the same year (2008), the ASACUSA collaboration published a paper in which antiproton clouds were radially compressed, but without the use of an electron plasma or any other source of cooling [201]. The antiproton cloud compression was achieved at frequencies between 200 kHz and 1000 kHz. Figure 4.10 shows the observed compression of the antiproton clouds as a function of the rotating wall frequency.

The ASACUSA collaboration concluded that there are no resonant structures in their range of frequencies, and that the compression is phenomenologically similar to the strong drive compression. At this point, there is no full understanding of the compression mechanism.

Even though the ASACUSA collaboration used the same frequencies that we use in the measurements of this thesis, the inclusion of electrons drastically changes the potential due to the space charge. Also, the cooling provided by the electrons could potentially change the behaviour of the antiprotons.
4.4. Sympathetic compression of antiproton clouds

Figure 4.10: Transport efficiency $\varepsilon_{\text{exp}}$ as a function of the rotating wall frequency. $\varepsilon_{\text{exp}}$ is the ratio of the number of antiprotons detected to the number of the trapped antiproton, which increases as the radius gets smaller. Figure a) shows a wide range of rotating wall frequencies, while figure b) shows the results of the compression around 247 kHz (sideband frequency). Image from [201].

4.4.2 Antiproton cloud compression by the ATHENA collaboration

In 2006, the ATHENA collaboration reported evidence of sideband cooling of antiprotons in an electron gas [202]. It consisted of applying a quadrupolar excitation at the cyclotron frequency (~45 MHz), which converts the magnetron motion of all or some of the antiprotons to cyclotron motion. The experiment was performed using thousands of antiprotons and between 1 and $3\times10^6$ electrons. In order to find the exact cyclotron frequency, the frequency of the quadrupolar excitation was scanned around the expected cyclotron frequency. It was found that about 20–40% of antiprotons appeared to be affected by the excitation. It was assumed that the final magnetron radius should be of the same order as the cyclotron radius, but no direct measurements were made that could support this.
Chapter 5

Experimental setup for the compression of antiproton clouds in ALPHA-2

In this chapter, we describe the experimental set-up used in the measurements on antiproton cloud compression in ALPHA-2. This includes: 1) antiproton capture in the Penning-Malmberg trap, 2) antiproton cooling by the electron plasma, 3) manipulation of the potential to move the particles axially, 4) ejection of the electrons from the trap, 5) application of the rotating wall and 6) detection of the particles.

5.1 Capturing antiprotons and secondary electrons

In this section, we first focus on the capture of antiprotons. Then, we introduce the production and capture of secondary electrons, which are used in the measurements of antiproton cloud compression.

5.1.1 Antiproton capture in ALPHA-2

The degrader in ALPHA-2 consists of four layers: two beryllium (Be) and two aluminium (Al) foils. Table [5.1] is a summary of the degrader layers’ thicknesses. The degrader is divided into four layers because each layer also has a secondary use. After entering the experiment from the AD, the antiprotons first encounter the tuneable Al degrader. It is possible to have access to this layer to change the thickness without dismantling most of the apparatus. This allows the thickness
to be optimized for the maximum number of antiprotons trapped. Nevertheless, this still requires opening the vacuum system and was performed only 5 times during 2012. The second layer, with a thickness of 10 µm, is part of the heat shield between the 4 K section and the room temperature environment, and is cooled to ~ 40 K. The third layer that the antiprotons encounter is the 50 µm Be vacuum window that separates the isolation vacuum and the ultra-high quality trap vacuum. The last layer is the Faraday cup (FC), which is made of Be with a thickness of 165 µm. The FC collects charge and can be used to measure the number of electrons that are incident on it. The precision of the thickness of the Be layers is quoted by the manufacturer to be between 10% to 15%. The Al layers were measured during commissioning of the trap and have an uncertainty less than 5%. Due to these uncertainties, it was necessary to experimentally optimize the thickness by measuring the antiproton capture efficiency for different thicknesses.

More information about the energy loss and the range of the antiprotons is presented in appendix A.

Figure 5.1 shows the results of an experiment to measure the efficiency of capturing antiprotons as a function of the tuneable degrader thickness. The antiproton capture efficiency is the percentage of antiprotons captured with the 5 keV electrodes, measured by annihilations on the scintillators, as a function of the initial number of antiprotons, measured by a current transformer in beam line (section 2.4.2). The best efficiency was achieved when the tuneable degrader had a thickness of (26 ± 1.3) µm.

The “closing time”, the time between the beam extraction signal from the AD and switching the E01 voltage to trap antiprotons (see figure 2.10 in section 2.4.2), is also experimentally tuned and figure 5.2 shows the antiproton capture efficiency as a function of the closing time. Note that there is
5.1. Capturing antiprotons and secondary electrons

![Graph: Measurement of the antiproton capture efficiency as a function of the thickness of the tuneable degrader. The efficiency was calculated from the incident number of antiprotons. The optimal thickness is \((26 \pm 1.3) \mu m\).

A constant offset, so a closing time \(= 0\) does not mean the time of the antiproton arrival. The optimal time is 430 ns, where the highest fraction of antiprotons are captured. If \(E_{01}\) is raised too late, the fastest antiprotons from the distribution reflected by the potential of \(E_{13}\) escape back towards the AD. If \(E_{01}\) is raised too fast, the voltage prevents a fraction of the antiprotons from even entering the capture region.

The 5 kV voltage applied to \(E_{01}\) corresponds to the highest possible voltage that can be applied to the electrodes and cabling without risking sparking or discharging. Figure 5.3 shows the measurements of the antiproton capture efficiency as a function of \(E_{01}\) voltage. As expected, we can see that the number of captured antiprotons increases monotonically with the voltage applied.

5.1.2 Secondary electrons

Electrons provide cooling to the antiprotons and, in ALPHA, were produced by thermionic emission from a filament and loaded into the trap before capturing the antiprotons (see section 2.4.2). For the measurements discussed in chapter 6 we used a new technique, where secondary electrons are created during the passage of the antiprotons during the degrading process. Antiprotons lose energy
5.1. Capturing antiprotons and secondary electrons

Figure 5.2: Antiproton capture efficiency as a function of the closing time. The optimal time is 430\,ns.

Figure 5.3: Antiproton capture efficiency as a function of E01 voltage.
5.1. Capturing antiprotons and secondary electrons

in the degrader via excitation and ionization of the atoms. When an antiproton deposits energy that exceeds the binding energy of an electron in an atom of degrader material, the electron is ejected from the atom. The electron can escape the material into free space. In some cases, these secondary electrons have enough energy to produce further ionization \[203\].

If the energy transferred by the antiproton to an atom is lower than the binding energy, electrons in low energy levels can be excited. When they decxite, the energy is released in the form of electromagnetic radiation or Auger electrons \[204\]. Finally, if an antiproton annihilates, high energy pions are produced which can also liberate electrons from the material.

In summary, there are many ways that electrons can be ejected from the atoms to become part of the particle beam.

Previously, production of secondary electrons was considered to be an undesirable effect. This is the first time they have been used to cool antiprotons. This technique can be useful when using the antiproton capture trap as an accumulator, since electrons do not need to be loaded while antiprotons are already present. Additionally, it can be useful as a backup if the electron gun is fails.

Figure 5.4 shows an schematic of the antiproton and secondary electron capture, similar to figure 2.10 which also shows the production and capture of secondary electrons.

Figure 5.5a shows the ratio of the number of secondary electrons captured to the number of antiprotons extracted from the AD, \(N_{e/\mathrm{p}}\), as a function of the closing time. The time at which the maximum occurs is shorter than that for antiprotons alone (figure 5.2) because for the same energy, electrons have a higher velocity than antiprotons. Figure 5.5b shows \(N_{e/\mathrm{p}}\) as a function of the E01 voltage, which only changes for voltages below about 2 kV.

To measure the energy of the captured secondary electrons, a voltage was applied to E02 during the extraction of the antiprotons, to block the secondary electrons with the axial energy below a certain level. \(N_{e/\mathrm{p}}\) as a function of the blocking voltage is shown in figure 5.5c. Almost all electrons are blocked at voltages above 10 V. Clearly, there is a contradiction between 5.5b and 5.5c. Almost all the secondary electrons are blocked at about 10 V, so it is not understood why only half of the
5.1. Capturing antiprotons and secondary electrons

Figure 5.4: Schematic illustration of the antiproton and secondary electron capture. The black curve is the electric potential, the red dots are the antiprotons and the blue dots are the electrons. a) Antiproton beam before passing though the degrader (grey layer). b) After the antiprotons pass through degrader, secondary electrons are created. c) Particles with an energy less than 5 keV are reflected by the high voltage electrode E13. d) The voltage in electrode E01 is then raised, and both the antiprotons and secondary electrons are trapped.
5.1. Capturing antiprotons and secondary electrons

Figure 5.5: a) The number of secondary electrons, normalized to the number of incident antiprotons as a function of the closing time. The optimal time is 200 ns. b) The number of secondary electrons normalized to the number of incident antiprotons as function of E01 at a closing time of 430 ns. c) The number of secondary electrons normalized to the number of incident antiprotons as a function of the blocking voltage.
electrons are trapped when E01 is at 0.5 keV.

5.2 Antiproton cooling

After capturing the antiprotons and the secondary electrons, we perform the cooling process. Our goal is to cool a large number of captured antiprotons to energies below a few electron-volts. A potential well is constructed so that the antiprotons and electrons can accumulate in the minimum of the well. The electrons exchange energy with the antiprotons through Coulomb collisions and lose this energy via cyclotron radiation emission. The cooling efficiency depends on the time for which the particles are allowed to interact, the number of electrons, and the radial overlap between the antiprotons and electrons.

After the cooling has finished and a large number of antiprotons have been cooled, the high voltage on E01 is turned off, and any uncooled “hot” antiprotons escape to annihilate on the degrader. The number of hot antiprotons is measured by detecting the particles resulting from the annihilation with the scintillators. Figure 5.6 illustrates the cooling process with secondary electrons.

We also varied the closing time to study how the antiproton cooling efficiency changes. The results are shown in figure 5.2. For loaded electrons separately, the number of electrons is constant. However, for secondary electrons the number changes with the closing time, as can be seen in figure 5.5. For loaded electrons, the antiproton cooling efficiency seems to be the same (40 %) at all values of closing time. For secondary electrons, the maximum cooling efficiency is around 90 %, but decreases for smaller numbers of secondary electrons (i.e. longer closing time). It is apparent that the radial size of the plasma plays an important role in the antiproton cooling. We can infer that the high antiproton cooling efficiencies are possible because the electrons occupy the same volume as the antiprotons. We estimated that the radial size of the secondary electron plasma is ~ 4 mm (see section ). When electrons are loaded from the filament, there is no guarantee that the electron plasma has the same radial size as the antiprotons, which can lead to lower antiproton cooling efficiency. Typical sizes of the loaded electron plasmas are ~ 0.5 mm.
Figure 5.6: Schematic illustration of the antiproton cooling process. a) Well potential produced by the electrodes after the capture. A 100 V voltage on two electrodes is used to create the cooling well. The electrodes are illustrated at the top of the image. b) Antiprotons and electrons after the cooling time. Cool antiprotons and electrons fall into the cooling potential well, but a few antiprotons remain hot. c) The voltage on E01 is turned off to release the remaining hot antiprotons, which strike the degrader and their annihilation is detected.
All the measurements of antiproton cloud compression reported in chapter [6] of this thesis were performed with secondary electron cooling. About $1.5 \times 10^5$ antiprotons are cooled with about $20 \times 10^6$ electrons participating in the cooling.

![Cooling efficiency and number of cold antiprotons](image)

Figure 5.7: a) Antiproton cooling efficiency as a function of closing time, and b) number of cold antiprotons as a function of closing time for secondary electrons and loaded electrons.

### 5.3 Pulsed electron ejection

By taking advantage of the difference between the masses of antiprotons and electrons, we can remove a fraction, or all, of the electrons from the antiproton-electron plasma. Figure [5.8] shows a schematic of the electron ejection method. The process works by applying a short pulse ($\sim 100$ ns) to the voltage of one of the electrodes that confines the electrons. The well opens and a fraction of the electron plasma escapes. On the other hand, the antiprotons remain trapped since they are heavier and move much more slowly than the electrons. The short voltage pulse can be applied several times, depending on whether a partial or total ejection of the electrons is needed.

During the measurements of the antiproton cloud compression, we used the electron ejection method to change the number of electrons after antiproton cooling while keeping the number of antiprotons constant. We used $20 \times 10^6$, $12 \times 10^6$, $7 \times 10^6$ and $4 \times 10^6$ electrons.
5.3. Pulsed electron ejection

Figure 5.8: Schematic illustration of electron ejection while holding antiprotons. 

a) Potential well produced by the electrodes before the electron ejection. The electrodes are illustrated at the top of the figure. 

b) E03 (hatched pattern on the top) is pulsed. A fraction of the electron plasma has enough time to escape from the well, while the antiprotons move too slowly to escape. 

c) The potential well is restored after the pulse. Most of the antiprotons are kept, while only a fraction of the electrons remain trapped.
5.4 Rotating wall application

Following removal of some of the electrons, the antiproton-electron plasma is moved to a position near the rotating wall electrode. The typical voltages applied to the electrodes and the resulting potential well in the absence of the plasmas are shown in figure 5.9. The bare potential was chosen to be harmonic near the centre of the potential. The harmonic approximation is shown as the red line. However, we will see later that, due to the electron space charge, the potential experienced by an individual particle is far from being harmonic.

![Diagram showing potential well and electrodes](image)

Figure 5.9: The boxes on the top represent the electrodes and show the voltage applied to them. The black curve is the resulting potential and the red curve is a quadratic function that approximates the potential in the central region, where it was intended to be harmonic.

Note that the rotating wall electrode (in purple) is at one side of the centre of the potential well. Experimentally, we have found that compression works better in this configuration than if the electrode is centred on the cloud.

Figure 5.10 shows the potential well including the space charge of the electrons, which is very different from the vacuum potential (the potential without space charge).

We typically apply the rotating wall for 100 s and the amplitude can be varied up to 10 V. At low
5.4. Rotating wall application

Figure 5.10: Voltage applied to the electrodes and the resulting on axis potential for different numbers of electrons. The potential is calculated by simultaneously solving the Poisson and Boltzmann equations. The purple electrode and hatched region illustrates the position of the rotating wall electrode. The black curve is the vacuum potential.
amplitudes, the generator itself produces low-quality waveforms. A 20 dB attenuator is used to provide weaker drives, while keeping the generator amplitude high. These amplitudes refer to the voltages at the input of the passive RC-filter. The signal then passes through the passive RC-filter and the electrode cabling, which attenuates the amplitude by an unknown factor.

The rotating wall frequency is defined by a sweep with initial and final frequencies separated by 0.2 kHz. These cannot be identical for technical reasons. During the measurements we usually sweep from high to low frequencies. Reverse sweeps were also applied and the results found to be identical. The width of the frequency sweep was chosen to be very small, so we can consider the frequency to be constant to a precision of 0.1 kHz.

5.5 Detection and analysis of antiproton clouds

After applying the rotating wall, the antiproton-electron plasma is “dumped” (ejected from the well) onto a micro-channel plate (MCP). For more information about the MCP/phosphor/CCD detector assembly, refer to section 2.7.2. The dump is performed by slowly raising the potential (i.e. reducing the depth of the well) on the right side of the well and letting the particles escape. Figure 5.11 illustrates how the potentials change during the dump of the antiproton-electron plasma onto the MCP.

When the particles are released, in the adiabatic limit the antiprotons and the electrons follow the axial magnetic field lines, which are generated by the 3 T solenoid and a transfer solenoid placed between the trap and the MCP. Figure 5.12 shows the magnetic field along z. The magnetic field at the MCP is 0.042 T, so the particles move from a high to a low magnetic field region. Since the magnetic field lines diverge, the sizes of the particles’ orbits increase. From the third adiabatic invariant, the total magnetic flux $\phi$ passing through a drift surface $S$ is conserved for adiabatic processes [133]:

$$\phi = \int_S B \cdot ds = \text{constant.}$$ (5.1)
5.5. Detection and analysis of antiproton clouds

Figure 5.11: Schematic illustration of the particle dump to the MCP. a) Potential well before the procedure. b) The potential is lowered before the ejection of the particles. c) The voltage on the electrode holding the particles is raised to allow the particles escape. The particles are released to the right, where they strike the MCP.
5.5. Detection and analysis of antiproton clouds

We can deduce that the radius of the plasma changes as:

\[ r_{\text{trap}} = r_{\text{MCP}} \sqrt{\frac{B_{\text{MCP}}}{B_{\text{trap}}}} \]  

(5.2)

where \( r_{\text{trap}} \) is the radius of the plasma in the trap region when the magnetic field is \( B_{\text{trap}} \). \( r_{\text{MCP}} \) is the radius of the plasma in the MCP region when the magnetic field is \( B_{\text{MCP}} \). When showing MCP images in this thesis, the scale bars are the size of the plasma inside the trap (3 T), calculated from equation (5.2).

Figure 5.12: Magnetic field as a function of the axial position. The vertical red line is the MCP position. \( z = 0 \) is the centre of the antiproton trap. A small solenoid is placed at \( z = 1.2 \) m to guide the particles.

We use this radius conversion for electron plasmas and antiproton clouds, even though it is not a perfect scaling since the adiabatic requirement may not always be fulfilled. This depends on the mass of the particles. The electrons are tightly bound to the field lines and follow them very closely, contrary to the antiprotons, which are not so strongly bound to the field lines and experience a centrifugal drift in the region of low magnetic field [85]. Also, the magnetic field axis and the electrode axis are not perfectly aligned, causing an off-set between the positions of the two particles. We always observe that the antiprotons are on the left side of the MCP image and electrons on the
5.5. Detection and analysis of antiproton clouds

right side, as shown in figure 5.13. If the alignment was perfect, the two species should overlap.

Figure 5.13: MCP image of an antiproton-electron plasma after applying the rotating wall. The large outer circle in the background of the image is due to a mechanical aperture. The antiproton cloud is at the left hand side of the image, with an ellipse-like shape. Next to the antiproton cloud, at the right hand side, the electron plasma has a circular shape. The scale bar is the size of the plasma inside the trap (3 T), calculated from equation 5.2.

To extract information from the image, we performed a two dimensional Gaussian fit. This is implemented in the ROOT Data Analysis Framework [205]. Since the antiproton cloud has an elliptical shape and has tilted axes, a fit of the following form was performed:

\[ B + n_\bar{p} \exp \left( - \left( a (x - x_0)^2 + 2b(x - x_0)(y - y_0) + c (y - y_0)^2 \right) \right) \] (5.3)

where \( B \) is the background on the MCP, \( n_\bar{p} \) is the height of the peak (central density) and \((x_0, y_0)\) is the centre of the cloud. The coefficients \( a, b \) and \( c \) are:

\[ a = \frac{\cos^2 \theta}{2\sigma_x^2} + \frac{\sin^2 \theta}{2\sigma_y^2} \] (5.4)

\[ b = -\frac{\sin 2\theta}{4\sigma_x^2} + \frac{\sin 2\theta}{4\sigma_y^2} \] (5.5)

and

\[ c = \frac{\sin^2 \theta}{2\sigma_x^2} + \frac{\cos^2 \theta}{2\sigma_y^2} \] (5.6)

where \( \theta \) is the angle between the ellipse axis and the vertical axis and \( \sigma_x \) and \( \sigma_y \) are the semi-axial
5.5. Detection and analysis of antiproton clouds

lengths of the cloud. There are a total of 7 free parameters.

For electrons, the distribution detected is nearly circular and is fit well by a generalized Gaussian:

\[ B + n_{e^-}\exp\left(-\frac{1}{2}\left(\sqrt{\left(\frac{x-x_0}{\sigma}\right)^2 + \left(\frac{y-y_0}{\sigma}\right)^2}\right)^k\right) \]  

(5.7)

where \( n_{e^-} \) is the central density of the electron plasma and \( k \sim 2 \). When an antiproton-electron plasma is detected, the fit with the sum of equation 5.3 and equation 5.7 is implemented. Figure 5.14 shows an example of the resulting fit for the data across one line of the MCP image.

Figure 5.14: a) MCP image of an antiproton-electron plasma after applying the rotating wall. The large circle in the background of the image is due to a mechanical aperture. The antiproton cloud is on the left hand side of the image, with an ellipse-like shape. Next to the antiproton cloud, on the right hand side, the electron plasma has a circular shape. b) Dots are the data from the radial profile across the arrow shown in a) and the (red) curve is the respective fit. Position and sizes of the plasma are calculated from equation 5.2 so that they correspond to the size in a magnetic field of 3 T.

To allow comparison of the images, the same voltages were always applied to the MCP, so the gain was fixed and low enough to avoid saturation of the signal. It is known that the brightness on the MCP is linearly proportional to the charge \[85\]. We calibrate the MCP brightness using independent measurements of the number of particles. The electron number is measured with the FC (see section 2.7.1) and the antiproton number is measured with the scintillators/PMTs (see section 2.7.3).

For all measurements of the antiproton cloud compression we use the central density \( n_p \), not the
5.5. Detection and analysis of antiproton clouds

radius, as a measure of the degree of compression. This is because for MCP images, when there is no significant compression and the plasma is larger than the mechanical aperture, the radius has to be determined indirectly, while the central density can always be observed.

However, even when the plasma is larger than the MCP mechanical aperture, it is necessary to estimate the radius of the plasma. For these cases, we use $n_\bar{p}$ and the number of particles from independent measurements, to calculate the radius of the plasma.
Chapter 6

Antiproton cloud radial compression measurements

In this chapter, we present data showing evidence of direct antiproton cloud compression.

The rotating wall is applied to a mixed antiproton-electron plasma and the degree of compression of the antiproton cloud is measured by imaging it on an MCP. As we will see, we can achieve good compression at frequencies in the range 100 kHz – 750 kHz.

We will examine different aspects of the compression. We study the performance of the compression as we vary the rotating wall frequency, the electron and antiproton number, the compression duration, and the rotating wall amplitude, among others.

6.1 History of the measurements

As already discussed in section 4.4 in ALPHA, we typically use sympathetic compression when reducing the radial size of the antiproton clouds. During the periods of antiproton beam, from around June to November each year, the ALPHA experiment receives about 8 hours of antiproton beam per day. During the beam time, one of our goals is to optimize the antiproton clouds for antihydrogen formation and trapping. Once this is successfully done, the beam time is dedicated to perform measurements on antihydrogen.

Since the antiproton beam is scarce, the baseline and optimization of the positron plasma is performed a few hours before the antiproton beam time. Similarly, a study of the electron plasma
6.2 Observation of a new regime of antiproton cloud compression

Compression is performed, so that we can use optimal parameters when the antiproton beam arrives. The parameters do not change very much from one day to another.

An advantage of sympathetic compression is that optimal parameters can be determined before the beam time. One must do this carefully because sympathetic compression involves requirements, such as the compression speed, which need to be slow enough to allow the antiprotons to follow the electrons. Some antiproton beam time can be used to check this.

Since this compression technique worked well for ALPHA’s purposes, measurements of the antiproton cloud compression at frequencies where the electron plasma does not compress had not been carried out.

However, during the ALPHA-2 apparatus commissioning in November 2012, we had an exceptional opportunity to study antiproton cloud compression in the antiproton capture trap, while the atom trap was being commissioned. Inspired by the ALPHA collaborators Isaac et al. paper “Compression of positron clouds in the independent particle regime” [206], where positron clouds were compressed by applying the rotating wall close to the axial bounce frequency, we decided to attempt compression of the antiproton clouds near the axial bounce frequency of the antiprotons (100 kHz range). We noted that the electron plasma does not compress in that frequency range.

During this time, for technical reasons, the loaded electron number and size were fluctuating on a day-to-day basis. The use of secondary electrons had proven to be more stable, thus we used them during the measurements of the antiproton cloud compression.

Once the atom trap was commissioned, the use of the beam time was fully used to trap antiprotons in the atom trap. Due to the scarcity of the antiproton beam, the data we were able to collect is relatively limited compared to experiments that do not depend on an accelerator beam.

6.2 Observation of a new regime of antiproton cloud compression

In this section, we give quantitative evidence of a new regime of antiproton cloud compression. We first present the initial conditions, and then results of the compression of the antiproton clouds.
6.2. Observation of a new regime of antiproton cloud compression

as a function of the rotating wall frequency. We performed these measurements when cooling with different numbers of electrons. We also report on experiments using only electrons or only antiprotons.

6.2.1 Initial conditions

Figure 6.1 shows a typical MCP image of the antiproton-electron plasma before applying the rotating wall. The intensity of the image is low and the edges of the plasma are not visible (the circle in figure 6.1 is the result of a mechanical aperture), meaning that the radius of the plasma is larger than the mechanical aperture. The aperture has a radius of about 1 mm in the trap.

![MCP image of antiproton-electron plasma](image)

Figure 6.1: MCP image of an antiproton-electron plasma before applying the rotating wall. The scale bar is calculated from equation 5.2, so that it corresponds to the size in a magnetic field of 3 T.

We indirectly estimated the radius in the initial conditions from MCP images by using the central density, and the number of particles measured by the Faraday cup. By inverting equation 5.7, we determined the radius to be $3.2 \pm 1.5$ mm. The error bar is the standard deviation of shot-to-shot fluctuations. Simulations of the antiproton degrading process predict that the radius is about 4 mm [63].
6.2. Observation of a new regime of antiproton cloud compression

6.2.2 Antiproton cloud radial compression for various frequencies and electron numbers

The measurements were performed with $1.5 \times 10^5$ antiprotons and with different numbers of secondary electrons: $4 \times 10^6$, $7 \times 10^6$, $12 \times 10^6$ and $20 \times 10^6$ electrons. The number of electrons is selected by executing the electron ejection procedure described in section 5.3 and by varying the number or strength of the pulses applied.

Examples of MCP images are presented in figure 6.2, for different numbers of electrons. Each image shows the best antiproton compression observed when varying the rotating wall frequency, for different number of electrons. Comparing the images, one can observe that compression of the antiproton cloud varies with the number of electrons. The smallest clouds are those cooled by a large number of electrons ($12 \times 10^6$ and $20 \times 10^6$ electrons). A striking difference between the images is the evident compression of the electron plasma when using high numbers of electrons ($12 \times 10^6$ and $20 \times 10^6$ electrons). About 15% of the electron plasma is being compressed in these images, with the rest appearing as a diffuse background. Such partial compression of the electron plasma is a qualitatively new behaviour since, as will be seen in section 6.2.3, a pure electron plasma does not compress in the frequency ranges used. We deduce that this new behaviour is due to the presence of the antiprotons.

After showing how compression changes as a function of the electron number, we will discuss compression as a function of frequency. Figure 6.3 shows MCP images of antiproton compression at different frequencies for different numbers of electrons. We observed, for different numbers of electrons, that at low frequencies ($\sim 100$ kHz), the compressions look very similar. As the frequency increases, compressions for $4 \times 10^6$ and $7 \times 10^6$ electrons seem similar (note that the frequencies are different), while when using $12 \times 10^6$ and $20 \times 10^6$ electrons, the compression process clearly produces a compressed electron plasma next to the antiproton cloud. We can conclude that partial compression of the electron plasma becomes evident around 300 kHz.

A summary of antiproton cloud compression as a function of the rotating wall frequency and electron number is shown in figure 6.4. Each point represents an independent measurement where we
6.2. Observation of a new regime of antiproton cloud compression

Figure 6.2: MCP images of an antiproton-electron plasmas after applying the rotating wall for 100 s with an amplitude of 1 V. Each image has about $1.5 \times 10^5$ antiprotons and different numbers of electrons providing cooling. The antiproton cloud has an ellipse-like shape at the left side of the MCP and the electron plasma has a round shape to the right, near the centre of the MCP. a) $4 \times 10^6$ electrons at 140 kHz, b) $7 \times 10^6$ electrons at 300 kHz, c) $12 \times 10^6$ electrons at 700 kHz and d) $20 \times 10^6$ electrons at 600 kHz. The scale bar is calculated from equation 5.2, so that it corresponds to the size in a magnetic field of 3 T.
6.2. Observation of a new regime of antiproton cloud compression

Figure 6.3: MCP images of antiproton-electron plasmas after applying the rotating wall for 100 s with an amplitude of 1 V. Each image has about $1.5 \times 10^5$ antiprotons with different numbers of electrons providing cooling. Row a) antiproton-electron plasma with $4 \times 10^6$ electrons when applying the rotating wall at different frequencies. Row b) antiproton-electron plasma with $7 \times 10^6$ electrons when applying the rotating wall at different frequencies. Row c) antiproton-electron plasma with $12 \times 10^6$ electrons when applying the rotating wall at different frequencies. Row d) antiproton-electron plasma with $20 \times 10^6$ electrons when applying the rotating wall at different frequencies.
apply the rotating wall for 100 s, with an amplitude of 1 V at the appropriate frequency, and with a width of 0.2 kHz. The central density is extracted from the fit, as described in section 5.5. The central density is a quantitative measure of the degree of compression of the cloud provided the number of particles remains constant. In all of these trials, we never observe the rotating wall to induce a loss of antiprotons, as monitored by the scintillators. Therefore, if the central density increases, the cloud radius must become smaller. In figure [6.4] we show the central density as a function of frequency for several electron numbers, with fixed antiproton number. The error bars on the central density are too small to be seen. The antiproton maximum central density increases with the electron number. When cooling with $4 \times 10^6$ electrons, the antiproton maximum central density occurs at $\sim 140$ kHz, when cooling with $7 \times 10^6$ electrons the maximum is at $\sim 400$ kHz and when cooling with $12 \times 10^6$ and $20 \times 10^6$ electrons, the maximum is at $\sim 600$ kHz.

Furthermore, increasing the electron number allows better compression and over a broader range of frequencies. When cooling with $4 \times 10^6$ and $7 \times 10^6$ electrons, the antiproton cloud compresses over the range 50 – 200 kHz and 50 – 600 kHz respectively. When cooling with $12 \times 10^6$ and $20 \times 10^6$ electrons, very similar compression is produced and the antiproton cloud compresses between 50 – 800 kHz. One might think that a higher number of electrons enhances the antiproton cloud compression because it provides a better source of cooling. However, we cannot ignore the fact that a fraction of the electron plasma is itself compressed for trials with large numbers of electrons (see figure [6.2] and [6.2]l) and that this might also explain the different antiproton cloud compression behaviour.

At the bottom of figure [6.4] we plot the central density of the electron plasma while compressing the antiprotons. We do not plot the central density for $4 \times 10^6$ electron plasma, since there is either no electron plasma compressing or if it is compressing, it is too diffuse to be seen in the antiproton cloud and the analysis cannot be performed.

During the measurement period of 5 weeks, we performed a series of baseline measurements on daily basis, where we checked the antiproton number, the secondary electron number and the compression of the antiproton cloud when applying the rotating wall at 500 kHz for 40 s, when cooled
6.2. Observation of a new regime of antiproton cloud compression

Figure 6.4: Central density after applying the rotating wall for 100 s, at 1 V and at a chosen frequency. a) Antiproton central density when cooled by different number of electrons. b) Electron central density from the same measurements in a). No points are shown for $4 \times 10^6$ electrons, because the electron plasma was not visible and a fit could not be performed. The arbitrary units (a.u.) are the same for antiprotons and electrons.
by $20 \times 10^6$ electrons. Compression baselines were always satisfactory and MCP images showing compression were reproducible. We observed that the secondary electron number may increase if the background pressure of the trap increases. This problem was solved by thermally cycling the trap (allowing the trap to warm to $\sim 100$ K and cooling again).

### 6.2.3 Electron plasma compression without antiprotons

Having observed compression of mixed antiproton-electron plasmas, it was important to study the radial behaviour of the electron plasma when applying the rotating wall, particularly when the electron plasma was alone, without antiprotons. This measurement was key to deciding if the antiproton cloud was sympathetically compressed by the electron plasma or not.

The measurement procedure was almost the same as the one with an antiproton-electron plasma, but instead of cooling for 80 s, the particles were cooled for only 5 s. After 5 s, almost all of the antiprotons were still hot, thus they were released by turning off E01 and only the electrons kept in the trap. It is important to note that the cyclotron cooling time for the electrons is $\sim 0.4$ s.

Figure 6.5 shows examples of MCP images of the electron plasma before and after compression. Before compression, the radial size of the plasma is estimated to be $3.2 \pm 1.5$ mm (see section 6.2.1) and after compression at 1.5 MHz, is $0.14 \pm 0.01$ mm.

![MCP images](image.png)

Figure 6.5: a) MCP image of the electron plasma before applying the rotating wall. b) MCP image of the electron plasma after applying the rotating wall for 100 s, with an amplitude of 1 V and at 1.5 MHz.
6.2. Observation of a new regime of antiproton cloud compression

The peak density of the electron plasma as a function of the rotating wall frequency is shown in figure 6.6. We observe that below \( \sim 750 \) kHz, there is no radial compression of the electron plasma, but above \( \sim 750 \) kHz, the plasma begins to compress.

![Figure 6.6: Central density of an electron plasma of about \( 20 \times 10^6 \) electrons as a function of the rotating wall frequency. The rotating wall was applied for 100 s with an amplitude of 1 V. The plasma radially compresses above 750 kHz.](image)

To closely observe the initial compression of the electron plasma, we show the MCP images of the electrons after compressing at 700 kHz, 800 kHz and 900 kHz (see figure 6.7). At 700 kHz, there is no sign of compression, but at 800 kHz, we observe that the plasma is a little more dense and the compression continues for higher frequencies.

6.2.4 Compression of antiproton cloud without electrons

We also performed measurements of the antiproton cloud compression without electrons. The electrons were ejected from the trap before applying the rotating wall. Figure 6.8 shows the MCP images after applying the rotating wall at different frequencies. There is no evident compression of the antiproton cloud. Furthermore, we detected an abnormal loss of about 30% of the antiprotons while applying the rotating wall. We think they might be lost due to heating by the electric field perturbation, but with no source of cooling to counteract this effect.
6.2. Observation of a new regime of antiproton cloud compression

![MCP image of the electron plasma](image)

Figure 6.7: MCP image of the electron plasma after the rotating wall for 100 s with an amplitude of 1 V at a) 700 kHz, b) 800 kHz and c) 900 kHz. The scale bars give the size the plasma would have in a 3 T magnetic field.

6.2.5 Compression at higher frequencies \((\omega_{RW}/2\pi > 750 \text{ kHz})\)

As already seen in section 6.2.3, a large fraction of the plasma \((\sim 8 \times 10^6 \text{ electrons})\) radially compresses for a rotating wall frequency above \(\sim 750 \text{ kHz}\). This drastically changes the potential well and dominates the compression of the antiproton cloud. A comparison between the MCP images at 600 kHz and 1 MHz shows two different behaviours of the antiproton-electron plasma (see images 6.9). We can see at 1 MHz how the electron plasma compresses to a higher density and how the antiproton cloud follows with a lower density. At this frequency, we think that the electrons are sympathetically compressing the antiprotons. The poor sympathetic compression of the antiproton cloud may be because the electrons compress so quickly that they do not efficiently compress the antiprotons.

Table 6.1 shows the densities and the numbers of particles that have been concentrated near the centre at 600 kHz and 1 MHz. Only about 10% of the antiproton cloud is radially compressed at 1 MHz. Also, a larger fraction of the electron plasma radially compresses at 1 MHz.
6.2. Observation of a new regime of antiproton cloud compression

Figure 6.8: MCP images of antiproton clouds after applying the rotating wall for 100 s and 1 V for different frequencies.

<table>
<thead>
<tr>
<th>$\omega_{RW}/2\pi$</th>
<th>$\bar{p}$ density</th>
<th>$\bar{p}$ number</th>
<th>$e^-$ density</th>
<th>$e^-$ number</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 kHz</td>
<td>$\sim 1 \times 10^8$ cm$^{-3}$</td>
<td>$\sim 1.5 \times 10^5$</td>
<td>$\sim 3 \times 10^9$ cm$^{-3}$</td>
<td>$\sim 3 \times 10^6$</td>
</tr>
<tr>
<td>1 MHz</td>
<td>$\sim 6 \times 10^6$ cm$^{-3}$</td>
<td>$\sim 1.5 \times 10^5$</td>
<td>$\sim 3 \times 10^9$ cm$^{-3}$</td>
<td>$\sim 8 \times 10^6$</td>
</tr>
</tbody>
</table>

Table 6.1: Number of particles and densities of the plasmas radially compressing at a specific rotating wall frequency (measurements performed with $1 \times 10^5$ antiprotons and $20 \times 10^6$ electrons).
6.2. Observation of a new regime of antiproton cloud compression

Figure 6.9: a) MCP image of an antiproton-electron plasma radially compressed by the rotating wall at 600 kHz and b) at 1 MHz. Both measurements were performed with \( \sim 1.5 \times 10^5 \) antiprotons and \( \sim 20 \times 10^6 \) electrons. In a), the antiproton cloud is at the left hand side of the MCP image and next to the antiproton cloud, the electron plasma is at the right hand side near the centre of the MCP. In b) the antiproton cloud is not very visible at left hand side of the image. The electron plasma has a circular shape near the centre of the MCP image.

6.2.6 Observation of a new mechanism?

We have observed compression of antiproton clouds when applying the rotating wall in the frequency range of 50–750 kHz. The radius of the antiproton cloud was reduced by up to a factor 20 and the smallest radius measured was \( \sim 0.2 \) mm (central density of \( 1 \times 10^8 \) cm\(^{-3}\)).

We have also observed that a pure electron plasma does not compress in the frequency range of interest and as a consequence it is very unlikely to induce sympathetic compression of antiproton clouds. We have also observed that the use of an electron plasma is necessary for the compression to be effective.

When compressing the antiproton clouds, it is evident that a fraction of the electron plasma (about 15\%) also compresses when using \( 12 \times 10^6 \) and \( 20 \times 10^6 \) electrons. Such an effect is not evident when using fewer electrons (\( 4 \times 10^6 \) and \( 7 \times 10^6 \) electrons).

We believe that the rotating wall is acting directly on the antiproton clouds and that we have observed a compression mechanism that is different from sympathetic compression [63] (see section 4.4) and also different from the compression reported by the ASACUSA Collaboration [57] (see section 4.4.1). Sympathetic compression is unlikely to be the mechanism of compression, since a pure
electron plasma does not compress when using the frequency range of interest. On the other hand, the compression observed here is distinguished from that reported by the ASACUSA Collaboration, since we used electrons as a source of cooling and observed a new behaviour in the compression of the antiproton clouds that depends on the number of electrons. In contrast, ASACUSA reported that they did not have any electrons present while the rotating wall was applied.

In chapter 7, we will discuss possible compression mechanisms that could explain the observed antiproton cloud compression. In the next section, we further investigate the antiproton cloud compression as a function of, for example, compression time and the potential well used.

6.3 Other measurements of the antiproton cloud compression

6.3.1 Compression as a function of duration of the rotating wall

Here we vary duration of the rotating wall time, with the frequency and amplitude fixed. These measurements allow us to observe how the antiproton cloud compression evolves over time. Figure 6.10 shows the antiproton central density when being cooled with $20 \times 10^6$ electrons at several frequencies.

When cooling with $20 \times 10^6$ electrons, we can see that the antiproton cloud compresses slowly at first, but after $\sim 10$ s, speeds up until levelling out between 20–40 s. Also, the antiproton cloud compresses to higher central densities at the higher frequencies (e.g. 350 kHz, 450 kHz and 550 kHz). This can also be seen in figure 6.4.

Figure 6.11a shows the MCP images at different times at 150 kHz, while figure 6.11b shows the MCP images at 450 kHz. We observe for both frequencies that during the first few seconds there is very slow compression. We also notice that the antiproton cloud reaches higher densities at 450 kHz and that the electron behaviour is different. We can barely see the electron plasma compressing at the right hand side of the antiproton cloud at 30 s and 40 s when applying the rotating wall at 150 kHz (figure 6.11a). In contrast, at 450 kHz (figure 6.11b), electron plasma compression is clearly
6.3. Other measurements of the antiproton cloud compression

![Graph showing central density of the antiproton cloud after applying the rotating wall at 1 V at different frequencies as a function of the rotating wall time when cooled by $20 \times 10^6$ electrons.](image)

Figure 6.10: Central density of the antiproton cloud after applying the rotating wall at 1 V at different frequencies as a function of the rotating wall time when cooled by $20 \times 10^6$ electrons.

observable after 17.5 s. From the fit to the compressed electron plasma, we conclude that there are about $3 \times 10^6$ electrons. It seems that the rest of the electron plasma remains in a larger, more diffuse distribution.

In figure 6.12 we show the central density as a function of time when cooling with $4 \times 10^6$ electrons. It takes a longer time (~ 20 s) before a noticeable compression begins. Also, the antiproton cloud does not compress as much as in the previous case. Some of the points at 140 kHz do not follow the trend (the points at 70 s and 100 s), which may indicate that the compression is unstable. We did not have enough time to investigate this fully.

Figure 6.13 shows the MCP images of the antiproton-electron plasma when applying the rotating wall at 140 kHz (with $4 \times 10^6$ electrons). There is no evident compression of the electron plasma, but we can not rule out that there could be a small number of electrons next to the antiproton cloud. We can see at 90 s, that the compressed antiproton cloud is in a different position, which we attribute to a diochotron instability [80]. We observed such position changes when using $4 \times 10^6$ and $7 \times 10^6$ electrons (figure 6.3), but not in other data sets. Diochotron motion has been often observed in
6.3. Other measurements of the antiproton cloud compression

Figure 6.11: a) MCP images after compression at 150 kHz for $1.5 \times 10^5$ antiprotons and $20 \times 10^6$ electrons at different times of compression. b) Same as in a) but at 450 kHz.
6.3. Other measurements of the antiproton cloud compression

![Figure 6.12: Central density of the antiproton cloud after applying a 1 Volt rotating wall at several frequencies as a function of the rotating wall duration. An electron plasma of $4 \times 10^6$ electrons was used to cool the antiprotons.](image)

ALPHA, often induced by rapid changes in the trap such as when the plasma is dumped to the MCP.

From these observations, we conclude that the rate of compression of the antiproton cloud depends on the electron number. Increasing the number of electrons causes the antiproton cloud to compress more quickly and to higher densities.

### 6.3.2 Compression when changing the potential well

Antiproton cloud compression was also performed using two other potential wells. Table 6.2 shows the electrode voltages used during the measurements. Potential A is the typical potential with a harmonic shape near the minimum with $\omega_b/2\pi \sim 270$ kHz, potential B is a non-harmonic potential and potential C is a steeper harmonic potential with a bounce frequency of $\sim 370$ kHz. The objective of these measurements was to determine whether compression could be achieved using other kinds of potentials and to check whether there is anything special with potential A, or not.
6.3. Other measurements of the antiproton cloud compression

Figure 6.13: MCP images after compression at 140 kHz for $1.5 \times 10^5$ antiprotons and $4 \times 10^6$ electrons at different times of compression.

<table>
<thead>
<tr>
<th>Potential</th>
<th>E04</th>
<th>E05</th>
<th>E06 (RW)</th>
<th>E07</th>
<th>E08</th>
<th>E09</th>
<th>E10</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0 V</td>
<td>18.7 V</td>
<td>25.8 V</td>
<td>30 V</td>
<td>25.8 V</td>
<td>18.7 V</td>
<td>0 V</td>
</tr>
<tr>
<td>B</td>
<td>0 V</td>
<td>15 V</td>
<td>30 V</td>
<td>30 V</td>
<td>30 V</td>
<td>15 V</td>
<td>0 V</td>
</tr>
<tr>
<td>C</td>
<td>0 V</td>
<td>37.5 V</td>
<td>51.6 V</td>
<td>60 V</td>
<td>51.6 V</td>
<td>37.5 V</td>
<td>0 V</td>
</tr>
</tbody>
</table>

Table 6.2: Voltages applied to the electrodes producing the potential well during application of the rotating wall. Potential A is the typical potential used during the measurements, potential B is a non-harmonic potential (even without charge), and potential C is a deeper potential.
Figure 6.14 shows the resulting potential for case A, B and C. The shapes of the potentials with and without space charge are shown.

![Graph of potentials](image)

Figure 6.14: Voltages applied to the electrodes and the resulting potential well for different number of electrons. The hatched region illustrates the rotating wall position. Potential A is the typical potential, potential B is the non-harmonic potential and potential C is a deeper well. The potential wells are offset so that the potential maxima without space charge are set at 0 V. For the voltages applied to the electrodes, see table 6.2.

Figure 6.15 shows the antiproton central density as a function of the rotating wall frequency when using different potential wells. One can observe that antiproton cloud is compressed regardless of the potential well used. When using $4 \times 10^6$ electrons with potential A and B, the antiproton cloud compression looks the same. We can deduce that potential A and B are not different enough to make a change in the compression. For an unknown reason, when using $20 \times 10^6$ electrons, the antiproton cloud does not compress at frequencies lower than $\sim 200$ kHz for potentials B and C. Because of the lack of the antiproton beam time, the set of measurements of compression of the antiproton clouds with potential B is incomplete. When using potential C, the compression of the antiproton clouds seems shifted to higher frequencies by $\sim 100$ kHz.

We have observed that compression is achieved regardless of the potential shape. Compression in a steeper potential well (higher axial bounce frequency) is slightly different as a function of the
6.3. Other measurements of the antiproton cloud compression

![Graph showing antiproton cloud central density as a function of the rotating wall frequency.]

Figure 6.15: Antiproton cloud central density as a function of the rotating wall frequency when using different potential wells and electron numbers for cooling. For more information about the potentials, see table 6.2.

6.3.3 Compression as a function of the applied rotating wall amplitude

The compression of the antiproton cloud was also measured using different rotating wall amplitudes. Figure 6.16 shows the results when cooling the antiprotons with $4 \times 10^6$ electrons. Higher voltages speed up the compression. For amplitudes used in the preceding sections of 1 V, compression became visible after 20 s. When the amplitude was increased to 1.5 V, the compression sped up and became visible after 10 s. When the amplitude was reduced, it took up to 50 s to see a compression at 0.5 V.

6.3.4 Compression for various numbers of antiprotons and electrons

We wanted to know if the number of antiprotons changes the compression, and moreover, if there is a minimum number of antiprotons needed to achieve compression. For these measurements, we
Figure 6.16: Antiproton cloud central density as a function of the rotating wall time for several voltages. The measurement was performed when cooling with $4 \times 10^6$ electrons and at a frequency of 140 kHz.

changed the number of antiprotons in the beam. This required of changing the intensity of the proton beam in the Proton Synchrotron, so the production of antiprotons is reduced. As a consequence, the number of secondary electrons is also reduced. In these measurements, we are changing both the number of cooled antiprotons, $N_p$, and the number of secondary electrons, $N_{e^-}$. We used roughly 25%, 50% and 100% of the usual number of antiprotons. We also obtained 200% by accumulating two pulses of the antiproton beam.

Figure 6.17 shows examples of MCP images of the antiproton-electron plasma after compression for frequencies where the central density is highest. Table 6.3 gives more information on the parameters used during these measurements. We use the ratio $N_{e^-}/N_p$ to provide information on the numbers of the electrons providing cooling versus the number of antiprotons.

Figure 6.18 shows the antiproton central density for different numbers of antiprotons and electrons. As expected, one can see that the antiproton central density increases at higher numbers of antiprotons. However, the electron number also changes so this may show the importance of the electrons’ role as a coolant.
6.3. Other measurements of the antiproton cloud compression

Figure 6.17: MCP images of antiproton-electron plasmas after applying the rotating wall for 100 s with an amplitude of 1 V for a) $6 \times 10^3$ antiprotons and $7 \times 10^6$ electrons at 600 kHz, b) $9 \times 10^4$ antiprotons and $12 \times 10^6$ electrons at 600 kHz, c) $1.5 \times 10^5$ antiprotons and $20 \times 10^6$ electrons at 600 kHz and d) $3.3 \times 10^5$ antiprotons and $30 \times 10^6$ electrons at 500 kHz.

<table>
<thead>
<tr>
<th>Beam percentage</th>
<th>$\bar{p}$</th>
<th>Secondary e$^-$</th>
<th>$N_{e^-}/N_\bar{p}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>$6 \times 10^3$</td>
<td>$7 \times 10^6$</td>
<td>117</td>
</tr>
<tr>
<td>50%</td>
<td>$9 \times 10^4$</td>
<td>$12 \times 10^6$</td>
<td>133</td>
</tr>
<tr>
<td>100%</td>
<td>$1.5 \times 10^5$</td>
<td>$20 \times 10^6$</td>
<td>133</td>
</tr>
<tr>
<td>200%</td>
<td>$3.3 \times 10^5$</td>
<td>$30 \times 10^6$</td>
<td>91</td>
</tr>
</tbody>
</table>

Table 6.3: Characteristics of the beam when using different beam percentages. 100% corresponds to 1 stack of the beam, and 200% corresponds to a stack of 2 beam pulses. $N_{e^-}/N_\bar{p}$ is the ratio between the electron and the antiproton number.
6.3. Other measurements of the antiproton cloud compression

![Graph showing central density of the antiproton cloud as a function of the rotating wall frequency for different numbers of electrons and antiprotons. For more information about the particle number, see table 6.3.](image)

**Figure 6.18**: Central density of the antiproton cloud as a function of the rotating wall frequency for different numbers of electrons and antiprotons. For more information about the particle number, see table 6.3.

### 6.3.5 Expansion after the rotating wall finishes

It is important to study how the plasma expands after we stop the rotating wall. Ideally, for further use in the experiment, one might hope that the plasma would maintain a small radius and expand slowly. If the plasma expands too quickly, it would be difficult to perform the further manipulations needed to produce antihydrogen. It is required that the antiproton cloud remains compressed with little expansion for at least 10 s.

Figure 6.19 shows how the antiproton cloud expands when cooling with $4 \times 10^6$ and $20 \times 10^6$ electrons after applying the rotating wall for 40 s or 100 s (see fig. 6.19). One can see that by about 10 s after the rotating wall is stopped, the compression has already been undone. When using $20 \times 10^6$ electrons, it does not matter for how long the rotating wall is applied (40 s or 100 s) since the central density has already reached a maximum, as seen in section 6.3.1. However, it seems that applying the rotating wall for 100 s helps to reduce the rate of expansion after stopping the rotating wall. When cooling with $4 \times 10^6$ electrons, the rate of expansion looks about the same, regardless...
of whether it was compressed for 40 s or 100 s.

Figure 6.19: Antiproton cloud central density as a function of the time after the rotating wall was applied. The rotating wall was applied either for 40 s or for 100 s. The antiprotons are cooled by $4 \times 10^6$ or by $20 \times 10^6$ electrons.

These measurements were performed without ejecting the electrons after application of the rotating wall, so that expansion is observed for both species. Figure 6.20 shows the MCP images of the expansion of the antiproton-electron plasma after applying the rotating wall. We observe that both species expand. The fraction of the electron plasma that is not compressed (~85% of the electrons) has a very large radius, and we think that after the rotating wall is applied, the antiproton cloud has a tendency to redistribute towards the outside of this distribution.

In future manipulations, it would seem more appropriate to eject the electron plasma after applying the rotating wall, so that the antiproton cloud compression will not be influenced by the electron plasma.

### 6.3.6 Plasma temperature before and after compression

It was not possible to perform more than few measurements of plasmas temperatures due to the restricted availability of the antiproton beam time. We measured the electron temperature after
6.3. Other measurements of the antiproton cloud compression

Figure 6.20: MCP images after stopping a 100 s rotating wall, for $1.5 \times 10^5$ antiprotons and $20 \times 10^6$ electrons.

applying the rotating wall to an antiproton-electron plasma. However, the temperature diagnostic of the antiprotons was not performed since the space charge of the electrons changes the shape of the potential well and the measurements are not easily interpreted (unless of course the electrons are ejected before the temperature measurements, but this can in turn affect the temperature). We performed measurements of the electron temperature when using $20 \times 10^6$ electrons and $1.5 \times 10^5$ antiprotons after applying the rotating wall for 100 s. Table 6.4 shows the temperature of the electrons after applying the rotating wall. We observe that for frequencies in the range 100 – 500 kHz, the temperature is $\sim 500$ K and at 700 – 900 kHz the temperature increases to $\sim 700$ K. The temperature before applying the rotating wall is $\sim 300$ K.

6.3.7 Compression as a function of magnetic field

Since the plasma rotation frequency depends inversely on the magnetic field (equation 4.8), we thought it could be useful to study how the compression of the antiproton clouds changes when increasing the magnetic field.

Figure 6.21 shows example MCP images of the antiproton-electron plasma after compression when
6.3. Other measurements of the antiproton cloud compression

<table>
<thead>
<tr>
<th>$\omega_{RW}/2\pi$ [kHz]</th>
<th>Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>557</td>
</tr>
<tr>
<td>300</td>
<td>539</td>
</tr>
<tr>
<td>450</td>
<td>580</td>
</tr>
<tr>
<td>500</td>
<td>561</td>
</tr>
<tr>
<td>700</td>
<td>758</td>
</tr>
<tr>
<td>900</td>
<td>727</td>
</tr>
</tbody>
</table>

Table 6.4: Temperature of $20 \times 10^6$ electrons after applying the rotating wall for 100 s at different frequencies.

using 3 T and 4 T magnetic fields (3 T is the typical magnetic field used in the measurements so far discussed). The antiproton central density as a function of the rotating wall frequency is shown in figure 6.22. Unfortunately, we can not directly compare the two measurements because the capture and the initial conditions of the antiproton-electron plasmas are different. At 4 T, there is about $1.9 \times 10^5$ antiprotons and $20 \times 10^6$ electrons, meaning that $N_{e^-}/N_p$ is different and the resulting compression could be influenced by the electron cooling, as previously observed. Also, since the magnetic field at the MCP position is slightly higher, the extraction properties of the particles is different.

Figure 6.21: MCP images of the antiproton-electron plasma after applying the rotating wall at 500 kHz, with an amplitude of 1 V and for 100 s. The magnetic field is a) 3 T and b) 4 T.

We conclude that there is still compression at 4 T, but there are too many changes of the initial
Figure 6.22: Antiproton cloud central density as a function of the rotating wall frequency at 3 T and 4 T. The antiprotons are cooled by $20 \times 10^6$ electrons.

conditions of the plasma (particle number, size, rotation frequency) to make a useful quantitative comparison.

### 6.4 Summary of observations

We will now present a list of key observations of the antiproton cloud compression:

- Antiproton cloud compression is achieved when cooled by $4 \times 10^6$, $7 \times 10^6$, $12 \times 10^6$ and $20 \times 10^6$ electrons in the range of hundreds of kHz. The rotating wall is applied for 100 s with an amplitude of 1 V.
- The antiproton cloud central density increases when the number of electrons is increased.
- The antiproton cloud radius before compression is estimated to be $\sim 4$ mm, and measured to be $\sim 0.2$ mm after compression.
- When increasing the electron number, the antiproton cloud is compressed over a wider range
6.4. Summary of observations

of frequencies.

- When using $12 \times 10^6$ and $20 \times 10^6$ electrons, antiproton cloud compression is observed over a range of $50 – 750$ kHz and the compressions are very similar. An evident partial electron plasma compression is observed on the MCP after the rotating wall is applied. About $3 \times 10^6$ of the electrons are compressed, while the rest seem to retain their initial conditions.

- When using a smaller number of electrons, $7 \times 10^6$ electrons, the antiproton cloud compresses over a range of frequencies $50 – 500$ kHz. The partial compression of the electron plasma is not so evident, but there is a shadow next to the antiproton cloud that resembles the electron plasma.

- When using $4 \times 10^6$ electrons, the antiproton cloud compresses at $50 – 200$ kHz. In this case, the electron plasma seems to retain their initial conditions. We cannot rule out that some electrons may be compressing, but they are not dense enough to be seen.

- The temperature after compression for $20 \times 10^6$ electrons is $\sim 500$ K at $100 – 500$ kHz, increasing to $\sim 700$ K at $700 – 900$ kHz, where the antiproton cloud is no longer compressing. The temperature before applying the rotating wall is $\sim 300$ K.

- The electron plasma (without antiprotons) compresses when applying the rotating wall at a frequency above $\sim 750$ kHz, but not at the lower frequencies where antiproton compression is observed.

- No compression is observed when applying the rotating wall to the antiprotons alone.

- When using $20 \times 10^6$ electrons, the antiproton cloud compresses very slowly during the first few seconds (0 – 10 s), and then the rate of compression increases until saturating after $\sim 40$ s.

- When using $4 \times 10^6$ electrons, the antiproton cloud compresses very slowly during the first 20 s.

- When using $4 \times 10^6$ electrons, the compression is sped up when using a higher amplitude (1.5 V) and slowed down when using lower amplitude (0.7 and 0.5 V).
6.5. Comparison of the direct compression of antiproton clouds versus sympathetic compression

- Compression is achieved independent of the shape of the potential.

- The antiproton cloud compression is undone within 10 s after stopping the rotating wall, at least when the electrons are present.

- When the antiproton number is increased, the central density is higher.

- Increase of the magnetic field from 3 T to 4 T changed the compression behaviour at rotating wall frequencies above about 500 kHz.

6.5 Comparison of the direct compression of antiproton clouds versus sympathetic compression

In this section we discuss the advantages and disadvantages of using direct compression of antiproton clouds and secondary electrons in an experiment such as ALPHA. First, we compare the compression method, regardless of the origin of the electrons, then we compare the use of secondary electrons and electrons from a source.

Advantages and disadvantages of direct compression of antiproton clouds (versus sympathetic compression)

Advantages

- In the sympathetic compression scheme, the antiproton clouds are compressed only indirectly and therefore compression relies critically on the coupling between the electrons and the antiprotons. As such, it occasionally exhibits instabilities, due possibly to the electron initial conditions and the speed of the electron plasma compression. For example, if the electron plasma is compressed too rapidly, the antiproton cloud can be left uncompressed. Also, it was occasionally observed that the antiproton clouds are not fully compressed, sometimes forming a halo around a partially compressed antiproton cloud.
6.5. *Comparison of the direct compression of antiproton clouds versus sympathetic compression*

Direct compression, on the other hand, does not rely on the coupling between the electrons and the antiprotons (at least with small electron numbers). Therefore it is expected to be more robust, regardless of the origin of the electrons. In fact, during the work reported here, we have observed that direct compression of antiproton clouds have been always reproducible at the same frequencies.

- While direct compression uses rotating wall frequencies in the range of a few 100 kHz, sympathetic compression uses higher rotating wall frequencies (a few MHz), which are more susceptible to phase shifts and attenuation that varies between the channels depending on technical variations in the electrical circuits. In ALPHA, the circuits were only guaranteed to pass frequencies below around 10 MHz with good fidelity. This could lead to defects in the rotating field, reducing the compression speed or the limit.

**Disadvantages**

- Electron ejection after direct compression can be difficult since the strength of the electron pulse has a radial dependence and the electron plasma is radially large. However, this could in principle be fixed by quickly compressing the electron plasma before the ejection. Electron ejection is of great importance because without ejection, the antiproton cloud will expand very fast to the size of the electron plasma. In this thesis we did not have the chance to perform measurements with electron ejection.

- If secondary electrons are not available (such as in the atom trap where there is not a degrader), an electron source can be used, but the radial size and density of the electron plasma must be tuned to similar initial conditions as when using secondary electrons.
Advantages and disadvantages of secondary electrons (versus electrons from a source)

Advantages

- One of the advantages of using secondary electrons is that the plasma has a big radius and thus a higher antiproton cooling efficiency can be achieved. Initial antiproton clouds have a radius similar to secondary electrons plasma radius, whereas when cooling with electrons from the source (described in section 2.6), the cooling efficiency is limited by the poor radial overlap. In principle, this characteristic can be reproduced with electrons loaded from the electron source by using the rotating wall to expand the plasma, but the plasma size and electron number is not always stable and the electron’s trajectory can be blocked by a mechanical aperture.

- In some cases, the use of secondary electrons can be advantageous because they can be captured and trapped in one end of the trap, while positrons or antiprotons are already trapped in the other end of the trap. This would not be possible with electrons from a source since they must go through the entire trap.

- The secondary electron plasma has a low density, which appears to be necessary for direct compression of the antiproton clouds.

Disadvantages

- Electrons from a source could have provide additional flexibility to investigate compression process. With secondary electrons it is not possible, for example, to increase the number of electrons.

- The use of secondary electrons could be inconvenient when the antiproton beam is fluctuating since the secondary electron number also changes.

- The number of secondary electrons increases when the vacuum in the apparatus is poor.
6.5. *Comparison of the direct compression of antiproton clouds versus sympathetic compression*

For antihydrogen experiments like ALPHA, where the goal for the antiproton capture procedure is to cool the highest number of antiprotons possible and to compress the cloud to be small enough to transfer to the atom trap, using a sequence that is as robust and as free of complicated steps as possible, direct compression has the potential to be the method of choice.
Chapter 7

Compression mechanisms and calculation of the plasma frequencies associated with the bounce resonant transport of antiprotons

In this chapter, we will discuss the possible mechanisms that could potentially explain the antiproton cloud compression. First of all, we will calculate the plasma parameters to determine if the antiprotons and electrons are in the plasma regime. As already discussed, compression can be achieved for plasmas, as well as for particles in the single particle regime. We will also investigate if diocotron modes can be excited in the kHz range, since there are indications we have observed this phenomenon for plasmas with $4 \times 10^6$ and $7 \times 10^6$ electrons.

We first discuss the possibility that the antiproton cloud compression is due to a resonance with the electron plasma. We will determine the Trivelpiece-Gould frequency and then discuss other mechanisms of compression, such as sympathetic compression and the strong drive regime. Later, we will discuss magnetron side band cooling and bounce resonant transport on the electrons and on the antiprotons.

After discussing possible compression mechanisms, we concentrate on the hypothesis that the antiproton cloud compresses by bounce resonant transport since it seems that to be the most likely mechanism of compression. To study the bounce resonant transport of antiprotons, we numerically
calculate the axial bounce frequency distribution of the antiprotons and the rotation frequency of the antiproton-electron plasma. The sum of these two frequencies gives a frequency distribution of the supposed resonance, which we can compare to the frequencies where compression was observed. We study two cases. The first is when the antiprotons are cooled by $4 \times 10^6$ electrons. The axial bounce and rotation frequency can be calculated straightforwardly because there is no evidence of compression of the electron plasma, so we assume that the electron plasma does not change while the rotating wall is applied. We then consider cooling with $20 \times 10^6$ electrons. This is a more complex case because the electron plasma partially compresses over time and in a way that varies with the rotating wall frequency. The partial compression of the electron plasma changes both the electrostatic potential and the rotation frequency of the system.

7.1 Radial compression mechanisms

Compression of single component plasmas has been extensively studied both theoretically [172, 184] and experimentally [168, 189, 190, 195, 206].

In this chapter, we intend to explain compression of an antiproton cloud embedded in an electron plasma. We believe that the rotating wall acts directly on the antiprotons. The challenge lies in the fact that we need to demonstrate that the electron plasma is not excited during the antiproton cloud compression, even though the electron plasma space charge dominates the rotational motion and distorts the potential well. Systems with two species have been studied, but in the independent particle regime [206, 211, 212] and never in the current situation, where the antiproton cloud motion is affected by the space charge of the electrons.

7.1.1 Plasma frequency

As already seen in section [4.2.1], a collection of charges is a plasma if it fulfills the condition:

$$\frac{\lambda_D}{L} \ll 1,$$

(7.1)
7.1. Radial compression mechanisms

<table>
<thead>
<tr>
<th>Number of electrons</th>
<th>Temperature [K]</th>
<th>Density [cm$^{-3}$]</th>
<th>Plasma radius [mm]</th>
<th>Plasma length [mm]</th>
<th>$\lambda_D$ [mm]</th>
<th>$\omega_p/2\pi$ [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4 \times 10^6$</td>
<td>500</td>
<td>$1 \times 10^7$</td>
<td>4</td>
<td>12</td>
<td>0.5</td>
<td>28</td>
</tr>
<tr>
<td>$20 \times 10^6$</td>
<td>500</td>
<td>$3 \times 10^7$</td>
<td>4</td>
<td>30</td>
<td>0.3</td>
<td>49</td>
</tr>
</tbody>
</table>

Table 7.1: Electron plasma parameters. $\lambda_D$ is calculated from equation \[4.3\] and $\omega_p/2\pi$ is calculated from equation \[4.2\].

where $\lambda_D$ is the Debye length and $L$ is the length of the plasma. Here we have $20 \times 10^6$ electrons with a radius $r_p \sim 4$ mm, and a length $L \sim 30$ mm giving a density of $\sim 3 \times 10^7$ cm$^{-3}$. Thus for $T = 500$ K, $\lambda_D \sim 0.3$ mm. Therefore, $L \sim 100 \lambda_D$ and $r_p \sim 13 \lambda_D$. $\lambda_D$ is much smaller than the length and the radius so it can be considered as a plasma.

Table 7.1 shows some parameters of the electron plasma.

7.1.2 Diocotron mode

The diocotron mode is not intentionally used for the radial compression of plasmas when applying the rotating wall, but it is helpful to be aware if diocotron effects can be excited during the compression. The diocotron modes are generally used for diagnostic purposes [207, 208] and for plasma control and manipulations [209, 210]. The diocotron motion occurs when the plasma moves off the axis of the cylindrical electrodes and the electric image charge in the conductive wall of the electrodes causes the plasma to move in an orbit around the magnetic field axis. The motion is an analogue to the $\vec{E} \times \vec{B}$ motion, but instead of the self electric field of the plasma, $\vec{E}$ becomes $\vec{E}_i$, the image electric field. The diocotron frequency is expressed as [80]:

$$\omega_{m_\theta} = \omega_{rot} \left( m_\theta - 1 + \left( \frac{r_p}{R_W} \right)^{2m_\theta} \right),$$

(7.2)

where $\omega_{rot}$ is the rotation frequency of the plasma, $m_\theta$ is the mode order, $r_p$ is the plasma radius and $R_W$ is the electrode radius. For the plasma used here, $\omega_{m_\theta=1}/2\pi \sim 1$ kHz and $\omega_{m_\theta=2}/2\pi \sim 40$ kHz. Thus, there is a possibility that high order diocotron modes can be excited.
7.1.3 Compression by Trivelpiece-Gould excitation

When the rotating wall frequency coincides with the Trivelpiece-Gould (TG) modes, angular momentum is injected into the system leading to radial compression of the plasma. The frequency of the first order TG mode is [80]:

\[ \omega_{TG} = \frac{k_z \omega_p}{k}, \]  

(7.3)

where \( \omega_p \) is the plasma frequency, \( k \) and \( k_z \) are typical values from a standing wave, \( k_z = m_z \pi/L \), \( k^2 = k_z^2 + k_\perp^2 \) and \( k_\perp = \frac{1}{r_p} \left( \frac{2}{m_e K_W/r_p} \right)^{1/2} \).

The plasma studied here has a first order TG frequency of \( \omega_{TG}/2\pi \sim 15 \) MHz and the subsequent modes can be excited at higher frequencies. The TG modes are excited at frequencies in the 10 MHz and higher range, thus this mechanism is not consistent with the compression observed in the 100 kHz range.

7.1.4 Strong drive regime

The strong drive regime has been observed in single component plasmas and can be achieved over a broad range of frequencies without tuning to plasma modes [195]. During compression, the maximum density occurs when the rotation frequency of the plasma is equal to the rotating wall frequency [195]. From the measurements of compression of a pure electron plasma (section 6.2.3), we have observed that compression occurs from \( \sim 800 \) kHz, which is probably in the strong drive regime. As for the antiproton cloud, we observe a resonant structures over a relatively narrow range of frequencies which implies that this is probably due to another kind of compression mechanism.

7.1.5 Sympathetic compression mechanism

For sympathetic compression, where the antiprotons follow the compressing electron plasma, we need the electron plasma to be able to compress in the frequencies of interest. We have observed that a pure electron plasma does not compress in the 50–700 kHz frequency range. This indicates
that sympathetic compression is not the observed mechanism. However, sympathetic compression is observed above about 800 kHz, where the electron plasma compresses.

### 7.1.6 Compression by magnetron sideband cooling

The magnetron motion can be cooled or heated by exciting either the cyclotron motion or the axial motion in the single particle regime [66]. The magnetron motion can be coupled to the axial motion, or to the cyclotron motion, by introducing oscillating electric fields into the trap, for example, by applying the rotating wall.

By exciting the cyclotron motion with an oscillating potential, the magnetron radius will decrease. Hence, the particles will move towards the center [202]. In our experiment, in a magnetic field of 3 T, $\frac{\omega_c}{2\pi} \sim 84$ GHz for electrons and $\sim 46$ MHz for antiprotons, therefore we are clearly not exciting the cyclotron motion when applying the rotating wall.

On the other hand, the coupling of the axial motion with the magnetron motion can also result in a decrease of the magnetron radius [66]. Theory says that the magnetron motion can be cooled when exciting the system at the frequency $\omega_b + \omega_M$, and heated when applying the frequency $\omega_b - \omega_M$. Here, $\omega_M$ is the magnetron frequency and $\omega_M/2\pi \sim 1$ kHz. The axial bounce frequency $\omega_b/2\pi \sim 12$ MHz for the electrons and $\sim 270$ kHz for the antiprotons. These frequencies are calculated by considering a very accurate harmonic potential. Recently, compression in a slightly anharmonic potential, for positrons in the single particle regime was achieved [211]. Sideband cooling is an appealing candidate because compression occurs around $\omega_b$. However, in our case, this mechanism becomes ineffective, since the space charge of the electrons greatly distorts the potential and it becomes highly anharmonic. Furthermore, if we consider the axial motion of the antiprotons, we can see that the upper and the lower band are very close together and we should be able to observe both compression and expansion of the cloud. Recently, a theory of a new form of sideband cooling was developed, where only one side band is active for positrons in the single particle regime [206]. However, since we are not in the single particle regime and the potential is highly anharmonic, we conclude that the antiproton cloud is not being compressed by this mechanism.
7.1.7 Compression by bounce resonance transport

It has been previously shown that particles with an axial bounce frequency and rotation frequency in resonance with an asymmetric time-varying potential (rotating wall), undergo radial inward or outward movement [198]. This mechanism has been studied theoretically and experimentally for pure electron plasmas [199, 213, 214] and has also been observed in positron plasmas [212]. Moreover, this phenomenon was observed for positrons in the single particle regime in a harmonic well [198], where it was hypothesized that the same bounce resonant transport mechanism applies, using the magnetron frequency as the rotation frequency. Generally, the axial bounce frequency is much higher than the magnetron frequency, so the resonance frequency is approximated as the axial bounce frequency.

We now present an overview of bounce resonant transport when using a rotating electric field for single particles and the plasma regime [198]:

A plasma is resonant with the asymmetry if

\[
\omega_{res} = \omega_b + m_\theta \omega_{rot}
\]

(7.4)
is equal to the rotating wall frequency \(\omega_{RW}\). Here, \(\omega_b\) is the axial bounce frequency, \(\omega_{rot}\) is the rotation frequency of the plasma and \(m_\theta\) is the azimuthal wavenumber of the asymmetry, where \(m_\theta = 1\) corresponds to the dipole mode and \(m_\theta = 2\) to the quadrupole mode of the rotating wall. Recall that for the experiments in chapter 6, we used the dipole mode. In this case equation 7.4 becomes:

\[
\omega_{res} = \omega_b + \omega_{rot},
\]

(7.5)

which can be generalized to:

\[
\omega_{res} = n\omega_b + l\omega_{rot},
\]

(7.6)

where \(l\) and \(n\) are the azimuthal and axial wavenumbers, and correspond to higher harmonics.
In non-neutral plasma physics, the resonance condition has also been developed as [214]:

\[
\omega_{RW} - l\omega_{rot} - \frac{n\pi v_z}{L} = 0,
\]

(7.7)

where \(v_z\) is the axial velocity, \(L\) is the length of the plasma, \(l\) and \(n\) are the azimuthal and axial wavenumbers. The resonance condition is the same as the one in equation 7.6.

Instead of all the particles having the same axial bounce frequency, the particles will have a distribution of axial bounce frequencies due to the non-harmonic potential, and this may explain why compression is observed over such a wide range of frequencies. From the measurement we know that \(\omega_{rot}/2\pi \sim 10 – 40\) kHz, the antiproton’s \(\omega_b\) is in the 100 kHz range and the electron’s \(\omega_b\) is in the 10 MHz range. From this information, we assess that the bounce resonance transport of the antiprotons is the more promising explanation.

### 7.2 Investigation of the bounce resonant transport of antiprotons

To further discuss if bounce resonant transport can be the compression of mechanism observed, we will calculate the resonant condition, so that we can compare it to the frequencies where compression is observed.

In our case, we have an antiproton cloud co-located with an electron plasma. The antiproton cloud rotates at the same frequency as the electron plasma due to the electron plasma’s self-electric field, where \(\omega_{rot} = (\vec{E} \times \vec{B})/(B^2 r)\). As a result of the space charge of the electrons, the potential well is not harmonic and there is not an unique axial bounce frequency. Instead, the bounce frequency of any single antiproton depends on several variables:

- Total electric field due to the electron plasma and the trap \(\vec{E}_{tot}\), which depends on the electron peak density \((n_0)\) or electron plasma radius \((r_e)\), electron temperature \((T_e)\) and electron number \((N_e)\).
- Antiproton energy \(E_\upbeta\).
7.3 Numerical calculation of the antiproton distribution \( f(\omega_b) \) and \( f(\omega_b + \omega_{\text{rot}}) \)

- Radial position of the antiproton \( r_{\bar{p}} \).

Averaging over the entire antiproton population yields a distribution of antiproton bounce frequencies \( f(\omega_b) \), which can be numerically calculated taking all these factors into account.

The distribution is written as:

\[
f(\omega_{\text{res}}) = f(\omega_b + \omega_{\text{rot}}),
\]

7.3 Numerical calculation of the antiproton distribution \( f(\omega_b) \) and \( f(\omega_b + \omega_{\text{rot}}) \)

We will first calculate the antiproton distribution \( f(\omega_b) \) and then \( f(\omega_b + \omega_{\text{rot}}) \). The latter is the frequency distribution, corresponding to particles in resonance if compression is due the bounce resonant transport mechanism on antiprotons. The potential and the electron density are calculated by self-consistently solving the Maxwell-Boltzmann distribution and Poisson’s equation, as described in section 4.2.4. The electron plasma is considered to be in global thermal equilibrium and the solution is sensitive to three parameters: \( T_e \), \( r_e \) and \( N_e \). The temperature of the electron plasma is \( \sim 300 \) K before the rotating wall and \( \sim 500 \) K after the rotating wall. The values 300 K, 500 K and 700 K are used to study the sensitivity of the bounce frequency to temperature. The initial size of the plasma was estimated to be \( r_e \sim 3.2 \pm 1.5 \) mm (see section 6.2.1). We study the dependance on radius for three values: 3.2 mm, 4.0 mm and 4.7 mm, which correspond to densities of \( 8 \times 10^6 \) cm\(^{-3} \), \( 10 \times 10^6 \) cm\(^{-3} \) and \( 12 \times 10^6 \) cm\(^{-3} \) respectively, for a plasma of \( 4 \times 10^6 \) electrons. We study large radii since the MCP image shows that the cloud initially has a radius larger than 3 mm. Figure 7.1 shows an example of the potential at various radial positions for \( N_e = 4 \times 10^6 \) electrons, \( r_e = 4 \) mm and \( T_e = 300 \) K. One can see that at small radii (where the electron plasma is concentrated), the potential is highly anharmonic due to the space charge and, as the radius increases, the effect of the space charge vanishes. Figure 7.2 shows the corresponding solved density.
7.3. Numerical calculation of the antiproton distribution $f(\omega_b)$ and $f(\omega_b + \omega_{\text{rot}})$

Figure 7.1: Calculated potential as a function of the axial position for $4 \times 10^6$ electrons, with $T_e = 300$ K and $r_e = 4$ mm ($n_0 = 10 \times 10^6$ cm$^{-3}$). The potential is shown for several radial positions. The black solid curve is the calculated potential without space charge.

Figure 7.2: Calculated density as a function of radius and axial position for $4 \times 10^6$ electrons with $T_e = 300$ K and $r_e = 4$ mm ($n_0 = 10 \times 10^6$ cm$^{-3}$).
7.3. Numerical calculation of the antiproton distribution \( f(\omega_b) \) and \( f(\omega_b + \omega_{rot}) \)

We assume the particles are in equilibrium and since we are interested in the axial energy of the particles, we have assumed that the energy of the particles follows a Maxwell-Boltzmann distribution with one degree of freedom:

\[
f(E) = \sqrt{\frac{E}{\pi k_B T}} \exp\left(-\frac{E}{k_B T}\right).
\]  

(7.9)

From figure [7.3] we can see the Maxwell-Boltzmann energy distributions for different temperatures that are used for the antiproton thermal distribution (300 K, 500 K and 700 K).

![Figure 7.3: Maxwell-Boltzmann energy distribution for 300 K, 500 K and 700 K, normalized to the peak value of 1.](image)

After generating the potential, the density and the energy distribution, we numerically calculate the axial bounce frequency for several thousand antiprotons. For each antiproton, a random energy is picked from the Maxwell-Boltzmann distribution. This energy is used as the initial potential energy of the particle, and we place the particle at an initial axial position when the particle is at rest and the kinetic energy is zero. Since the potential changes with radius, a random radial position is also selected from the density distribution. We assume that the antiprotons follow the same density distribution as the electrons.
7.3. Numerical calculation of the antiproton distribution \( f(\omega_b) \) and \( f(\omega_b + \omega_{rot}) \)

These two parameters \((E_p \text{ and } r_p)\) define a position where the antiproton can be released from rest to calculate its trajectory.

We perform a fourth-order Runge-Kutta integration of the motion \([215]\). By definition:

\[
F_z = m \frac{d^2z}{dt^2} = eE_z \tag{7.10}
\]

Where \( E_z = -\frac{d\Phi(r,z)}{dz} \), so:

\[
\frac{d^2z}{dt^2} = -\frac{e}{m} \frac{d\Phi(r,z)}{dz} \tag{7.11}
\]

A single antiproton moves in the potential well and the calculation is stopped when the velocity changes sign (i.e. it is at its turning point). The time taken for the antiproton to reach this point is \( T/2 \), where \( T \) is the period. The frequency is calculated:

\[
\omega_b/2\pi = \frac{1}{T} \tag{7.12}
\]

Figure 7.4 shows the calculated antiproton axial bounce frequencies as function of the antiproton’s energy and radial position for one set of parameters. The axial bounce frequency ranges from \( \sim 10 \) kHz to \( \sim 400 \) kHz. The axial bounce frequency increases with energy and radius because of the shape of the potential.

Figure 7.5 shows the energy distribution and the calculated axial bounce frequency as a function of the energy for two radial positions: \( r = 0 \) mm and \( r = 4 \) mm. One can see that for the same energy, the axial bounce frequency is slightly higher for larger radii. At the peak of the energy distribution, \( \omega_b/2\pi \) is between \( \sim 100 \) kHz and \( \sim 150 \) kHz.

The rotation frequency of the plasma is calculated as a function of the radial position from:

\[
\omega_{rot}/2\pi = \frac{1}{2\pi B r} \frac{d\Phi(r,z)}{dr} \tag{7.13}
\]

Where \( d\Phi(r,z)/dr \) is the radial electric field and \( B \) is the magnetic field.
7.3. Numerical calculation of the antiproton distribution \( f(\omega_b) \) and \( f(\omega_b + \omega_{\text{rot}}) \)

Figure 7.4: \( \omega_b / 2\pi \) as a function of radius and energy. The bounce frequency of antiprotons was calculated for 300 K and \( r_e = 4 \text{ mm} \) (\( n_0 = 10 \times 10^6 \text{ cm}^{-3} \)).

Figure 7.5: Energy distribution for 300 K and also the antiprotons’ bounce frequency as a function of the energy at the radial positions \( r = 0 \text{ mm} \) and \( r = 4 \text{ mm} \), with \( r_e = 4 \text{ mm} \).
7.3. Numerical calculation of the antiproton distribution \( f(\omega_b) \) and \( f(\omega_b + \omega_{rot}) \)

7.3.1 \( f(\omega_b + \omega_{rot}) \) of antiprotons cooled by \( 4 \times 10^6 \) electrons

This is the simplest case since the measurements do not show a measurable change in the electron density (at least as observed via the MCP image), as seen in section 6.2.2. We therefore assume that any change in the electron density is too small to affect the potential or the rotation frequency during the 100 s of compression. The distributions of bounce frequency and rotation frequency are then calculated from the initial conditions.

Figure 7.6 shows the calculated thermal equilibrium potential and the density for different electron radii at 300 K. One can see that as the density increases, the corresponding radius gets smaller and the space charge becomes larger.

![Figure 7.6: Self-consistent on-axis potential (left plot) and radial density (right plot) for different plasma radii at 300 K for \( 4 \times 10^6 \) electrons.](image)

If we fix the plasma radius to \( r_e = 3.2 \text{ mm} \) \((n_0 = 8 \times 10^6 \text{ cm}^{-3})\) and we change the temperature (see figure 7.7), we observe a less pronounced change in the height of the potential, but the shape is slightly different, since for colder temperatures, the density is flatter than for warmer temperatures.

The antiproton axial bounce frequency \( (\omega_b) \) was calculated for several thousand antiprotons. The individual values of \( \omega_b \) were then binned to create the distribution, \( f(\omega_b) \). Figure 7.8 shows the antiprotons’ \( f(\omega_b) \) for different electron densities and temperatures. To allow comparison, the distributions are normalized to their maximum value. We also plot the data (solid black dots), which shows the antiproton cloud central density on the MCP as a function of the applied rotating wall fre-
7.3. Numerical calculation of the antiproton distribution $f(\omega_b)$ and $f(\omega_b + \omega_{rot})$

Figure 7.7: Self-consistent on-axis potential (left plot) and radial density (right plot) for different temperatures for $r_e = 3.2 \text{ mm}$ for a plasma with $4 \times 10^6$ electrons.

It is important to note that we are not intending to directly compare the two quantities, we only want to compare the frequency range of the distribution and the frequencies where compression is achieved. At first glance, we can see that the bounce frequencies cover a similar frequency range as the rotating wall frequencies where the compression occurs. However, we have not yet taken the rotation frequency of the plasma into account.

We calculate the rotation frequency as a function of radius using equation 7.13. Figure 7.9 shows the resulting rotation frequency for different temperatures and plasma radii. As we can see from equation 4.8, $\omega_{rot}$ depends on the density of the plasma. For the peak densities that we are studying, the peak rotation frequency varies between 4 kHz and 6 kHz and it is mostly constant over the plasma. When the temperature increases, the rotation frequency becomes less flat, but this effect is small.

Figure 7.10 shows $f(\omega_b + \omega_{rot})$ for different temperatures and plasma radii. We remark that $\omega_{rot}$ is typically negligible ($4 \text{ kHz} < \omega_{rot}/2\pi < 6 \text{ kHz}$), compared to $\omega_b$, whose peak frequency ranges from 100 kHz to 200 kHz. There is a very small shift to the right at higher electron density due to the contribution of the rotation frequency, but is almost negligible. $f(\omega_b + \omega_{rot})$ is more sensitive to the plasma temperature than to the radius (for the studied values). There is little change when varying the radius, but when the plasma is warmer, there is a shift in the distribution to higher frequencies. Overall, the calculated antiproton distribution $f(\omega_b + \omega_{rot})$ has a range of frequencies similar to the
7.3. Numerical calculation of the antiproton distribution $f(\omega_b)$ and $f(\omega_b + \omega_{rot})$

Figure 7.8: Bounce frequency distribution of antiprotons as a function of the antiproton bounce frequency for different temperatures and electron densities for $4 \times 10^6$ electrons. Black solid dots are the measured antiproton central density (arbitrary units) as a function of the applied rotating wall frequency.
7.4 \( f(\omega_b + \omega_{rot}) \) of antiprotons cooled by \( 20 \times 10^6 \) electrons

In this section we study the case where the antiprotons are cooled by \( 20 \times 10^6 \) electrons. This case is different from the previous case (when the antiprotons are cooled by \( 4 \times 10^6 \) electrons) because the electron plasma partially compresses, which means that the system behaves differently. Moreover, the measurements show that the antiproton cloud can be compressed using rotating wall frequency as high as \( \sim 700 \) kHz.

7.4.1 \( f(\omega_b + \omega_{rot}) \) distribution at the initial conditions

As for the case of \( 4 \times 10^6 \) electrons, we numerically calculate the antiprotons’ \( f(\omega_b + \omega_{rot}) \) at the initial conditions. Figure 7.11 shows \( f(\omega_b + \omega_{rot}) \) for \( r_e \sim 4 \) mm \((n_0 = 28 \times 10^6 \text{ cm}^{-3})\) and at different temperatures \((300 \text{ K}, 500 \text{ K} \text{ and } 700 \text{ K})\). All the distributions have a rotation frequency \( \omega_{rot}/2\pi \sim 13 \) kHz. The peak of \( f(\omega_b + \omega_{rot}) \) is at \( \sim 150 \) kHz and the resonant frequencies range

Figure 7.9: Rotation frequency of the electron plasma as a function of radius for several plasma radii and temperatures of a \( 4 \times 10^6 \) electron plasma.

frequency where compression was observed. This suggests that a resonance between the motion of the antiprotons and the rotating wall drive might be the explanation of compression.
7.4. $f(\omega_b + \omega_{rot})$ of antiprotons cooled by $20 \times 10^6$ electrons

Figure 7.10: Antiprotons $f(\omega_b + \omega_{rot})$ as a function of the temperature and plasma radii when cooled by $4 \times 10^6$ electrons. Black solid dots are the measured antiproton central density (arbitrary units) as a function of the applied rotating wall frequency.
between 10 kHz and 250 kHz. These distributions can only explain the antiproton compression at low frequency (up to \( \sim 250 \text{ kHz} \)), but not at higher frequencies.

![Figure 7.11: \( f(\omega_b + \omega_{rot}) \) of antiprotons when cooled by \( 20 \times 10^6 \) electrons at the initial conditions for different temperatures.](image)

The observation of compression at higher frequencies (\( \omega_{RW} > 250 \text{kHz} \)) by the bounce resonant transport implies that there should be a resonance in that range of frequencies. Furthermore, there should be a resonance with the initial conditions of the plasma to at least start the compression. For example, if we apply the rotating wall at 550 kHz, why is there compression, even though the initial resonance is between 50 kHz and 250 kHz (see figure 7.11). To resolve this, we call on the azimuthal and axial wavenumbers of the resonant bounce transport resonance condition (equation 7.7). It is possible that the antiprotons bounce axially several times for each rotation. As well as being resonant at a frequency of \( \sim 150 \text{ kHz} \), we infer that the antiprotons should also be in resonance at integer multiples of this frequency (i.e. \( \sim 300 \text{ kHz}, \sim 450 \text{ kHz}, \sim 600 \text{ kHz} \)). Note that we did not observe this effect when using \( 4 \times 10^6 \) electrons. It may be that compression via a resonance at higher harmonics requires a better source of cooling and \( 4 \times 10^6 \) electrons do not provide enough cooling. \( 7 \times 10^6 \) electrons provide more cooling and perhaps for this reason, it is possible to achieve compression to frequencies up to \( \sim 500 \text{ kHz} \). If this explanation holds, it indicates that above a
certain electron number, one can get the same cooling effects (as for $12 \times 10^6$ and $20 \times 10^6$ electrons), where the antiproton cloud has almost the same compression behaviour. However this effect only indicates an initial resonance but does not explain why a better antiproton cloud compression is achieved at higher frequencies. As we observed in chapter 6, there is a partial compression of the electrons, which clearly modifies the potential and the rotation frequency of the system. The effect of such partial compression will be studied in the next section.

### 7.4.2 $f(\omega_b + \omega_{rot})$ as a function of the partial compression of the electron plasma.

Figure 7.12 shows MCP images of the antiproton-electron plasma (with $20 \times 10^6$ electrons) after applying the rotating wall for 100 s at different frequencies. Recall that the electrons do not compress when the antiprotons are absent, as seen in section 6.2.3. There is an evident partial compression of the electron plasma after applying the rotating wall at 200 kHz and higher frequencies. The electron plasma compresses when applying the rotating wall from 200 kHz to 800 kHz, and is most intense at 500 kHz, 600 kHz and 700 kHz. At these frequencies, a fraction of the electron plasma (about $3 \times 10^6$ electrons) becomes denser and the rotation frequency of the system increases.

Figure 7.13 shows the MCP images when applying the rotating wall at 550 kHz for different times to $\sim 1 \times 10^5$ antiprotons and $20 \times 10^6$ electrons. We can see that from 1 s to 10 s, the antiproton cloud is still large, revealing that the compression is very slow. Here we speculate that compression is due to a resonance with higher harmonics.

Faster compression of the antiproton cloud can be observed from $\sim 15$ s to $\sim 20$ s. In those images, one can see on the right hand side, next to the antiprotons, a fraction of the electron plasma compressing. After $\sim 30$ s, one can see that the density of the antiproton cloud and the electron plasma reaches a maximum.

Figure 7.14 shows the data of the antiproton cloud central density as a function of the rotating wall application time for $\omega_{RW} = 350$ kHz and $\omega_{RW} = 550$ kHz. Note that the antiproton cloud compression speeds up earlier when $\omega_{RW} = 350$ kHz than when $\omega_{RW} = 550$ kHz. The antiproton cloud compresses fastest at the point of steepest slope: in the $\omega_{RW} = 550$ kHz data, this happens
7.4. \( f(\omega_b + \omega_{rad}) \) of antiprotons cooled by \( 20 \times 10^6 \) electrons

Figure 7.12: MCP images after 100 s of compression for various frequencies for \( 1 \times 10^5 \) antiprotons and \( 20 \times 10^6 \) electrons. About 15\% of the electron plasma compresses.
7.4. $f(\omega_b + \omega_{rot})$ of antiprotons cooled by $20 \times 10^6$ electrons

Figure 7.13: MCP images for various compression times at 550 kHz for $1 \times 10^5$ antiprotons and $20 \times 10^6$ electrons.
7.4. $f(\omega_b + \omega_{\text{rot}})$ of antiprotons cooled by $20 \times 10^6$ electrons

<table>
<thead>
<tr>
<th>$\omega_{RW}/2\pi$ [kHz]</th>
<th>Time [s]</th>
<th>Density [cm$^{-3}$]</th>
<th>$\omega_{\text{rot}}/2\pi$ [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>20</td>
<td>$9 \times 10^8$</td>
<td>440</td>
</tr>
<tr>
<td>350</td>
<td>15</td>
<td>$5 \times 10^8$</td>
<td>220</td>
</tr>
</tbody>
</table>

Table 7.2: Peak density and rotation frequency of a fraction of the electron plasma ($3 \times 10^6$ electrons) at 500 K.

at $\sim 20$ s, and for $\omega_{RW} = 350$ kHz at $\sim 15$ s. By analyzing the corresponding MCP image, we can find the peak density and the rotation frequency of the electron plasma, which is shown in table 7.2. The electron plasma is denser and $\omega_{\text{rot}}$ is not negligible anymore, but is close to the rotating wall frequency.

![Figure 7.14: Antiproton cloud central density as a function of the rotating wall application time when cooled by $20 \times 10^6$ electrons at $\omega_{RW} = 350$ kHz and $\omega_{RW} = 550$ kHz.](image)

We plot the calculated distributions $f(\omega_b + \omega_{\text{rot}})$ for these two points in figure 7.15. The vertical lines show the applied rotating wall frequencies. The applied rotating wall frequency is close to the peak of $f(\omega_b + \omega_{\text{rot}})$ at the moment when the rate of compression is fastest. This indicates that this occurs when the largest number of antiprotons are in resonance. We conclude that, as the fraction of the electron plasma compresses, $\omega_{\text{rot}}$ increases and brings a larger number of particles into resonance, which speeds up the compression.

The calculations of $f(\omega_b + \omega_{\text{rot}})$ allow us to make an interpretation of the antiproton cloud com-
7.4. $f(\omega_b + \omega_{rot})$ of antiprotons cooled by $20 \times 10^6$ electrons

![Figure 7.15: The antiprotons' $f(\omega_b + \omega_{rot})$ distribution when cooled by an electron plasma with electron densities $5 \times 10^9$ cm$^{-3}$ and $9 \times 10^9$ cm$^{-3}$, which correspond to the fastest compression when applying the rotating wall at 350 kHz and 550 kHz, respectively. Vertical lines show the applied rotating wall frequency.](image)

Figure 7.15: The antiprotons’ $f(\omega_b + \omega_{rot})$ distribution when cooled by an electron plasma with electron densities $5 \times 10^9$ cm$^{-3}$ and $9 \times 10^9$ cm$^{-3}$, which correspond to the fastest compression when applying the rotating wall at 350 kHz and 550 kHz, respectively. Vertical lines show the applied rotating wall frequency.

... compression. However, another question remains: why there is a partial compression of the electron plasma? This is not yet understood. As observed in section 6.2.3, for a pure the electron plasma (no antiprotons), there is no compression at all. We speculate that it could be an inverse sympathetic mechanism: the antiproton cloud compresses during the first seconds, which sympathetically compresses a fraction of the electron plasma. We cannot rule out that it could also be an effect of the mixed antiproton-electron plasma. As already seen in section 7.1, the electron plasma has plasma modes in the 10 MHz region and the electron bounce frequency is at $\sim 12$ MHz, which indicates that the compression of the antiprotons cannot be linked to a resonance with the electron plasma, but with a resonance with the antiprotons themselves. It seems that the partial compression of the electron plasma is a secondary effect, which in turn, after a certain time, enhances the compression of the antiprotons at high frequencies (e.g. 500 kHz and 600 kHz) by providing cooling and increasing the rotation frequency of the system and consequently $f(\omega_b + \omega_{rot})$ to higher frequencies.
7.5 Conclusion

We have discussed possible compression mechanisms. We have found that bounce resonant transport is the most likely explanation for the compression of the antiproton clouds. For this mechanism, there is compression if the particles’ $\omega_b + \omega_{rot}$ is equal to $\omega_{RW}$.

To further investigate this mechanism, we calculate the frequency distribution $f(\omega_b + \omega_{rot})$, which should indicate if the motion of the antiprotons is in resonance with the rotating wall drive. We have observed that the antiprotons’ $f(\omega_b + \omega_{rot})$ is highly dependent on the electron plasma characteristics since the space charge makes significant changes to the potential well and the rotation frequency.

When the antiprotons are cooled by $4 \times 10^6$ electrons, the electron plasma remains in conditions similar to the initial conditions, and there is no major change in the potential well or the rotation frequency over time. The simulation shows that the antiprotons’ frequency distribution $f(\omega_b + \omega_{rot})$ is very close to the frequencies where the compression of antiproton cloud occurs. This result indicates that the antiproton cloud may be compressed by a resonance between $\omega_b + \omega_{rot}$ and $\omega_{RW}$.

If the number of electrons is increased, the same underlying mechanism of compression seems to apply. However, a fraction of the electron plasma compresses, which complicates the analysis. We think that the antiproton cloud causes a partial compression of the electron plasma. As a consequence, the potential well changes and thus $f(\omega_b)$ and $f(\omega_b + \omega_{rot})$ of the antiprotons change over time. We specifically studied the case when the antiprotons are cooled by $20 \times 10^6$ electrons. Here, there is an evident compression of a fraction of the electron plasma, which changes the potential well and consequently, the rotation frequency of the system increases. By analyzing the electron plasma on the MCP image, we calculated the antiprotons’ $f(\omega_b + \omega_{rot})$ in these new conditions. We found that $f(\omega_b + \omega_{rot})$ is shifted to higher frequencies, and the fastest compression occurs when its peak is close to the rotating wall frequency.
Chapter 8

Summary and conclusion

Antihydrogen holds the promise of a stringent test of CPT invariance. In the first part of this thesis we have discussed the first measurements on antihydrogen trapping and spin-flip transitions in the ALPHA apparatus. In the second part, we have observed a new mechanism of compression of the antiproton clouds. Compression of antiproton clouds is an important tool for antihydrogen formation and trapping.

In 2010, the ALPHA collaboration trapped 38 atoms for the first time. Antihydrogen trapping measurements continued until 2011 and a total of 595 antihydrogen atoms were trapped. In 2011, the ALPHA collaboration induced spin-flip transitions of antihydrogen with microwave radiation. The transition frequencies at the minimum trap were localized to a relative precision of $4 \times 10^{-3}$. These experiments have demonstrated that antihydrogen can be trapped for enough time to be interrogated and enable other experiments.

In 2012, the ALPHA apparatus was upgraded and renamed ALPHA-2. The ALPHA-2 apparatus has laser access and a new era of antihydrogen research is around the corner. Future experiments on antihydrogen include 1S–2S two photon spectroscopy, 1S–2P one photon spectroscopy and cooling, and gravity experiments among other (for a detailed list, see section 3.5).

The second part of this thesis focuses on antiproton cloud radial compression using the rotating wall technique and performed in the antiproton capture trap of the ALPHA-2 apparatus. Compression of an antiproton cloud ($\sim 1.5 \times 10^5$ antiprotons) was observed over a frequency range of $50 – 750$ kHz, when cooled by $4 \times 10^6$, $7 \times 10^6$, $12 \times 10^6$ and $20 \times 10^6$ electrons. The radius of the antiproton cloud was decreased by up to a factor of 20, with the smallest radius being $\sim 0.2$ mm. Different
compression behaviours were observed that depended on the electron number. A higher number of electrons ($12 \times 10^6$ and $20 \times 10^6$ electrons) enhances and allows antiproton cloud compression over a wider range of frequencies. For those electron numbers, we also observed that about 15% of the electron plasma compresses.

After discussing several mechanisms of compression, we concluded that bounce resonant transport is the most likely mechanism to explain compression of the antiproton clouds at these frequencies. To further study this mechanism, we calculated the axial bounce and rotation frequency distributions of the antiprotons for a comparison with the frequency range where compression was observed. We have found that both ranges of frequencies are similar when cooling the antiprotons with $4 \times 10^6$ electrons, but not when using higher numbers of electrons. However, the partial compression of the electron plasma increases the rotation frequency of the system and seems to be the reason behind compression at slightly higher frequencies. This is the first time that bounce resonant transport has been observed on antiprotons. The explanation of compression was challenging because we have a two species plasma in which the electron plasmas space charge dominates the rotation frequency and the potential shape.

Nevertheless, compression of the antiproton clouds could be further studied by measuring the temperature during compression and at higher rotating wall amplitudes. Another remaining experiment is to perform ejection of the electron plasma to study the antiproton cloud expansion after compression. Antiproton cloud compression by resonant bounce transport has proven to be consistent and reproducible and has the potential to be an excellent alternative to the well-established sympathetic compression technique for antihydrogen formation and trapping.
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Appendix A

Antiproton energy loss

During degrading, antiprotons lose energy as they pass through the material, as mentioned in section 5.1.1. The energy loss per length unit ($-dE/dx$) for charged heavy particles is also called the stopping power. The energy loss is mainly due to inelastic collisions where target atoms are ionized or excited (electronic stopping power). At low energy, elastic collisions become important since the probability of the atomic target to recoil becomes higher and contributes to the energy loss of the incident particle (nuclear stopping power).

The stopping power is accurately described by the Bethe formula for high energies (see equation [A.1]) [109].

$$\frac{dE}{dx} = \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \frac{4\pi z^2}{m_e c^2 \beta^2} \frac{N_A Z}{A} L_0,$$

(A.1)

where

- $E$: particle energy
- $x$: the distance travelled
- $e$: elementary charge
- $z$: charge of incident particle
- $Z$: target atomic number
- $\epsilon_0$: vacuum permittivity
- $N_A$: Avogadro’s number
- $A$: atomic mass of the target
- $m_e$: mass of the electron
- $L_0$: Bethe stopping function
- $c$: speed of light
- $\beta$: particle velocity ($v/c$).

The Bethe stopping function is [216]

$$L_0 = \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2}.$$

(A.2)
Appendix A. Antiproton energy loss

where $\gamma$ is the Lorentz factor $1/\sqrt{1-\beta^2}$, $I$ is the mean excitation energy, $\delta(\beta\gamma)$ is the density effect correction and $T_{\text{max}}$ is the maximum kinetic energy that can be transferred to an electron in a single collision. $T_{\text{max}}$ can be written as

$$T_{\text{max}} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2},$$  \hspace{0.5cm} (A.3)

where $M$ is the mass of the incident particle.

Note that the Bethe stopping function is independent of $z$. The Bethe stopping function can be generalized and higher-order $z$ terms are introduced:

$$L(\beta) = L_0(\beta) + zL_1(\beta) + z^2L_2(\beta) + ..., \hspace{0.5cm} (A.4)$$

where the $zL_1(\beta)$ term is known as the Barkas correction and the $z^2L_2(\beta)$ term is called the Bloch correction.

The Barkas correction is responsible for the difference in the stopping power between protons and antiprotons. Antiprotons are negatively charged, hence the Barkas term will decrease the magnitude of the stopping power. Figure [A.1] shows the stopping power for protons and antiprotons as a function of energy in aluminium and beryllium. For antiprotons, the maximum stopping power is about 35% smaller. This difference can be explained by the polarization of the target by the projectile.

When the antiproton is slow enough, it repels electrons along its path, so the energy loss is smaller than for protons (figure [A.1] [216].

The mean particle range is the distance traveled by the particle before depositing all its kinetic energy in the material and can be directly calculated from the stopping power:

$$R(E_0) = \int_{E_0}^0 dx = \int_{E_0}^0 \frac{dE}{dE} dx = \int_0^{E_0} \frac{dE}{-dE/dx}, \hspace{0.5cm} (A.5)$$

where $E_0$ is the initial energy of the incident particle. The range for protons and antiprotons in Al
Figure A.1: Stopping power as a function of the particle energy for antiprotons and protons in aluminium and beryllium. Data extracted from GEANT4 [217].

and Be are shown in table A.1.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Material</th>
<th>Range [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>antiproton</td>
<td>aluminium</td>
<td>227</td>
</tr>
<tr>
<td></td>
<td>beryllium</td>
<td>269</td>
</tr>
<tr>
<td>proton</td>
<td>aluminium</td>
<td>211</td>
</tr>
<tr>
<td></td>
<td>beryllium</td>
<td>260</td>
</tr>
</tbody>
</table>

Table A.1: Range for protons and antiprotons with kinetic energy of 5.3 MeV for aluminium and beryllium. Data extracted from GEANT4 [217].
Appendix B

Electrodes cabling and connections

The antiproton capture Penning-Malmberg trap is composed of 20 cylindrical electrodes, where two of them are high voltage electrodes and two are six-segmented electrodes (rotating wall), as described in section 2.3.3. Figure B.1a is a picture of the electrode stack. The electrodes are independently connected to electric feedthrough using a designed flexible (flex) circuit, with 35 µm thick copper conducting layers and with kapton insulating layers. The layer with the traces is sandwiched between two ground layers to improve the insolation between the traces and the rejection of external noise. The flex circuit is connected with screws to the electrodes as shown in figure B.1b.

High voltages that are supplied to high voltage electrodes cannot be applied through the flex, and so are directly connected with 50 coaxial cable (KAP50) [218], as shown in figure B.1c.

The end of the flex has a serpentine shape to increase the path of the circuit and by consequence, to decrease the heat flow. This is necessary to allow the electrodes to cool to temperatures close to ∼4 K. The ground layer of the flex circuit is directly clamped to different regions of the apparatus. In figure B.1, on the left hand side, the red circle shows where the flex circuit is clamped to the 40 K region. On the right hand side, the blue circle shows where the flex is clamped to the 4 K region.

Micro-D connectors are soldered to the flex and connected to the 40 K flange that separates the UHV region and the OVC region. In the OVC region, small PCBs (printed circuit boards) connect the micro-D connectors and coaxial wires as shown in figure B.2a. The coaxial cables (KAP3) [218] have a copper conductor with a diameter of 0.25 mm and a length of ∼1.5 m. The end of the cables are soldered to small PCBs with subminiature-D (sub-D) connectors. The sub-D are connected to the flange between the OVC and the room temperature area, as shown in figure B.2b.
Appendix B. Electrodes cabling and connections

Figure B.1: a) Stack of electrodes of the antiproton capture trap. The green double arrow shows the length of the stack. b) A close up picture of the connection of the electrode with a circuit flex. c) Picture of the high voltage electrode connected to a coaxial wire. The white ceramic spacer insulates the high voltage electrode. d) Picture of the end of the flex. The blue circle on the left represents the area that is clamped to the 4 K region. The red circle on the right represents the area that is clamped to the 40 K region.
Appendix B. Electrodes cabling and connections

Figure B.2: a) Micro-D connector and PCB connected in the flange between the UHV and OVC region. b) Sub-D connectors and PCB connected in the flange between the OVC and the room temperature region.

temperature sub-D are connected to a circuit board with a passive RC-filter (one for each electrode), which are connected to the respective amplifiers (see section 2.3.2).
Appendix C

Veto detector simulations

In 2010, ALPHA studied the possibility to implement a cosmic veto detector around the apparatus. I performed Monte Carlo simulations to study if a cosmic veto detector was suitable to discriminate between antiproton/antihydrogen annihilations and cosmic rays.

The prototype cosmic veto detector consisted of two parallel scintillator pads, one on the top of the apparatus and one on the bottom of the apparatus (on the floor). Using the time of detection of the scintillator on the top \( t_{\text{top}} \) and the scintillator on the bottom \( t_{\text{bottom}} \), we can calculate the time difference \( \Delta t = t_{\text{bottom}} - t_{\text{top}} \). Because of the different origin of the cosmic rays and antiproton annihilations, \( \Delta t \) is different for each case. Cosmic rays passing through the apparatus are expected to pass first through the scintillator on the top and then, after \( \Delta t_{\text{cosmic}} \), through the scintillator on the bottom. Antiproton/antihydrogen annihilations originate close to the center of the apparatus, thus the resulting particles from the annihilation are detected by the scintillators on the top and on the bottom almost simultaneously, with \( \Delta t_{\text{annihilation}} < \Delta t_{\text{cosmic}} \). Figure C.1 shows a schematic of the geometry of the prototype detector. The challenge of the cosmic veto detector resided in the detector time resolution needed and on the space and geometry available in the experiment.

Monte Carlo simulations were performed using GEANT3 package as described in Ref. [102]. Two scintillator pads were implemented. The distance between the scintillators was varied, as well as the resolution time of the detector. The distance from the centre to the bottom is fixed to \( d_{\text{bottom}} = 110 \text{ cm} \) since it is limited by the floor. Because of the space available in the experimental zone, the bottom pad dimensions are also limited to \( 160 \text{ cm} \times 110 \text{ cm} \). The distance from the centre to the top scintillator is not fixed but has to be greater than \( d_{\text{top}} > 150 \text{ cm} \). Figure C.2 shows the distribution of \( \Delta t \) for...
Figure C.1: Schematic of the cosmic veto detector. The silicon detector is represented in yellow. An example of a cosmic ray path is represented in green and the path from an antiproton annihilation is represented in red.
Appendix C. Veto detector simulations

cosmic rays and antiproton annihilations for a distance of $d_{top} = 150\,\text{cm}$ (centre to top scintillator) and for various time resolutions. For this distance, $\Delta t$ for cosmic rays has a distribution with a mean around $\Delta t_{\text{cosmic}} \sim 10\,\text{ns}$, while the distribution for annihilations has a mean around $\Delta t_{\text{annihilation}} \sim -1\,\text{ns}$. Even though the two distributions have means about $10\,\text{ns}$ apart, both distributions are wide and a time resolution of $2\,\text{ns}$ is not enough to detangle both signals.

Figure C.3 shows the distribution of $\Delta t$ for cosmic rays and antiproton annihilations for a distance of $d_{top} = 200\,\text{cm}$ (centre to top scintillator) and for various time resolutions. If the top scintillator is placed further from the centre, the signal of the cosmic rays and antiproton annihilations almost completely separated when using a time resolution of $1\,\text{ns}$. However, when the top scintillator is moved farther up, the size must be increased to cover sufficient solid angle.

The project of a cosmic veto detector was delayed since scintillators with so large area and short time resolution were not found. A new project is been studied, where a structure with various small scintillator pads are placed around the external magnet [219].
Figure C.2: Distribution of $\Delta t$ of cosmic rays and antiproton annihilations for $d_{\text{top}} = 150$ cm. On the top: time resolution of 1 ns. On the bottom: time resolution of 2 ns.
Figure C.3: Distribution of $\Delta t$ of cosmic rays and antiproton annihilations for $d_{top} = 200$ cm. On the top: time resolution of 1 ns. On the bottom: time resolution of 2 ns.
Appendix D

Derivation of the magnetic dipole force in GEANT4

D.1 Magnetic dipole introduction

The magnetic potential energy of a magnetic dipole in an inhomogenous magnetic field is:

\[ U = -\mu \cdot \vec{B}, \]  

(D.1)

where \( \mu \) is the magnetic dipole moment and \( \vec{B} \) is the magnetic field.

There are two stable configurations (\( \mu \) and \( \vec{B} \) parallel or antiparallel). A particle can be trapped in a magnetic field minimum if its magnetic moment is antiparallel to the magnetic field \( (\mu \cdot \vec{B} = -\mu |\vec{B}|) \).

The force acting on such a "low field seeking" particle is:

\[ \vec{F} = \frac{d\vec{B}}{dt} = -\mu \nabla |\vec{B}|. \]  

(D.2)

Note that equation (D.2) only applies when the rate of change of the direction of the magnetic field
at the particle’s position is slow compared to the Larmor frequency \( \omega_l \):

\[
\frac{1}{B} \frac{d\vec{B}(\vec{r})}{dt} \ll \omega_l,
\]

(D.3)

where \( \omega_l = \gamma B \), \( \gamma \) being the gyromagnetic ratio of the system. This requirement is easily fulfilled for most experiments.

### D.2 GEANT4 implementation

The force acting on a magnetic dipole can be described as the differential equation:

\[
F_i = \frac{dP_i}{dt} = -\mu \frac{\partial |\vec{B}|}{\partial x_i},
\]

(D.4)

where \( i \) is 0, 1 or 2 corresponding to \( x, y \) or \( z \).

However, GEANT4 uses the derivative along the curved trajectory \( \frac{dP_i}{ds} \) to calculate the trajectories of particles, so:

\[
\frac{dP_i}{ds} = \frac{dP_i}{dt} \frac{dt}{ds} = -\mu \frac{\partial |\vec{B}|}{\partial x_i} \frac{dt}{ds}.
\]

(D.5)

We can replace \( \frac{dt}{ds} \) by \( \frac{1}{|\vec{P}|} \). And since \( E = \gamma mc^2 \) and \( P = \gamma mv \), we get:

\[
\frac{dt}{ds} = \frac{E}{|\vec{P}|c^2}.
\]

(D.6)
In reality, GEANT4 deals with the quantity $P_c$ (in MeV) instead of $P$, so equation (D.4) becomes:

$$\frac{d(P_i c)}{dt} = -\mu \frac{\partial |\vec{B}|}{\partial x_i} c,$$

and the units are:

$$\left[ \frac{\text{MeV}}{\text{ns}} \right] = \left[ \frac{\text{MeV}}{\text{Tesla}} \right] \left[ \frac{\text{Tesla}}{\text{mm}} \right] \left[ \frac{\text{mm}}{\text{ns}} \right].$$

Equation (D.6) is the same:

$$\frac{dt}{ds} = \frac{E}{(|\vec{P}|c) c},$$

with units:

$$\left[ \frac{\text{ns}}{\text{mm}} \right] = \left[ \frac{\text{MeV}}{\text{MeV}} \right].$$

In GEANT4, equation (D.5) becomes:

$$\frac{d(P_i c)}{ds} = -\mu \frac{\partial |\vec{B}|}{\partial x_i} c \frac{E}{(|\vec{P}|c) c},$$

$$= -\mu \frac{\partial |\vec{B}|}{\partial x_i} \frac{E}{(|\vec{P}|c)} .$$

The quantities $\frac{d(P_i c)}{ds}$ in GEANT4 are $dydx[3], dydx[4]$ and $dydx[5]$, $E = \sqrt{(pc)^2 + (mc^2)^2}$ and $|\vec{P}| = \sqrt{(p_x c)^2 + (p_y c)^2 + (p_z c)^2}$ where $p_i c$ are $y[3], y[4]$ and $y[5]$. 

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