PULSED ANTIHYDROGEN PRODUCTION

FOR DIRECT GRAVITATIONAL MEASUREMENT

ON ANTIMATTER

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Un importante obiettivo di ricerca da parte della comunità dell'antimateria è quello di misurare la gravità su un sistema di antimateria neutro, attraverso un test di verifica diretto della validità del Principio di Equivalenza Debole (WEP). Il WEP è una pietra miliare della Relatività Generale e un tale test di verifica non è mai stato effettuato con antimateria. Ci si aspetta che il comportamento dei sistemi di antimateria elettricamente neutri sia esattamente lo stesso delle loro controparti composte di materia. Diversi argomenti indiretti indicano che se ci fossero differenze tra la caduta libera di sistemi di materia e sistemi di antimateria, queste sarebbero inferiori a $10^{-6}$ g. Ad oggi, tuttavia, la domanda se l'antimateria cade nel campo gravitazionale terrestre con la stessa accelerazione $g$ della materia ordinaria non ha ancora ottenuto una risposta sperimentale diretta.

L'antiidrogeno ($\bar{\text{H}}$) è lo stato legato di un antiprotone ($\bar{\text{p}}$) e di un positrone ($\text{e}^+$). È l'atomo di antimateria più semplice - e l'unico mai sintetizzato. In AEgIS, l'antiidrogeno si forma mediante reazione di scambio di carica tra positronio eccitato via laser e antiprotoni intrappolati e portati a basse temperature. Il positronio ($\text{Ps}$) è uno stato legato puramente leptonico, simile all'idrogeno, composto da un elettrone e un positrone.

In questa tesi, presento la prima formazione pulsata di antiidrogeno, realizzata in AEgIS come argomento principale del mio lavoro degli ultimi tre anni, a partire dalla fine del 2016 all'inizio del 2020. Il lavoro qui presentato è stato svolto tra la fine del Run 2 e l'inizio della Lunga Sosta 2 (LS2). Durante questo periodo, sono stato membro della Collaborazione AEgIS e parte del Gruppo AEgIS di Genova. La ripresa delle attività sperimentali per quanto riguarda gli antiprotoni è prevista per il 2021.

La produzione di antiidrogeno pulsato rappresenta il risultato cruciale per convalidare l'approccio sperimentale di AEgIS per effettuare la misura gravità sull'antimateria. Una caratteristica fondamentale di questo risultato è la conoscenza, entro poche centinaia di ns, dell'istante in cui l'antiidrogeno viene prodotto. I precedenti schemi di produzione forniscono una sorgente quasi continua di antiidrogeno, senza la possibilità di identificarne con precisione l'istante di formazione. La realizzazione di una produzione pulsata di antiidrogeno apre la possibilità di misurare il tempo di volo degli anti-atomi, non determinabile altrimenti con i metodi attualmente disponibili basati su intrappolamento. Questo è un traguardo importante e un articolo con i risultati presentati in questa tesi è stato inviato alla rivista Nature Physics.

Il Gruppo AEgIS di Genova è responsabile del sistema di trappole, dei sistemi di rivelazione e di acquisizione dati. Il sistema di trappole elettromagnetiche è il sistema principale dell'apparato sperimentale. L'elettronica di tutti gli altri sistemi dipende fortemente da quella del sistema di trappole elettromagnetiche. Ho contribuito fortemente allo sviluppo delle procedure di manipolazione degli antiprotoni e relative tecniche di misura. Tra i risultati di questo lavoro di tesi, è stata ottenuta una compressione notevole dei plasmi di antiprotoni, in modo che il trasferimento nella trappola di produzione risultasse più efficiente con il plasma in condizioni adeguate per la formazione di antiidrogeno e la sua rivelazione. Con un raggio minimo del plasma di 0,17 mm, tale compressione è la migliore mai raggiunta per gli antiprotoni. Il numero di antiprotoni immagazzinati nella trappola di produzione è stato circa 10 volte maggiore rispetto a quanto atteso stando al proposal originale di AEgIS. Inoltre, è stato possibile un immagazzinamento del plasma di antiprotoni per tempi macroscopici, nonostante i limiti di progettazione degli elettrodi della trappola.
Anche grazie al mio contributo, sono state implementate diverse nuove tecniche di misura nella diagnostica dei positroni. In particolare, un elettrodo impulsato è stato sviluppato e testato per la misura della carica indotta dal passaggio di pacchetti di positroni. Tale elettrodo è stato utilizzato come rivelatore di riferimento per il monitoraggio delle condizioni dei positroni all’ingresso nell’apparato principale. Questo lavoro è stato svolto dal Gruppo di Genova, responsabile inoltre della linea di trasferimento dei positroni, della sua meccanica e del sistema di misura. Inoltre, la conversione di un MCP in un rivelatore sensibile alla posizione del positronio a bassa energia ha permesso di caratterizzare lo stato di Rydberg in campo magnetico di questo atomo instabile. Il lavoro per la messa a punto e la caratterizzazione delle nuove tecniche di rivelazione ha fatto parte delle attività che ho svolto durante il periodo di presa dati. Infine, ho valutato la possibilità di utilizzare un nuovo materiale scintillante per la rivelazione di positronio eccitato nella regione di produzione di antiidrogeno per superare le limitazioni attualmente esistenti. Ho completato un’ampia calibrazione del materiale e ho assemblato un rivelatore basato su di esso con un tubo fotomoltiplicatore a risposta rapida. Questo rivelatore è riuscito a rivelare la formazione di positronio e ha dato risultati incoraggianti per la misura degli stati di positronio Rydberg in presenza di campo magnetico. Ho scritto un articolo su questa attività per la presentazione ad un giornale tecnico. L’articolo è al momento sotto revisione interna.
Abstract

One of the biggest efforts of the antimatter community is to measure gravity on a neutral antimatter system towards a direct test of the validity of the Weak Equivalence Principle (WEP). WEP is a cornerstone of the General Relativity and such a test has never been carried out on antimatter. Electrically neutral antimatter systems are expected to behave in exactly the same way as their matter counterparts. Several indirect arguments indicate that possible differences between the free fall of matter and antimatter, if existing, wouldn’t be greater than $10^{-6}$ g. To date, however, the question of whether antimatter falls in the Earth’s gravitational field with the same acceleration $g$ as ordinary matter does not yet have a direct experimental answer.

Antihydrogen ($\bar{\text{H}}$) is the bound state of an antiproton ($\bar{\text{p}}$) and a positron ($\text{e}^+$). It is the simplest antimatter atom - and the only one ever synthesised. In AEgIS, antihydrogen is formed through charge exchange reaction between laser-excited positronium and cold trapped antiprotons. Positronium (Ps) is a purely leptonic hydrogen-like bound state composed of an electron and a positron.

In this thesis, I present the first pulsed formation of antihydrogen, achieved in AEgIS as a core topic of my work in the last three years, from late 2016 to early 2020. The work here presented was carried out between the end of the Run 3 and the beginning of the Long Shut down 2 (LS2). During this period, I was a member of the AEgIS Collaboration and part of the AEgIS Genoa Group. The experimental activities involving antiprotons are expected to resume in 2021.

Pulsed antihydrogen production is the crucial achievement to validate the AEgIS experimental approach to perform the gravity measurement on antimatter. A key feature of this result is the knowledge, within few hundred ns, of the $\bar{\text{H}}$ production time. Previous production schemes provide a quasi-continuous source of antihydrogen without the possibility of precisely tagging the time of formation. The achievement of a pulsed production of antihydrogen opens the possibility to measure the atoms’ time-of-flight, unavailable from currently available trap-based methods. This is an important accomplishment and a paper with the results presented in this thesis was submitted to Nature Physics.

The AEgIS Genoa Group is responsible for the trap system, detection and data acquisition systems. The trap system is the main system of the experimental apparatus. The electronics of all the other systems depend on that of the trap system. I strongly contributed to the developments on antiproton manipulation procedures and related detection techniques. Among the results of this thesis work, an outstanding antiproton plasma compression was obtained, allowing the movement of antiproton clouds into the production trap in suitable conditions for the formation of antihydrogen and its detection. Remarkably, with a minimum cloud radius of 0.17 mm, such compression is the best ever reached for antiprotons. A number of stored antiprotons about 10 times larger than expected in the original AEgIS proposal was stored in the production trap for macroscopic times, despite the design limitations of the electrodes.

Several novel detection techniques were implemented in the positronium diagnostics, also with my contribution. In particular, the use of a kicker pulser to detect the charge induced by the passage of the positron bunch was developed, tested and used as a main technique to monitor the condition of the positrons entering the main apparatus. This work was carried out by the Genoa Group, also responsible for the $\text{e}^+$ transfer line, its mechanics and detection system. On the top of this, the conversion of the MCP into a position sensitive detector for slow positronium allowed to characterise the Rydberg state.
of this unstable atom in magnetic field. The work for the fine tuning and characterisation of the new
detection techniques was part of the activities I carried out during the data taking period. Finally, I
evaluated the possibility to use a novel scintillating material in the detection of excited positronium
produced in the $\bar{\text{H}}$ production region to fully overcome the present existing limitations. I completed an
extensive calibration of the material and I assembled a detector coupling such scintillator with a fast
response photomultiplier tube. Such detector succeeded in detecting the formation of positronium
and gave encouraging results for the detection of the elusive Rydberg-Ps states in magnetic field. I
wrote a paper on this activity for the submission to a technical newspaper. At the moment, the article
is under internal review.
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AEgIS (Antimatter Experiment: gravity, Interferometry, Spectroscopy) is an experiment presently running at CERN’s Antiproton Decelerator (AD) facility. According to the original proposal [1], its primary goal consists in performing a direct test of the validity of the Weak Equivalence Principle (WEP) on neutral antimatter systems by measuring the Earth gravitational acceleration $g$ on a beam of cold antihydrogen. The Weak Equivalence Principle is a pillar of the Einstein’s General Relativity and such a test has never been carried out. Electrically neutral antimatter systems are expected to behave in exactly the same way as their matter counterparts. Indirect arguments indicate that possible differences between the free fall of matter and antimatter, if any, should be below $10^{-6} g$ [2, 3, 4] and the question of whether antimatter falls in the Earth’s gravitational field with the same acceleration $g$ as ordinary matter does not yet have a direct experimental answer.

Antihydrogen is formed in AEgIS through charge exchange reaction between cold antiprotons stored in a Malmberg-Penning trap and a cloud of Rydberg-excited positronium atoms ($Ps^*$). $Ps^*$ is obtained by a two-steps excitation of positronium ($Ps$). Positronium is a purely leptonic hydrogen-like bound state of an electron ($e^-$) and its antiparticle, the positron ($e^+$). In AEgIS, $Ps$ is produced by the conversion of a positron bunch hitting a nano-porous target. The target converter is installed above the trap. The electrodes below the converter have an opening that allow the entrance of the positronium cloud.

The pulsed production of antihydrogen, with the knowledge within few hundred ns of the $\bar{H}$ production time, is the crucial achievement to validate the AEgIS experimental approach for the gravity measurement on antimatter. Such information is unavailable in currently used trap-based methods. Previous production schemes provide a quasi-continuous source of antihydrogen without the possibility of precisely tagging the time of formation. Instead, knowing the formation time with a good resolution opens the possibility of an efficient and immediate manipulation of the formed antiatoms to perform the free fall measurement on antihydrogen. The first pulsed antihydrogen production was achieved in 2018, before the beginning of the planned CERN’s Long Shut down 2 (LS2). The experimental activities involving antiprotons are expected to resume in 2021. I led most of the data-takings to get the results presented in this thesis, as shift leader and run coordinator. I also contributed providing raw analyses, on-line monitoring, detector cross-checks and reference measurements. In addition, I was in charge of the maintenance of the main apparatus during the whole data-taking period. The establishment of a pulsed production of antihydrogen is an important accomplishment and a paper with the results presented in this thesis was submitted to Nature Physics.

The AEgIS Genoa Group of the Italian National Institute for Nuclear Physics (INFN) is responsible for the charged particle traps and related electronics, detector system and data acquisition. The trap system is the main system of the experimental apparatus. The electronics of all the other systems depend heavily on the electronics of the trap system. The main activity of the Group was to continue to develop and commission the steps towards the antihydrogen production, defining stable and relying procedures and improving them towards an increase of the production rate and an enhancement of the reaction efficiency. A final protocol for the antihydrogen production was defined in 2018. I made a substantial contribution through the development of data taking, data analysis, calibration of components and fine tuning of parameters for the optimisation of the procedures. The plasma manipulation techniques were refined to reach an outstanding compression of antiproton clouds. A full implementation of the
stacking procedure was also achieved to substantially increase the number of antiprotons available per antihydrogen production trial. The compression of several AD shots of antiprotons resulted in the possibility to store of up to $10^6$ antiprotons for relatively very long times in stable conditions without any further manipulation. I also contributed in the estimation of the beam parameters required for detector exposures to low-energy antiprotons working both on a Monte Carlo simulation and directly on the beam-line facility. In general, the availability of dead times for detector tests in the secondary beam-line is a sign of good health. It indicates that the procedure running on the main apparatus is stable over long times and it does not need continue corrections and readjustments.

Detection of antihydrogen is operated by a scintillator paddle array which surrounds the experimental apparatus. It is also a main detection system for positronium in the production region together with an MCP used as a position-sensitive detector for positrons. On this respect, part of my activities also included calibrations, cross-checks and data analysis. However, detection of Rydberg states of positronium in high magnetic field in a non-optimal geometry, like in the production region of AEgIS, requires special attention. The decay of the Ps long-lived component has to be searched in the tail of the signal of the scintillators. Typically, the signal tail includes the contribution from the delayed light component characteristic of each scintillating material, the so-called afterglow. Laser excitation of Ps to Rydberg states, necessary for antihydrogen formation, increases the Ps lifetime producing slight variations in the tail of the signal. The resolution of the deviations in the tail of the signals allows to assess the Ps production or its excitation to a specific state. Taking all the above in consideration, the search of new detectors to overcome the present existing limitations is of paramount importance for the Collaboration. One promising solution could be given by a new scintillating material produced at the Livermore Lawrence National Laboratory (LLNL), in the US, with good rise time, large light yield and nearly no afterglow component. A sample of such material was kindly sent as a courtesy of Dr. N. Zaitseva (LLNL) to AEgIS for tests and evaluation. I studied the detection performance of the material coupling the sample to different fast response photomultiplier tubes. I tested such detectors in different conditions developing a complete and extensive characterisation through several data taking campaigns for the requirements of the experiment. Finally, I wrote the draft of a paper on this activity and I submitted it for internal review.

In this thesis, I will give an introduction of the framework and the motivations for a gravity measurement on antihydrogen in Chapter 1. Then, in Chapter 2 I will outline the experimental apparatus, its relevant details and main operations. I will give details on manipulation and detection techniques for antiprotons and positrons in Chapter 3 and 4, respectively. In Chapter 5, I will describe the detector calibration for the detection of antihydrogen, the datasets acquired and the data analysis to assess the result. I will illustrate the results of a simulation for the estimation of the beam parameters required for experiments of detector exposure in a dedicated secondary beam-line for low-energy antiprotons, in Chapter 6. Finally, in Chapter 7 I will describe the work I carried out with the new fast rise low afterglow new scintillating material for positronium detection in the main apparatus.
Chapter 1

Introduction

The idea of antimatter arose as a result of one of the first attempts to combine quantum mechanics with special relativity, carried out by Dirac for the purpose of describing the behaviour of an electron moving at a relativistic speed\(^1\), in 1928. His world-famous linear equation (see e.g. \([5]\)) admits four independent solutions, two with positive and two with negative energy, accounting for free for the existence of two spin states\(^2\). While it was straightforward to associate the solutions with positive energy to the electron, the correct interpretation of the negative solutions required quite a long time, until Anderson showed his notorious picture of the positron from cosmic rays passing through the iron plate in a cloud chamber\(^3\), in 1932. Antinucleons were only discovered after the first particle accelerators came into operation, the antiproton in 1955 and the antineutron in 1956 at the Bevatron at Berkeley, while the in-flight production of the first antinmatter atoms, antihydrogen, at relativistic energies, was reported by the LEAR collaboration at CERN in 1996. Modern synthesis techniques of antihydrogen allow to produce it at energies suitable for trapping for antinmatter studies.

In this chapter, I will introduce the motivations for the gravity measurement on neutral antimatter and I will briefly describe the mechanisms used so far for producing antihydrogen. Then, I will present the AE\(\bar{e}\)GIS experiment and illustrate the charge-exchange reaction used for the production of antihydrogen in pulsed mode.

1.1 Motivations

The Standard Model of particle physics (SM) together with Einstein’s General Relativity (GR) are the most widely accepted theories for the description of nature. The SM is a relativistic quantum-field theory (RQFT) explaining the existence of elementary particles and their fundamental interactions (e.g. \([7, 8, 9]\)) while the GR describes the gravitational force through a non-quantum field theory, providing a unified description of gravity as a geometric property of space and time, with the curvature of the space-time directly related to the energy and momentum of whatever matter and radiation act as source of distortions (e.g. \([7, 10, 11]\)). Both the theories have been soundly confirmed by a large number of direct and indirect measurements performed by several experiments but, to date, many questions (e.g. \([12, 13]\)) still remain unanswered. In addition, despite many attempts to describe gravity in terms of a quantum field theory and to include it in the SM, there is still no unified theory of the four fundamental

\(^1\)It was the second attempt. The first one, the Klein-Gordon equation, quadratic in time while the Schrödinger’s was linear, incompatible with Born’s statistical interpretation and abandoned.

\(^2\)The Klein-Gordon equation couldn’t admit the spin, forcing all the particles in a spin-0 configuration and failing to reproduce the electron levels in the Bohr atom, once included the Coulombian potential.

\(^3\)Physicists of that time had been seeing positron images for many years, without realizing the discovery of antimatter. In particular, Skobeltsyn since 1924 and Beckett and Occhialini since 1931 with experiments similar to those of Anderson. The publication of Anderson’s result was hampered by Millikan, his professor, who did not believe in the interpretation of a new particle. Dirac himself didn’t understand the discovery when in 1931 Beckett and Occhialini showed him their photos in a confidential way \([6]\).
forces. Furthermore, theoretical limitations of the SM let physicists think that a more complete theory of fundamental interactions able to describe gravitational interaction together with the other three fundamental forces should exist.

The universality of free fall, given by the Weak Equivalence Principle (WEP), is the cornerstone of General Relativity. Direct verifications of the WEP are only available for matter with an accuracy of \(10^{-16}\) [14]. No direct measurement have been carried out for antimatter so far. Remarkably, General Relativity predicts the same gravitational behaviour of matter and antimatter systems. With the exception of the weak interaction, all the fundamental interactions including gravity are expected to show complete symmetry between matter and antimatter systems. In RQFTs, like the SM, the CPT symmetry (Charge, Parity, Time reversal) is a consequence of few basic hypotheses (Lorentz invariance, locality and unitarity [15]). In particular, it predicts that bound states of antimatter should have the same energy levels and lifetimes as the corresponding matter systems. So far, no CPT or WEP violations have been observed in any physical system [2]. Experimental searches for possible violations of these principles with continuously increasing sensitivity provide constraints to extended and unified models [16] of all the fundamental interactions as well as to cosmology [17].

A measurement on gravitational interaction between neutral antimatter and the Earth fits this framework, providing a way to confirm (or disprove) the WEP and, most significantly, contributing to probe the foundations of humans’ understanding of nature. Indirect arguments indicate that possible differences between the free fall of matter and antimatter, if any, should be below \(10^{-5}\) \(g\) and the question of whether antimatter falls in the Earth’s gravitational field with the same acceleration \(g\) as ordinary matter does not have yet a direct experimental answer.

### 1.2 Production mechanisms of antihydrogen

While ordinary atoms are available in the laboratory in large numbers, working with antimatter requires dealing with very few antiatoms and special working conditions to prevent it from annihilation with ordinary matter. Antihydrogen (\(\bar{\text{H}}\)) is the bound state of an antiproton (\(\bar{\text{p}}\)) and a positron (\(\text{e}^+\)) and it is the simplest antimatter atom – and the only one ever synthesised. Its intrinsic lifetime allows for the realization of experiments with long observation time, thus giving chances for the search of tiny violations of CPT and of the WEP for antimatter with extremely high sensitivity.

The first production of low energy antihydrogen in Rydberg states, \(\bar{\text{H}}^*\), dates back nearly twenty years ago, in 2002. It was reached by means of the three-body radiative recombination reaction:

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

mixing clouds of antiprotons and positrons inside electromagnetic traps [18, 19]. Two years later, a double charge-exchange reaction with Rydberg caesium positronium atoms was demonstrated [20]:

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

as a basis for the pulsed production of antihydrogen in use in AEgIS and paving the way for the gravity measurement technique presented later in this chapter.

Since then, the antimatter community has come a long way on antihydrogen. Trapping experiments have been performed [21] in 2010. Few years later, in 2017, 15-25 transition of magnetically trapped antihydrogen have been measured and compared with the corresponding transition calculated for hydrogen in the same magnetic field, providing a CPT test with \(2 \cdot 10^{-12}\) accuracy [22] and, in the same year, the hyperfine splitting of the fundamental states of \(\bar{\text{H}}\) has been measured to be consistent with that of hydrogen with an accuracy of \(4 \cdot 10^{-4}\) [23]. Today, three different projects aim at a direct measurement of \(g\) on antihydrogen, AEgIS [24], ALPHA-g [25] and Gbar [26].
1.3 The AEГІS experiment

AEГІS (Antimatter Experiment: gravity, Interferometry, Spectroscopy) [24] is an experiment presently running at CERN’s Antiproton Decelerator (AD) facility. Its primary goal consists in performing a direct test of the validity of the Weak Equivalence Principle (WEP) on neutral antimatter system by measuring the Earth gravitational acceleration g on a beam of cold antihydrogen. Antihydrogen is formed through charge-exchange reaction between laser-excited positronium and cold trapped antiprotons. The picture in Figure 1.1 outlines the antihydrogen formation process and the subsequent gravity measurement. Once produced, the antihydrogen has to be conveyed into a Stark-accelerated beam towards a grating system including a time/position detector. The g value will be obtained by measuring the vertical displacement of the antiatoms flying through a two-grating system. The expected precision is at %-level using sub-Kelvin antihydrogen and a grating system operated in the classical regime (moire deflectometer). Higher accuracy could be obtained by using colder antihydrogen and quantum interferometers.

Antihydrogen temperature, and thus its velocity, are mainly determined by the antiproton temperature. To perform the gravity measurement, the antihydrogen atom has to be horizontally conveyed towards a detector able to resolve the annihilation position of the antiproton. The temperature of antihydrogen, the sensitivity of the detector at the end of the antihydrogen trajectory and the dimension of the gratings are parameters of paramount importance. It is worthy to remark that the antiproton temperature achieved so far is still too high to allow a gravity measurement in the present experimental configuration. A discussion about possible future upgrades of the experiment is currently ongoing.

1.3.1 charge-exchange reaction for antihydrogen formation in AEГІS

Antihydrogen production in AEГІS is based on charge-exchange reaction between Rydberg-excited positronium and cold antiprotons:

\[ Ps + \gamma_{IR} + \gamma_{UV} \rightarrow Ps^* \]  \hspace{1cm} (1.3a)
\[ \bar{p} + Ps^* \rightarrow \bar{H}^- + e^- \]  \hspace{1cm} (1.3b)

The left side of Figure 1.1 gives an outline of the production scheme with the charge-exchange reaction. A bunch of positrons impinges a nanoporous target. A fraction of the positrons in the bunch gets converted into positronium. Positronium is a purely leptonic hydrogen-like bound state composed of an electron (\( e^- \)) and its antiparticle, the positron (\( e^+ \)). Ps decays with different lifetimes in vacuum depending on the spin configuration of its components. To increase the reaction cross section and to extend its lifetime, Ps gets excited by means of UV and IR lasers to Rydberg states.

Charge-exchange reaction, first envisaged in [27, 28], has some advantages with respect to other \( \bar{H} \) production techniques. First of all, the cross-section scales as \( \sigma \propto n_{Ps}^6 \), where \( n_{Ps} \) is the positro-
nium principal quantum number. The classical trajectory Monte Carlo simulations indicate that $\sigma \approx 10^{-8} \div 10^{-9}$ cm$^2$ for $n_{Ps} \sim 18$. Furthermore, the principal quantum number of antihydrogen $n_{\bar{H}}$ is determined by the quantum state $n_{Ps}$ of the interacting positronium: $n_{\bar{H}} \sim \sqrt{2} n_{Ps}$. The average $n_{Ps}$ value can be controlled by lasers used for positronium excitation. Finally, the temperature of the resulting antihydrogen is given by the temperature of antiprotons prior to formation. Effects connected to electron recoil energy only become significant for temperatures largely inferior to 100 mK [1].

A detailed set of numerical calculations of the $\bar{H}$ charge-exchange production cross-section, both in field-free and for a 1 T magnetic field, were performed using the Classical Trajectory Monte Carlo (CTMC) approach [29]. The calculation method consisted in numerically integrating the classical equations of motion of an electron and a positron in external fields. The particles were initially positioned on a classical elliptical orbit associated to a choice of the $n, l$ quantum numbers with random angular orientation at the Ps formation point in the space, far away from the position of antiprotons, set in the axis origin. The center of mass velocity $v_{cm}$ was chosen so that the atom trajectory was hitting the antiproton with a specific impact parameter $b$ (here expressed in atomic units). The production cross-section was thus calculated by measuring the probability for the positron to end up bound to the antiproton, over many realizations of the initial conditions and multiplied by the impact surface. The plot in Figure 1.2 shows the charge-exchange cross section as a function of the Ps centre-of-mass energy. The plateau at high energies mitigates the dependence of the cross-section on the Ps excitation level. Importantly, the reaction cross section assumes higher values for low-energy Rydberg positronium.

The cross-section was evaluated with respect to several parameters. Among them, a central role was played by the relative velocity $k_\nu$ of the Ps atom with respect to the positron in the orbit. Left side of Figure 1.3 shows the $\sigma/n^4$ ratio as a function of the relative velocity $k_\nu$, for Ps states with principal quantum number between $n = 13$ and $n = 27$, in a 1.0 T magnetic field. The cross-section scales as $n^4$ for almost the entire considered region of $k_\nu$. The right side of the same figure shows that the cross-section does not significantly depend on the incidence angle $\theta$ of the Ps atom with respect to the magnetic field. This consideration opens up the possibility to consider sending the Ps atoms on the $\bar{p}$ cloud with different angles, without significantly affecting the $\bar{H}$ production cross-section.
Finally, simulations showed that the $\bar{H}$ atoms are produced, on average, on a Rydberg level with principal quantum number $n_{\bar{H}} \sim \sqrt{2}n_{Ps}$, corresponding to the same binding energy as the positrons in the initial Ps. A coarse control over the produced antihydrogen quantum states distribution could be envisaged in future developments by tuning the Ps Rydberg state, under the limitations set by Ps level mixing in the high external magnetic field.

A quantum calculation was recently carried out in [30]. Predictions from the two different approaches furnish the same scaling law. The principal quantum number of positronium and numerical values are in agreement within some tens of percent for $n_{Ps} \geq 3$ and down to very low collision energy of tens of $\mu$eV.
Chapter 2

Layout of the AEgIS apparatus

AEgIS is one of the six experiments\(^1\) studying antimatter at CERN. Antihydrogen is the unique stable bound state of pure antimatter that presently can be synthesized in laboratories. To produce antihydrogen, antiprotons and positrons are needed. While positrons can be collected from spontaneous \(\beta^+\) emitters or produced by small linear accelerators, antiprotons, at energies feasible for manipulation, are only available at the CERN’s Antiproton Decelerator (AD). This aspect makes the AD the only place in the world where study of fundamental physics with cold antimatter can be performed.

After a brief overview of the antiproton production, collection and slowing down in the AD facility, I will introduce in this chapter the layout of the AEgIS apparatus in order to give an outline of its most important subsystems from both hardware and software perspective.

2.1 The CERN’s Antiproton Decelerator

The Antiproton Decelerator ring is one of the accelerators of the CERN Accelerator Complex (Fig. 2.1). Bending and focusing magnets keep the antiprotons on the same track, while strong electric fields slow them down. The spread in energy of the antiprotons and their deviation from their track is reduced by cooling techniques. Antiprotons are produced in the CERN’s Proton Synchrotron (PS) via collisions with a metallic target by use of the following reactions

\[
p + n \rightarrow p + n + p + \bar{p} \tag{2.1a}
\]

\[
p + p \rightarrow p + p + p + \bar{p} \tag{2.1b}
\]

and then collected and injected into the AD. Protons are accelerated towards the metallic fixed target by LINAC\(^2\), Booster and Proton Synchrotron at 26 GeV energy. Either copper, tungsten, rhenium or iridium could have been chosen as metallic material for the core of the target to give rise to the reaction for antiproton production [32]. A high density target made of a thin iridium rod embedded in graphite and enclosed in a sealed, water cooled, titanium container, gave the best match for \(\bar{p}\) production and target cooling efficiency [33]. The highest yield of antiprotons is at their output kinetic energy of 3.57 GeV, resulting in a production efficiency of \(10^{-4}\). Once produced, antiprotons are collimated and momentum-selected to prepare for their injection into the 184 m long decelerator where their energy is reduced to \(\sim 5.3\) MeV (\(\sim 100\) MeV-momentum) which is a suitable energy for manipulation for physics studies. Besides the reverse use of radiofrequency (RF) cavities, **stochastic cooling** and **electron cooling** are implemented in the AD. Antiprotons undergo several cooling and deceleration cycles while being monitored through advanced beam diagnostic techniques [34, 35] until they are cooled down to about a tenth of the speed of light. At that point, they are ready to be extracted towards the antimatter experiments. Considering the antiproton collection efficiency of \(10^{-2}\) in the target region, the overall

\(^1\)As well as ALPHA, ASACUSA, ATRAP, BASE and GBAR. PUMA will provide antiprotons to ISOLDE from 2021 onwards.

\(^2\)To be replaced by LINAC4 after LS2.
CHAPTER 2. LAYOUT OF THE ÅEGIS APPARATUS

Figure 2.1: The CERN’s accelerator complex in 2019 [31]. Antiprotons are produced, extracted and slowed down to energies feasible for fundamental physics studies in the AD region.

Production efficiency is $10^{-6}$, sufficient to provide $\sim 3 \times 10^7$ antiprotons to the experiments every $\sim 110$ s. The bunch length is $\sim 600$ ns. Having short bunches is crucial for the capture. The AD repetition rate, in fact, is not exactly 100 s also due to the PS super-cycle.

Experiments use degraders and sometimes RF cavities to further slow down antiprotons to few keV energies for plasma manipulations. In today’s set-ups, most of the antiprotons delivered through the AD ejection lines are lost due to scattering reactions taking places within the degrader foils. Remark-

Figure 2.2: The entrance to the AD facility (on the left) and a schematic of the AD hall with all the experiments connected to the accelerator (on the right).
ably, about 50% of the initial antiprotons survive annihilation and a few percent of this fraction leaves the degrader with energies below 10 keV, within reach of ordinary high-voltage electrodes. AEgIS provides deceleration using a silicon aluminium degrader (170 μm of aluminium and 55 μm of silicon) and captures them in a Penning-Malmberg trap placed in the 5 T trap with a 1.3% efficiency.

The Extra Low Energy Antiproton ring (ELENA) is a 30 m long decelerator located inside the AD ring (Fig. 2.2) which will further decelerate antiprotons up to 100 keV [36]. It will become full operational in 2021 and will allow all the experiments to receive antiprotons at the same time.

2.2 AEgIS hardware overview

Antimatter experiments need high magnetic fields and electromagnetic trap systems to manipulate charged particles and non-neutral plasmas. To manipulate antiprotons for antihydrogen production, AEgIS uses a two-stages Penning-Malmberg trap immersed in a 5 T and a 1 T magnetic fields and contained in a single, cryogenic and ultra-high vacuum cryostat. Capture, compression and a first stage of the cooling process are performed in the 5T region\(^3\), while more refined procedures aimed to antihydrogen production and beam formation are performed in the 1T region with the availability of antiprotons already cooled down. AEgIS is a small size experiment, as it can be noted from the comparison with the dimension of an average human in Figure 2.3, which also shows the main elements of the hardware apparatus.

Positrons are produced by the \(^{22}\text{Na}\) source, trapped and accumulated and compressed. Then, they can be sent either inside the AEgIS main apparatus or in the dedicated Positronium (Ps) test chamber. The AEgIS positron system is represented in the upper left part of Figure 2.3, and described in more details in Sec. 2.8. Antiprotons come from the AD beam pipe through a vacuum line and a series of valves to ensure a suitable vacuum level and mutually prevent the vacuum system (both of AEgIS and of the AD ring) from failures. Traps in the AEgIS higher magnetic field region are used to capture antiprotons while those in the lower magnetic field region host antiproton clouds already prepared for antihydrogen formation.

The main vacuum chamber hosts the cryostat, the ultra-high vacuum regions, together with the magnets, traps and some of the detectors. Outside the main cryostat are installed all the other systems requiring neither proximity to the traps nor vacuum nor cryogenic temperature, such as the laser system on one experiment’s side, the positron system above the AD injection line (connected to the main cryostat with a \(45^\circ\) tilted magnetic transfer line) and the data acquisition system, the traps electronics and the detector electronics in external racks.

2.2.1 Magnet system

Magnetic fields in the AEgIS apparatus are generated by a superconducting solenoid (Niobium Titanium alloy, Nb:Ti) chilled by liquefied Helium to \(4.2\) K. The helium vessel, in turn, is surrounded by liquid Nitrogen chamber at \(78\) K to reduce thermal dispersion. The AEgIS main magnets were thus designed to have two distinct field regions, each with a homogeneity target level of one part in \(10^{-4}\).

The use of a two magnetic field system allows to have a magnetic field as high as possible in the capture region and, at the same time, a field as low as possible in the production region. At the same time, the two regions are clearly separated from each other. This is an important feature for an experiment like AEgIS which needs to perform precision studies and quite a wide range of operations in its apparatus. High magnetic field is desirable in order to maximize the radial confinement of antiprotons and electron cooling efficiency. In fact, the charged particles driving process and their cyclotron radiation losses scale as \(B^2\). Although a higher magnetic field would have been desirable, 5 T was chosen as a suitable magnetic field in the capture region as a good trade-off between technical limitation and efficiency of plasma manipulation techniques. On the other hand, a small magnetic field reduces the

\(^3\)Actually, the magnetic field in the capture region is 4.46 T rather than 5 T to reduce the risk of magnetic quenching.
mixing of atomic levels in Rydberg positronium and Rydberg antihydrogen in the antihydrogen production trap [1]. Again, the value of 1 T for the magnetic field in the antihydrogen production region was chosen as a result of a compromise, to guarantee the possibility to work with antiproton plasma reducing the mixing of atomic levels of Rydberg atoms.

Another important requirement in the AEgiS magnet design was their mutual alignment. Traps are located inside the magnets. The possibility to align the traps with respect to each other is essential to obtain long plasma lifetimes and lossless plasma transportation. At each opening/closing of the apparatus, magnets can be aligned to each other with respect to the central region mounting flange with an angular accuracy of 300 μrad.

The final system is constituted of two main superconducting Nb:Ti solenoids and two groups of axial correction coils for proper field termination. Importantly, to reduce the risk of magnetic quenching, the 5 T magnet is regularly operated at 4.46 T as a conservative field value.

### 2.2.2 Vacuum cryogenics

As the lifetime of antiprotons is ultimately limited by annihilations with residual gases, storage of \( \bar{p} \) requires state-of-the-art ultra-high vacuum in particle traps. Typical pressure values in AEgiS are below \( 10^{-13} \) mbar to make it possible to achieve macroscopic antiproton lifetimes.

The AEgiS vacuum system implements the cryogenics needed to bring the magnets to their superconducting state (9 K or less for Nb:Ti) and to cool down the whole ultra-high vacuum region. To keep the magnets cold, 5T and 1T regions share the same cryostat for liquid nitrogen and liquid helium. The external surface of the cryostat is at nitrogen temperature (77 K), whilst the internal bore tube is at 4 K. In these conditions, all the internal surfaces behave like cryo-pumps for all the residual gases heavier than helium and hydrogen in the traps. Additionally, to minimize heat conduction, an Outer Vacuum Chamber (OVC) was realized around the magnet cryostat and insulating material was placed around the entire external surface of the cryostat to minimize heat transfer through radiation. The thermal insulation around the transfer region and between the two sections of the apparatus was reinforced before the 2018 data taking run. Two series of vacuum feed-troughs allow to convey electrical, optical
### 2.3. AEĠIS SOFTWARE OVERVIEW

<table>
<thead>
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<th>Subsystem</th>
<th>Software architecture</th>
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<tr>
<td>Trap system</td>
<td>LabView/Windows + LabView/RTOS + FPGA</td>
</tr>
<tr>
<td>Magnet system</td>
<td>LabView/Windows + PLC</td>
</tr>
<tr>
<td>Data acquisition</td>
<td>Custom/Linux</td>
</tr>
<tr>
<td>Vacuum and cryogenics</td>
<td>LabView/Windows</td>
</tr>
<tr>
<td>Positron system</td>
<td>LabView/Windows</td>
</tr>
<tr>
<td>Laser system</td>
<td>Python/Windows + FPGA</td>
</tr>
</tbody>
</table>

Table 2.1: List of software architecture for the control of each of the AEĠIS subsystems.

AEĠIS reaches $10^{-14}$ mbar or better in the trap region thanks to the combined pumping action of cryo-surfaces. As vacuum gauges do not allow to measure such low values, vacua are extrapolated by the lifetime of antiprotons stored inside the traps. The vacuum is estimated by measuring the antiproton lifetime inside the trap. To determine an absolute value of the residual pressure, the cross section for antiproton annihilations would be needed. Relative measurements are of course possible and sufficient for the experiment. Vacuum gauges only allow to measure pressures greater than $10^{-12}$ mbar, typically. The traps are located in a cryogenic environment where gauges cannot be mounted. It is interesting to note that assuming typical values of cross sections of the order of $10^{-16}$ cm$^2$, the residual pressure is significantly lower than $10^{-13}$ mbar. Such UHV condition is reached in the trap region via the combined pumping action of cryo-surfaces, four big getter pumps for hydrogen and a ionic pump installed outside the main vacuum chamber for helium. Three hydrogen pumps are inside the central region while the main one is installed in the flange at the entrance upstream region of the experiment, which takes the name of sun flange, after its shape. After recent improvements in the thermal insulation, the full closing, leak-testing, pumping, baking and cool-down procedure was significantly reduced to a couple of weeks in lieu of about a month.

### 2.3 AEĠIS software overview

AEĠIS is managed by several control systems interacting together via network. Table 2.1 shows List of software architecture for the control of each of the subsystems. The trap control system acts as master controller and sends instructions to the other systems, when running experiments. All time-critical operations are synchronized on the same master clock distributed by the realtime computer in the traps electronics. Table 2.1 summarises the software architecture of each of the AEĠIS subsystems.

A run includes operations like particles loading, manipulation, particles dump and measurements. Typical runs involve electrons, positrons, antiprotons or combinations of the three. A run is thus composed of a set of operations fully specified by a sequence description file processed by the trap control system.

### 2.4 The AEĠIS $\bar{p}$ trap system

The AEĠIS trap system is a Malmberg-Penning multi-electrode trap connected to the AD beam line and installed in the high vacuum region of the apparatus over the two magnetic field regions. The control electronics is placed on the outside of the vacuum chamber and it constitutes the AEĠIS trap system hardware.

The entire trap system is composed by 102 electrodes organised into several trap regions located either in the 5T magnetic region for antiproton and positron catching and in the 1T magnetic field region...
Figure 2.4: On the top: overview of the Malmberg-Penning trap system. The connection to the AD is upstream the sun region. Mimito is a 50 µm thinned version of the Mimotera detector [37], able to image beam profiles even at low particle intensities. On the bottom: detail of the trap stages in the AEgIS trap system. The sectored BO electrode, installed on a movable actuator between the end of the transfer region and the beginning of the Big trap, is not reported here.

for antihydrogen production. Electrode configuration and logical trap regions are sketched in Figure (2.4) and listed in Table (2.2).

The first stage of the AEgIS trap system, the 5T trap, is divided into two smaller, general-purpose trap regions with shorter electrodes to shape harmonic potentials and sectored rotating-wall electrodes in their center. These are the C-trap and P-trap, in the upstream to downstream direction. Antiprotons are captured in the first region of the 5T traps, the C-trap. More refined p manipulations normally happen in the following P-trap. A longer capture trap configuration, including electrodes from both C and P traps, could also be possible. For such a reason, C and P traps are terminated by high-voltage electrodes reaching up to 9 kV (HV1 to HV3, in upstream to downstream direction). A series of transfer electrodes (the T-trap) connects 5T traps to iT traps and conveys the particles as they traverse the non-homogeneous region of the magnetic field. The transfer section has at its centre a fourfold sectored 50 mm long electrode (Bo), installed on a movable actuator for particle steering. The actuator also allows
a Faraday cup (CRFC) to be put in place.

Traps in the 1T region are designed to allow more complex manipulations than in 5T traps. The first sector in the 1T traps, named Big trap (B) after the size of its radius, was designed to send positron clouds to an off-axis trap via plasma excitation modes. Once the trap was loaded, the electrodes voltages could be raised to few kV for e⁺ implanting into the Ps converter. In order to simplify positron manipulations procedures, the off-axis trap was removed in 2016 experiment upgrade to switch to a direct acceleration-and-injection scheme with magnetic off-axis steering. Antiprotons, instead, pass through B-trap without manipulations and are recaptured in the On-axis trap (OnAx) trap which is aligned to the whole trap system and follows the B-trap in the upstream to downstream direction. OnAx trap is made of smaller diameter electrodes with respect to the Big trap to prepare the antiproton plasma cloud for the antihydrogen production trap.

The production trap, also indicated as antihydrogen trap ($\bar{\text{H}}_{\text{Trap}}$), is located at the end of the 1T section of the experimental apparatus. It is a Malmberg-Penning trap composed by 15 electrodes (each labelled as $\bar{\text{H}}_{\text{Trap}}^{\text{B}1,\text{B}2,...,\text{B}15}$ hereinafter) with 5 mm radius and mounted 10 mm below the Ps converter target. A schematic of the production trap is sketched in Figure 2.5. Due to the need for an entrance for the laser excited Ps, the central electrodes of the production trap, $\bar{\text{H}}_{\text{Trap}}^{\text{B}1,\text{B}2,...,\text{B}10}$, have a 2 mm wide opening on their top to let Ps atoms fly in towards the $\bar{\text{p}}$ cloud. As any opening in the electrode walls is known to produce electric field distortions, the slits are covered by a 80%-transparent honeycomb geometry mesh designed to minimise the field distortions due to the opening. All the design parameters in the production region, like the $\bar{\text{H}}_{\text{Trap}}$ radius, the distance between the trap walls and the target converter (considering a $\bar{\text{p}}$ radius of $\approx$1 mm), the size of the opening and the design of the grid were chosen in order to maximise the efficiency of $\bar{\text{H}}$ production at the experimental conditions foreseen for $\bar{\text{p}}$ and Ps [38]. Furthermore, $\bar{\text{H}}_{\text{Trap}}$ is equipped with the electronics needed for the implementation of resistive cooling technique. In particular, the instrumentation includes a cryogenic amplifier tuned in the range of an electron plasma axial oscillation frequency. This is in view of the possibility, as a future development, to resistively cool down electrons to reduce the antiproton temperature in the mixed plasma [39].

The production trap is the only one in the AEgIS trap system without a sectored rotating-wall electrode in the center, but as upstream end-cap.

A Micro-Channel plate (MCP) detector is positioned further downstream, few cm away from the last production trap electrode $\bar{\text{H}}_{\text{Trap}}^{\text{B}15}$ and aligned to it, to provide high-resolution diagnostics for plasma manipulations.

### 2.5 Electronic trap control

The AEgIS control electronics was designed at the time of the plan and commissioning of the apparatus and did not undergo significant variations in recent time.

A custom-made trap controller is connected to the electrodes via filtered vacuum connections. The control electronics is built of several elements dedicated to the different trap manipulations that needs to be performed. Accurate Digital-to-Analogue Converter (DAC) boards are used to apply bias voltages

<table>
<thead>
<tr>
<th>Trap region</th>
<th>Electrodes</th>
<th>$\delta$ [mm]</th>
<th>B [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>C1 to C19</td>
<td>30</td>
<td>4.5</td>
</tr>
<tr>
<td>P</td>
<td>P1 to P13</td>
<td>35</td>
<td>4.5</td>
</tr>
<tr>
<td>T</td>
<td>T1 to T6</td>
<td>44</td>
<td>4.5 to 0.8</td>
</tr>
<tr>
<td>Big</td>
<td>B1 to B15</td>
<td>44</td>
<td>0.8 to 1.0</td>
</tr>
<tr>
<td>OnAx</td>
<td>OnAx1 to OnAx28</td>
<td>10</td>
<td>1.0</td>
</tr>
<tr>
<td>Prod</td>
<td>$\bar{\text{H}}<em>{\text{Trap}}^{\text{T}1}$ to $\bar{\text{H}}</em>{\text{Trap}}^{\text{T}5}$</td>
<td>10</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 2.2: Details of the main trap regions.
to trap electrodes. DACs allow independent voltages to be set on all electrodes in a range between -200 to 200 Volts with 16-bit resolution (corresponding to 6 mV) with a delay of 150 μs and a time-resolution of 1 μs. Remarkably, an accurate and versatile pulsing system allows to send pulses of variable length between 1 ns and 64 μs. Such pulses can also be summed to the bias voltage of some selected electrodes, being of the same voltage amplitude and resolution of the signals form DACs. A programmable, multi-channel sinusoidal waveform synthesizer adds on the bias voltage of sectored electrodes pure phase-shifted sinusoids up to 5 V in amplitude. Furthermore, it allows rotating-wall radial manipulations to be performed in a frequency range from 0 to 30 MHz and it also features frequency, amplitude and mixed sweeps. To synchronize all other equipments (laser, positron system, detectors) to trap operations, the trap controller electronics also produces the high resolution programmable triggers.

A NI PXI Embedded Real-Time controller (RT) computer via asynchronous communication externally program the trap electronics. Importantly, all instructions corresponding to operations that need to be performed by the traps (e.g. electrode voltages, triggers to raise, pulses to send) are stored in a buffer and periodically downloaded by the master Field-Programmable Gate Array (FPGA) in the trap controller. The latter takes care of executing the specified operation at the absolute time of the master clock specified by the RT in a specific programming word so that all trap operations are time-deterministic and procedures are reproducible. Furthermore, the 1 ppm GPS-disciplined master clock generator is installed within the same crate of the RT, as well as several general purpose I/O boards, counters and acquisition cards for providing precise triggers and acquiring trap diagnostic detectors.

Figure 2.5: A schematics of the AEgis production trap. Electrodes $E_{\text{trap}}$ have an open slit on their top to allow the Ps atoms to fly in.
2.6 Detectors in AEgis

AEgis makes use of several detectors for the diagnostics of charged particles, non-neutral plasma, positronium and antihydrogen operating both destructive and non-destructive detection techniques. Six main detector classes are employed in AEgis, as reported in Figure 2.6. The figure also depicts the position of each detector with respect to the apparatus and the main operations it is devoted to.

At the entrance of the apparatus from the AD line, a degrader/beam monitor structure is installed on movable actuator. It is composed by a wafer of two thin aluminium foils and a ~53 μm silicon detector used as beam monitor. The two aluminium-silicon wafers are 50 μm and 100 μm thick and they are used both as degraders and as non-sectored Faraday cups (FC). In the central region of the experiment, a two-sided, sectored Faraday cup detector is installed on the movable actuator shared with the B electrode allowing an accurate estimation of the total charge contained in a plasma.

Micro-Channel Plates (MCP) and Faraday cups are typically installed along the way travelled by particles inside the AEgis apparatus to monitor the plasma cloud profiles and detect the total electrical charge of a non-mixed plasma. Radial shape of the plasma is measured with the imaging system and the number of positrons and electrons with the FCs. A complementary technique to measure the number of particles passing into the line requires the charge pick-up from an electrode with proper amplification chain. Such method is implemented in the transfer line from the e^- accumulator to the main apparatus.

Antiproton and positron losses are typically monitored with the external scintillators. Also the number of β is measured using the scintillators externally surrounding the apparatus after intentional dumps on the trap walls. The longitudinal size of the antiproton plasma is then estimated using a self-consistent thermal equilibrium model.

2.6.1 External Scintillator Detector Array (ESDA)

The AEgis External Scintillator Detector Array consists of twelve general-purpose, fast plastic scintillator paddles made of commercial EJ-200 from Eljen Technology coupled to two photomultiplier

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4The technique, widely used in accelerator physics, was implemented in AEgis in 2016 [40].
CHAPTER 2. LAYOUT OF THE AEgIS APPARATUS

tubes, one at each scintillator end. ESDA slabs externally surround the vacuum chamber for monitoring p and e\textsuperscript{+} annihilations and turned out to be a crucial tool for antihydrogen detection in 2018. Each scintillating slab is 1 cm thick, 150 cm long, and shaped to cover a 120° arc of the cryostat containing the superconducting magnet. The four scintillators surrounding the 5T traps are 20 cm wide while the eight surrounding the 1T traps are 10 cm wide for a better spatial resolution. Each 1T slab covers a solid angle of about 3% with respect to an annihilation happening in its center. The overall ESDA coverage around the antihydrogen production region is \( \approx 20\% \) of \( 4\pi \). Each slab is optically coupled to two independent heavily shielded photomultiplier tubes, typically counted in coincidence within a window of 50 ns for cleaner signals. Photomultiplier tubes used to acquire the scintillator slabs are EMI 9954B and Philips XP2020, with slightly different features between each other which, however, can be neglected for the AEgIS purposes. Among the 24 PMTs coupled to the external scintillators, those deputed to Ps studies are also acquired on a parallel acquisition chain using a fast 12 bit, 2 GS/s oscilloscope to diagnose positronium in the antihydrogen production region.

2.6.2 Micro-channel Plate (MCP) detectors for plasma imaging

Micro-channel plates (MCP) coupled to optical sensors allow the diagnostics of all trappable particles in the experiment, as they can images plasmas of either electrons, positrons and antiprotons with a 20 \( \mu \)m resolution and mechanical stability. The 1TMCP consists of a 1 inch MCP assembly in chevron configuration with a P67 fast phosphor screen on the back. The light information from the phosphor screen is conveyed by a magnifying telescopic system to an Hamamatsu Flash\textsubscript{e} v2 CMOS camera with a quantum efficiency of 87\%. Importantly, it can potentially allow unambiguous proof of antihydrogen formation through its three field-ionization electrodes and single particle sensitivity. The 5T micro-channel plate (5TMCP) is installed on a tiltable flip mount controlled by pressure actuators. It is a 2 inches MCP in chevron configuration with a P67 phosphor screen and metallized surface and able to image the entire full radius of the traps. Light is conveyed on a Hamamatsu Orca R\textsubscript{2} camera by a placeable mirror positioned just out of the main vacuum chamber.

2.6.3 Fast Annihilation Cryogenic Tracking detector (FACT)

The dedicated detector for antihydrogen annihilation is the Fast Annihilation Cryogenic Tracking detector (FACT) [41]. It is composed by 794 ring-shaped scintillating fibres (Kuraray SCSF-78 M) disposed in two concentric double-layer cylinders around the antihydrogen production trap at cryogenic temperature with an active region of about 300 mm in length. Each scintillating fibre is coupled to a plain fibre that conveys the scintillation light to a Multi-Pixel Photon Counter (MPPC) detector at the external flange of the experiment, at room temperature. Each fibre is monitored at 5 MHz and comparing the output of the silicon photomultiplier tubes with a predefined threshold results in a purely digital hit map of all fibres with 5 ns temporal resolution. The passage of a particle through a fibre generates is recorded as two spatial coordinates and one temporal data. Tracks and vertexes have to be reconstructed from such information.

2.7 AEgIS data acquisition system

Data Acquisition system in AEgIS centrally controls run opening/closing and data taking. All data from a run can be collected by all the detectors connected to the central DAQ and stored in the same Root file, physically residing in the same place(s). To acquire data from measurements in a run, the trap controller sends a run start request; DAQ opens a new incremental run number, starts listening for connections on a TCP/IP port linked to the run number and communicates the next run number to the trap controller. As it receives the new run number, the trap controllers starts to execute trap operation in the current sequence. In the meanwhile, the DAQ starts receiving TCP connection on the open port by the many other systems in AEgIS asking to save data. It is worthy to note that connection requests
are handled in parallel by different devices. The output Root file is thus regenerated every 10 s for on-line analysis purposes. When the procedures listed in the run are over, trap controller issues a run stop request and DAQ sets ready for opening a new run, while keeping listening for further data still belonging to the old run, for some seconds. It stop waiting for connections of the old TCP/IP port after a safe time.

The main DAQ server organises the received data using one different tree per detector using the detector name as a key in the structure name. Subsequently, data is automatically copied on a CERN tape library for long term archiving. Raw data acquisition is demanded to individual detectors, with the sole exception of coincidence scintillators, digitized PMTs and FACT fibres which are acquired directly in the main DAQ environment. The main DAQ server also manages continuous acquisition of environmental monitors and subsystem settings. A dedicated service with its own TCP/IP port and output Root file is used for this purpose.

2.8 AEGIS positron system

The positron system in AEGIS is composed by a $^{22}$Na source and a trap-based apparatus whose goal is to make use of positrons produced by the source. A representation is given in Figure 2.7. A dedicated test chamber is also available next to the accumulator to allow positronium studies in preparation of the most complex operations in the main apparatus. Positrons are moderated by a layer of solid neon deposited on the walls of the source shield opening which acts as a collimator. Then, they are accumulated, cooled down and stored in the subsequent trap stage of the system. The trap is filled with a mixed CO$_2$+N$_2$ gas which cools down the positron plasma. Positrons can then be moved either directly to a dedicated Ps test chamber or inside the main apparatus through a transfer line. The positron transfer line is a $45^\circ$ tilted, about 2.5 m long sequence of coils that produces the guiding magnetic field, between 0.05 T and 0.25 T. It makes e$^+$ steering possible through the whole path and, most importantly, allows to get to the extraction point without losses.

The cooling trap also collects positrons in small spills named pulses which are periodically transferred to the magnetic accumulator trap and keeps accumulating them until an extraction triggers is received.

The dedicated test chamber used to perform Ps excitation studies, consists in a magnetic/electrostatic transfer line including a buncher and multiple view-port vacuum chamber where the target performing Ps conversion is installed on a movable sampler holder.
2.9 AEgIS laser system

Production of antihydrogen through charge-exchange requires laser excitation of Ps atoms to Rydberg levels both for increasing the production cross-section and for Ps lifetime extension in vacuum. An efficient laser excitation would excite as many Ps atoms as possible of those leaving the converter to Rydberg levels without depositing a significant amount of energy in the cryogenic region of the experiment. For such reason, the AEgIS laser system makes use of two pulsed lasers. Both of them are used for exciting Positronium to Rydberg levels. The first one provides efficient Rydberg Ps producing broadband pulses to cover the Doppler-profile of 100 K Ps. It uses $3\,^3P$ as intermediate level for excitation to Rydberg levels as it is expected to deposit about 30% less energy than $2\,^3P$ in the vacuum chamber ($\lambda_1=205$ nm and $\lambda_{R,1} = 1710$ nm). On the other hand, the second laser system is narrow-band and uses $2\,^3P$ as intermediate level. It is tunable over a wide range of wavelengths ($\lambda_2=243$ nm and $\lambda_{R,2} = 750$ nm) and is meant for trying a first attempt of laser-cooling on Positronium.

The two laser pulses are let into the vacuum chamber by dedicated view-ports and transported to the antihydrogen production region by a prism transfer line suitable for both wavelengths. Laser alignments are monitored by observing their image on a small MACOR screen on the back of the target. Their temporal synchronization is verified at the target position using two scintillating fibres (same as those used in the FACT detector) able to both scintillate on Ps annihilation and photo-convert UV radiation.
Chapter 3

Antiprotons manipulation for antihydrogen production in AEgIS

As it is before the full coming into operation of ELENA, the Antiproton Decelerator delivers pulses of antiprotons to the experiments every \( \sim 110 \) seconds, with the antiproton availability shared between the 6 AD experiments and organised in 8-hours shifts, 24 hours per day, few months per year.

Experiments receive antiprotons at \( \approx 5.3 \text{ MeV}/c^2 \) (\( \approx 100 \text{ MeV}/c \)) in bunches 200-500 ns long, containing \( \approx 3 \times 10^7 \) \( \bar{p} \) each \([43]\). To get \( \bar{p} \) to energies suitable for trapping, experiments have to provide further deceleration. AEgIS captures \( \approx 4 \times 10^5 \bar{p} \) per AD shot with energies up to 10 keV/c\(^2\) using a degrader for such first deceleration stage. Once captured, antiprotons have to be driven to the production trap to wait for the arrival of the Rydberg Ps cloud in suitable condition for efficient antihydrogen production. The overall procedure to drive antiprotons from the AD gate valve to the \( H_{\text{trap}} \) at \( \sim 10^{-3} \text{ eV}/c^2 \) or less and outstanding plasma compression (Section 3.3.1.2) is composed of several steps which were sequentially developed, commissioned and optimised over past few years and finalised for efficient production during the last antiproton run. Due to limitations in the available antiproton time, plasma manipulation procedures for antiprotons are typically developed and extensively tested with pure electron plasmas. The motion of electrons in traps, in fact, well reproduces that of antiproton and allows to predict several features of their behaviour. Only when the procedures look reliable and capable of providing satisfactory results, antiproton time can be invested.

The work described in this chapter was the core activity of the AEgIS Genoa Group, which I contributed to as my main task during the past three years. A brief overview of antiproton plasma physics and basics of particle trapping is given Section 3.1 to contextualise the fundamental operations in electron work (Section 3.2) and the work on antiproton manipulation. Remarkably, the work here presented builds on several years of efforts carried out by the Group to establish a protocol for pulsed production of antihydrogen. The steps required to drive bunches of antiprotons from the exit of the AD beam-line to the final stage of the AEgIS experimental apparatus in suitable conditions for antihydrogen production are presented in Section 3.3.

3.1 Trapped non-neutral plasmas

The usage of trapped, charged particles in physics is widely spreads from high to low-energy and from fundamental research through quantum engineering, to simulations of space plasmas or solid state systems. Electromagnetic trapping turned out to be a flexible precision tool for the manipulation of charged particles, opening the way to the rapid rise of novel applications \([44]\).

Currently, electromagnetic traps are the only solution for containing antimatter particles for low-energy experiments. Charged particles, like antiprotons, positrons or electrons, moving under the effect of fields, either external or self-generated, constitute a plasma if both particle inter-spacing \((n^{-1/3})\), with
Figure 3.1: On the left: depiction of the motion of a confined particle in a Penning trap. On the right: oscillation frequencies of a proton in a Penning trap as a function of the trap potential U. Pictures are taken from [48].

\[ \lambda_D = \sqrt{\frac{\varepsilon_0 K_B T}{nq^2}} \] (3.1)

\( n \) being the particle density), and the Debye length

are significantly smaller than the size of the space distribution of the particles. In Eq. 3.1, \( \varepsilon_0, K_B, T \) and \( q \) are the permittivity of the free space, the Boltzmann constant, the temperature and the elementary charge, respectively. If the overall charge neutrality of the particles is violated, the system is called a non-neutral plasma.

In Aegis experimental conditions, with a non-neutral plasma with electron densities in the range of \( \approx 10^{14}-10^{15} \text{ m}^{-3} \), the Debye length is of the order of tens of \( \mu \text{m} \) only. Non-neutral plasmas are trapped by magnetic and electric fields with their mutual interactions producing non-negligible contributions. Self-generated electric and magnetic fields in a plasma can be sufficiently large to significantly affect the dynamics of particles. In addition to electrically neutral plasmas, non-neutral plasmas show a broad range of collective properties, e.g. plasma waves, Debye shielding or collective modes. However, unlike neutral plasmas, non-neutral ones can be cooled to very low temperatures, can be confined for very long times and can reach a thermal equilibrium state [45, 46].

Antiproton plasmas as well as mixed antiproton-electron plasmas are a type of non-neutral plasma of particular relevance for low-energy antimatter experiments. Trapping is the only way to study antimatter, as it has to stay separated from ordinary matter in order to prevent annihilation. Typical antimatter experiments make extensive use of electrons and ions to manipulate antiprotons and positrons to provide the desired conditions.

3.1.1 Traps for non-neutral plasma

Electromagnetic trap designs have to take into account that a static electromagnetic field cannot confine charged particles in all the three spatial dimensions at the same time (Earnshaw’s theorem, 1842 [47]). Considering a simple ring geometry and a cylindrical coordinate system, a harmonic potential well along the \( z \)-axis would generate a repulsive potential in the radial direction, like in a saddle-shaped potential in a \( \rho-z \) plane. Confinement can be achieved by rotating the saddle in order to prevent the particle from escaping (RF or Paul traps) or by adding a strong homogeneous magnetic field in the axial direction (Penning traps). In a Penning trap, charged particles are confined radially by the magnetic field and axially by a harmonic potential well. Due to the Lorentz force, a charged particle moving in the radial direction, perpendicular to the magnetic field direction, is bent into a cyclotron orbit. The motion of a single particle in a Penning trap (Figure 3.1) has an axial and two radial components that are periodic at the frequencies \( \omega_z \) (axial frequency) and \( \omega_{\pm} \) (modified cyclotron frequency and magnetron frequency, respectively). While amplitudes of motion are independent from one another but depend
on frequencies, frequencies are mutually dependent and depend on the trap geometry. In fact,

\[
\omega_x = \sqrt{\frac{qV_0}{md^2}},
\]

\[
\omega_\pm = \frac{1}{2} \left( \Omega_C \pm \sqrt{\Omega_C^2 - 2\omega_0^2} \right),
\]

where \( \Omega_C \) is the cyclotron frequency of the particle, \( V_0 \) the potential between the end-cap electrode and the term \( d^2 = \frac{1}{2} \left( r_0^2 + \frac{1}{2} r_0^2 \right) \) takes into account \( r_0 \) and \( z_0 \), the minimum distances of ring and end-cap to the trap centre.

A simple hollow cylindrical electrode ended by two end-caps (Malmberg trap) would also work for trapping particles. In such configuration, a flat potential is applied between the central electrode and the two end-caps producing a square-shaped potential well on the trap axis, at relatively long distances between the two end-caps. Pure square-shaped potential wells, however, are not suitable for antimatter plasma manipulation needed in AE\(\bar{g}\)IS.

Further design improvements produced many other trap schemes. The Cylindrical Penning trap is a geometrically simplified version of a Penning trap with a hollow cylinder as ring electrode and flat closed, end-cap electrodes, which generally leads to non-harmonic axial confinement. However, an appropriate choice of the end-cap distance with respect to the inner diameter of the electrodes can restore the axial harmonicity of the trap, although only for a short distance around the trap centre. Penning-Malmberg trap [49] provides axial confinement with a cylindrical geometry immersed in an axial magnetic field for the radial confinement. It offers an extended confinement volume along the trap axis with respect to a cylindrical Penning trap [48]. The high harmonicity of the confining potential can be recovered with a multi-ring configuration of the cylindrical structure.

Multi-ring Malmberg-Penning traps are widely used in antimatter physics as they allow for the movement of the potential configuration and the implementation of specific techniques of plasma manipulation. Providing an harmonic potential between the ring electrodes, the conditions for the simple Penning trap are matched and the equations for single particle hold. In first approximation, collective motion inside the trap is well approximated by the dynamics of the single particle. For typical AE\(\bar{g}\)IS conditions, with a 4.46 T magnetic field and a 100 V trapping potential, relations in Eq. 3.1 result in the frequencies values reported in Table 3.1, for \( \omega = 2\pi f \).

### 3.1.2 Sympathetic cooling in traps

Cooling down a particle in a trap means reducing its kinetic energy and the amplitude of its oscillation. Trapped particles moving under the action of magnetic and electric fields dissipate their energy through cyclotron emission due to the acceleration from the confining potentials. The process is only significant for light particles such as electrons or positrons. Magnetron motion gets its oscillation amplitude reduced even though the total energy increases as the reduction of kinetic energy corresponds to an increase in potential energy. This is not the case with axial motion, for which both potential energy and kinetics decrease. The reduction of energy per unit time can be calculated for both the axial

<table>
<thead>
<tr>
<th>Axial freq. ( f_z )</th>
<th>Mod. cycl. freq. ( f_\pm )</th>
<th>Magn. freq. ( f_\mp )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^-/e^+ )</td>
<td>30 MHz</td>
<td>139 GHz</td>
</tr>
<tr>
<td>( \bar{p} )</td>
<td>680 kHz</td>
<td>76 MHz</td>
</tr>
</tbody>
</table>

Table 3.1: Typical motional frequencies for charged particles in AE\(\bar{g}\)IS. [38].
and radial energy components starting from the power emitted by an accelerated charge [38, 50]:

\[
\frac{dE_r}{dt} = -\gamma_r E_r(t), \\
\frac{dE_z}{dt} = -\gamma_z E_z(t).
\]  \(\text{(3.3)}\)

Here, \(\gamma_z\) and \(\gamma_r\) are the inverse of the characteristic radial and axial cyclotron cooling times:

\[
\gamma_z = \frac{q^2 \omega_z^2}{6\pi\varepsilon_0 m_e c^3} = 6.25 \times 10^{-10} \text{ Hz} \cdot \left(\frac{m}{m_e}\right)^{-1} \left(\frac{\omega_z}{10 \text{ MHz}}\right)^2,
\]

\[
\gamma_r = \frac{q^4 B^2}{3\pi\varepsilon_0 m^3 c^3} = 0.39 \text{ Hz} \cdot \left(\frac{m}{m_e}\right)^{-3} \left(\frac{B}{1 \text{ T}}\right)^2,
\]  \(\text{(3.4)}\)

resulting in the values reported in Table 3.2 for the typical AEgIS conditions.

While the decrease of radial energy for cyclotron oscillations is exponential, collisions are needed to speed up the reduction of axial energy. In a mixed electron-antiproton plasma, antiprotons interact with electrons transferring energy which is then dissipated. This is known as sympathetic or indirect cooling. It is mostly effective for antiprotons while their energy is still relatively high, from MeV to keV and it is the only method used to reduce \(\bar{p}\) energies from keV to eV. Notably, direct cooling of antiprotons via synchrotron emission would take a time \(\sim 10^{10}\) longer than in a mixed \(e^-\bar{p}\) plasma. In principle, one can use any species that does not annihilate antiprotons in a mixed plasma to sympathetically cool them down. Sympathetic cooling is also effective making use of reasonably heavy ions whose cooling is obtained with lasers. However, in a highly-collisional plasma, the axial energy is efficiently dissipated too. The electromagnetic interaction among the particles plays as a heat transfer mechanism from the axial to the radial degrees of freedom with denser plasmas having faster heat transfer. [51].

### 3.1.3 Plasma regimes

Different plasma regimes can be described via the plasma coupling parameter \(\Gamma_p\):

\[
\Gamma_p = \frac{q^2}{4\pi\varepsilon_0 a_{WS} K_B T} = 2.69 Z^2 \left(\frac{n}{10^9 \text{ cm}^{-3}}\right)^{\frac{1}{3}} \left(\frac{K}{T}\right),
\]  \(\text{(3.5)}\)

It is defined with respect to the average of all the individual particles in a plasma as the ratio between the potential Coulomb energy from the nearest neighbour to the kinetic thermal energy of the particle itself [46]. The Wigner-Seitz radius \(a_{WS}\) is the radius of a sphere whose volume equals the volume occupied by one charged particle in a plasma of density \(n\).

The plasma coupling parameter increases with high plasma intensity and low temperature. We can distinguish four main cases:

- \(\Gamma_p \ll 1\) \(\rightarrow\) Weakly coupled plasma (gas);
- \(\Gamma_p \sim 1\) \(\rightarrow\) Strongly interacting plasma (cold plasma);
- \(\Gamma_p \in [2, \sim 170]\) \(\rightarrow\) Fluid-like plasma;
- \(\Gamma_p \geq 170\) \(\rightarrow\) Coulomb crystal.
3.1.4 Modification of axial potential well due to space-charge

Space-charge is the mutually repulsive interaction between a collection of charged particles in a trap, and can also be seen as the emittance growth of a charged particle bunch in a beam. In contrast to the situation with a single particle in a trap, the presence of many charged particles gives rise to long-range particle-particle interactions, collective effects, and partial shielding of the trap potential that leads to shifts of the oscillation frequencies [48]. This also sets a limit to the amount of charge that can be confined in a given trap.

A naive model of a single species non-neutral plasma composed by non-relativistic electrons only, with a uniform cylinder-shaped distribution gives good results for cold plasmas at T=0. Results could be easily extended to pure-ion plasmas or to multicomponent non-neutral plasmas [46]. Ideally, the Electric field will have only a radial component, so that one can easily write the expressions for the electrical field inside and outside the plasma

\[ E_{r \leq r_p} = \frac{q n_0}{2 \varepsilon_0} r, \quad E_{r > r_p} = \frac{q n_0 r_p^2}{2 \varepsilon_0} r^{-1}, \] (3.6)

with density \( n_0 \), radius \( r_p \), which lead to the expression for the space-charge potential inside the plasma

\[ \Phi_P(r) = \frac{q n_0 r_p^2}{4 \varepsilon_0} \left( \frac{2 l n \frac{r_w}{r_p} + 1 - \frac{r^2}{r_p^2}}{r^2} \right), \] (3.7)

with \( r_w \) indicating the physical radius of the trap. The space-charge potential modifies the potential applied to the trap and, in particular, it raises the trap depth. In fact, the real potential to take into account has to be the sum of the two.

As a result, the minimum of the trap depth falls close to the trap axis. The hottest particles will escape the potential well from the centre of the cloud which is the region of minimum potential.

3.1.5 Space-charge and plasma rotation

In the model considered so far, a plasma column confined by an uniform magnetic field, \( B_0 \hat{e}_z \), would have a plasma equilibrium density profile \( n_e \) rectangular in shape inside the region occupied by the plasma. Hence, the electron space-charge would produce an equilibrium electric field, \( E(x) = E_r(r) \hat{e}_r \), in the radial direction. The expression for \( E_r(r) \) can be obtained integrating the Poisson's equation inside and outside the plasma:

\[ E_r(r) = \begin{cases} -\frac{1}{2} \frac{m_e}{q_e} \omega_{pe}^2 r, & 0 \leq r < r_b \\ -\frac{1}{2} \frac{m_e}{q_e} \omega_{pe}^2 \frac{r_b^2}{r^2}, & r \geq r_b \end{cases}, \] (3.8)

where the electron plasma frequency, \( \omega_{pe} \), is constant. Within the above assumptions, electrons can be treated as a cold fluid. The computation of all the radial contributions on an electron fluid element will thus result in the balance between the outward centrifugal and electric forces and the inward magnetic one. The resulting equilibrium relation for particles inside the plasma \( (0 \leq r < r_b) \) can be expressed as

\[ -\omega_{re}^2 = \frac{1}{2} \omega_{pe}^2 - \omega_{re} \Omega_C, \] (3.9)

where \( \Omega_C \) is the electron cyclotron frequency and \( \omega_{re} \) the cold-fluid rotation velocity. Equation (3.9) gives two solutions for the cold-fluid rotation velocity for the plasma column,

\[ \omega_{re} = \omega_{re}^\pm = \frac{1}{2} \Omega_C \left[ 1 \pm \sqrt{1 - \frac{2 \omega_{pe}^2}{\Omega_C^2}} \right]. \] (3.10)
which correspond to a fast rotation velocity, \( \omega_{re}^+ \), and a slow one, \( \omega_{re}^- \). The expressions for plasma rotation velocities given in Eq. (3.10) do not depend on the distance of the particle from the centre. As a consequence, the average azimuthal motion of the plasma column corresponds to a rigid rotation around the axis of symmetry.

The action of the defocusing space-charge force over the focusing magnetic force on a fluid element can be described by the definition of a self-field parameter for the electron:

\[
s_e = 2 \frac{\omega_{pe}^2}{B^2}.
\]

Low-energy plasmas \( s_e \ll 1 \) have \( \omega_{re}^+ \approx \Omega_C \), which corresponds to a fast rigid rotation of the plasma column at the electron cyclotron frequency and \( \omega_{re}^- = \frac{1}{2} \frac{\omega_{pe}^2}{\Omega_C} \pm \omega_D \), representing a slow rotation of the plasma at the diocotron frequency. Sufficiently large density such that \( s_e = 1 \) would lead to the Brillouin density limit, \( \omega_{re}^\pm = \frac{1}{2} \Omega_C \), which is the maximum density allowed given a magnetic field.

### 3.1.6 Plasma in thermal equilibrium

Removing the assumption of a cold plasma, the problem becomes to examine the equilibrium properties of an axially symmetric, non-neutral plasma that is confined by a uniform magnetic field, \( B_0 \hat{z} \).

Trapped non-neutral plasmas can reach thermal equilibrium. The axial symmetry implies the sum of the Hamiltonian of the system and the canonical angular momentum to be conserved. This quantity is contained in the expression for the position and velocity distribution at equilibrium:

\[
f(\vec{r}, \vec{v}) = \frac{m}{\sqrt{(2\pi K_B T)^3}} e^{-\frac{\mathcal{H}_{\text{one particle}}}{K_B T}} \frac{\mathcal{H}_{\text{one particle}}}{K_B T}. \tag{3.12}
\]

Here, \( T \) indicates the electron temperature, \( \mathcal{H} \) is the Hamiltonian of the system and \( p_\theta \) is the canonical angular momentum, \( p_\theta = mv_\theta r + \frac{qB}{2} r^2 \). Equation (3.12) is the one-particle equilibrium distribution function into which an isolated, non-neutral plasma column would relax through binary collision processes. The whole plasma column rotates with angular velocity \( \omega_{re} \). It can be shown (e.g. [46]) that the plasma column is radially confined for the choice of the distribution function, provided that

\[
\Omega_C \omega_{re} - \omega_{re}^2 - \frac{1}{2} \omega_{pe}^2 > 0, \tag{3.13}
\]

with the full solution determined by the total number of particles, the total energy and the total angular momentum. The condition set in equation (3.13) is equivalent to say that

\[
\omega_{re}^- < \omega_{re} < \omega_{re}^+, \tag{3.14}
\]

where \( \omega_{re}^\pm \) are the cold-fluid rotation velocities defined in equation 3.10. Angular rotation velocities within such range correspond to radially confined equilibrium configurations for the non-neutral plasma column.

The plasma density profile can be written as

\[
n(r, z) = n_0 e^{-\frac{1}{\lambda_D^2}} \left[ \frac{1}{\lambda_D^2} \right]^2 \left[ \frac{1}{\lambda_D^2} \right]^2, \tag{3.15}
\]

where \( \Phi(r, z) = \Phi_{\text{trap}}(r, z) + \Phi_p(r, z) \) is the whole potential felt by the plasma. If \( \omega_{re} \) is far from the cold fluid rotation limit velocities for equilibrium, the density profile of the plasma will be bell-shaped and few Debye length wide in radial dimension. Otherwise, if it is close to one of the two rotation limit velocities, the density profile is approximately uniform over many Debye lengths before abruptly falling down. In the limit for \( T=0 \) the axial electric field is null inside the plasma. The space-charge electric field
of the plasma enforces the radial field and cancels the applied field in the z direction. Particles inside
the plasma volume move by thermal motions and they bounce at the plasma edge. Also, developing
the \( q\Phi_p(r, z) \) term in Eq. (3.15) once rewritten for the T=0 approximation, it is possible to show that
the plasma shape becomes a spheroidal with the dimensions and the density varying with the rotation
frequency.

### 3.1.7 Energy equipartition rate and collision rate

Let’s consider a pure electron plasma immersed in a magnetic field \( B \) and characterized by an
anisotropic velocity distribution, with parallel and perpendicular components of the temperature
with respect to the direction of the magnetic field different from each other [52]. The rate \( \nu \) is formally
defined through the relation \( \frac{dT}{dt} = \nu(T_{\parallel} - T_{\perp}) \), where the first term is interpreted as the rate of
change of the mean perpendicular kinetic energy and the difference between the components of the
temperature is assumed to be small in order to have \( \frac{dT}{dt} \) linear in \( (T_{\parallel} - T_{\perp}) \). If the electron cyclotron
radius is large compared to the Debye length, the equipartition rate does not depend on the magnetic
field strength and the orbit of a particle can be considered as a straight line over the range of the
shielded interaction. On the contrary, if the cyclotron radius is smaller than the Debye length, the rate
can be written as

\[
\nu = n\bar{v}^2 I(\kappa),
\]

(3.16)

where \( \bar{v} \) is the thermal spread for the distribution of relative velocities, \( \bar{d} \) is twice the classical distance
of the closest approach to the collision, \( \kappa \) is the measure of the magnetic field strength and the function
\( I(\kappa) \) accounts for all the dependence on the magnetic field strength. Strongly magnetized plasma, i.e.
with \( \kappa \gg 1 \), have an equipartition rate that is exponentially small: \( I(\kappa) \sim e^{-\frac{1}{2} \sqrt{3\pi \kappa^2}} \). For a weakly
magnetized plasma \( (\kappa \ll 1) \), the equipartition rate is the same as for a non-magnetized plasma, with
a logarithmic dependence on the magnetic field strength: \( I(\kappa) \sim \ln(\kappa) \).

Considering an electron plasma with a density \( n = 10^{15} \text{ m}^{-3} \) at the temperature \( T = 10 \text{ K} \), like in typical
AEgIS conditions, the mean time between two collisions will be few microseconds in a magnetic field
\( B = 1 \text{ T} \) and about 30 ms if \( B = 5 \text{ T} \).

### 3.1.8 Centrifugal separation on multispecies plasma

When different particle species with different m/q ratios are confined in the same trap volume,
they can assume different radial equilibrium distributions with respect to the trap centre. At very low
energies, this may lead to complete separation of species inside the trap into concentric rings with the
ions of smaller m/q on average assuming smaller radii.

Due to the geometry of the Penning–Malmberg traps, the clouds of trapped charged particles have
a cylindrical symmetry with the particle density being a function of the axial and radial coordinates.
In the simplest case, with a plasma composed of two different species with different masses and same
charge, e.g. electrons and antiprotons or other negative ions which are trapped together, the two
species (labelled with i={1,2}) will have density given by

\[
n_i(r, z) = n_0 e^{\Psi_i(r, z)},
\]

(3.17)

where the z-axis points along the magnetic field axis and \( (r, z) = (0, 0) \) is the cloud center. In Eq. 3.17,
\( n_0 \) is the density at the centre of the cloud and \( \Psi \) indicates the particle distribution function:

\[
\Psi_i = \left[ \frac{1}{k_B T} \right] \left[ \frac{m_i \omega_i}{2} r^2 (\omega_{z_i} - \omega_r) + q\Phi \right]^2,
\]

(3.18)

where, as above, \( \Phi(r, z) = \Phi_{r2p}(r, z) + \Phi_p(r, z) - \Phi(0, 0) \) is the whole potential felt by the plasma.
It can be shown that the ratio of the densities at a given distance from the centre is not constant but it will depend on $r$:

$$\frac{n_2(r, z)}{n_1(r, z)} = \frac{n_{02}}{n_{01}} e^{\left[\frac{(m_2 - m_1)\omega_r^2}{2K_BT}\right]}.$$  \hfill (3.19)

If the exponent is much greater than the unity, i.e. the density of the second specie, is much larger than that of the first, its rotational energy turns out to be much larger than $K_BT$, leading to a centrifugal separation, as $\frac{1}{2}m_2\omega_r^2 > K_BT$ while $\frac{1}{2}m_1\omega_r^2 \approx K_BT$.

In the AEgIS experiment, with a cylindrical symmetry due to the trap shape and a Debye length of the order of tens of only microns, plasmas are expected to have a constant radial density profile, which suddenly drops off to zero within few Debye lengths from the centre. Cold plasma at thermal equilibrium can be assumed to rigidly rotate around the $z$-axis with frequency $\omega_r$, due to the presence of the axial magnetic field $B$ and the radial electric field caused by the plasma’s space-charge. The central density will then be

$$n_0 = \frac{2me_0\omega_r(\Omega_C - \omega_r)}{q^2},$$  \hfill (3.20)

where, as above, $\Omega_C$ is the particle cyclotron frequency and $\omega_r$ is the plasma rotation frequency \[53\]. In the AEgIS conditions, the plasma rotation frequency is much smaller than the cyclotron frequency $\omega_r \ll \Omega_C$ and the relation between the central density and the rotation frequency becomes

$$\omega_r = \frac{qn_0}{2e_0B},$$  \hfill (3.21)

with $n_0$ linearly dependent on $\frac{m}{e}$ and the rotation frequency $\omega_r$ directly dependent on the mass-to-charge ratio. For such reason, in the mixed $\text{e}^-\bar{\text{p}}$ plasma, the two populations rotate at different velocities and thus the collisions between electrons and antiprotons tend to shift antiprotons to larger radii. The effect depends on the temperature, radius of the plasma and its density, and it becomes significant when the centrifugal potential difference for any of the species becomes larger than the thermal energy of the plasma \[54\],

$$|m_p - m_e| \frac{\omega_r^2r^2}{2} > K_BT.$$  \hfill (3.22)

Centrifugal separation, for a given plasma radius, occurs either if the plasma is very cold or if the density is very high. In AEgIS conditions, electrons are two orders of magnitude more abundant than antiprotons and it can be assumed that antiprotons do not contribute to the density. During the antiproton cooling process, they start to centrifugally separate from the much lighter and denser electron cloud that cools them. Figure 3.2 shows centrifugal separation of a $\text{e}^-\bar{\text{p}}$ mixed plasma in AEgIS after three different cooling time periods. The pictures are obtained by dumping the plasma onto the MCP at the downstream end of the $\text{ST}$ trap.

### 3.2 Handling electrons

Handling electrons is a key point in AEgIS. None of the antiproton manipulations in AEgIS, in fact, would be possible without the use of electrons. First cooling stage of antiprotons, in $\text{ST}$ traps, for instance, need a preloaded cloud of electrons. In addition, systematic study on electron dynamics allow to predict antiproton behaviour, as the motion of electrons in traps well reproduces that of antiproton. This turned extremely useful in the preparation of new procedures making the use of electrons and understanding their dynamics even more important.
3.2. HANDLING ELECTRONS

Figure 3.2: Centrifugal separation in AEgIS after three different cooling time periods. The x and y axes denote the hit positions of antiprotons on the MCP surface. The color scale indicates the number of MCP counts.

3.2.1 Electron gun

The source of electrons at AEgIS is an electron gun that is mounted in the region of the sun flange at the entrance of the 5T magnet, downstream of the AD valve as previously described in Chapter 2. The emitted electrons are collected and moved into the 5T traps for manipulation. The electron gun is installed on one of the pistons of a precise linear motion ultra-high vacuum drive on the sun flange. The linear drive allows positioning of the electron gun on the trap axis for electron injection and retraction of it when $\bar{p}$ or $e^-$ beams are arriving from AD towards the 5T magnet. Figure 3.3 shows the electron gun assembly inside the flange.

The core of the electron gun consists of an electrode made of two small resistive heating wires connected to an emitting plate, the cathode. The wires heat up at the passage of a current and warms up the plate, releasing electrons by the thermionic effect.

3.2.1.1 Emitter cathode

Emitter cathodes for electron guns are commercially available both with or without a surrounding vacuum chamber and that are endowed with factory electronic system. A spare electrode like the one shown on the right side of Figure ??, Kimball Physics Barium Oxide Cathode ES-015, is implemented in AEgIS. The cathode structure consists of a barium oxide(BaO) coated, disk substrate that is heated by conduction from a tungsten hairpin and mounted on an industry-standard, insulating, ceramic base. Such a model is considered among small coated disk cathodes. Different factors influence the choice of

Figure 3.3: On the left: the sun flange. The electron gun assembly is visible on the top of the picture, inside the flange [38]. On the right: the electron gun mounted in AEgIS, Kimball Physics ES-015 Barium Oxide-Coated. The electrode cathode is mounted on a standard ceramic base [55, 56].
the cathode size. Larger discs with larger pins tend to have a longer lifetime. In addition, a larger disc has a larger emission area and more total current for a given current density, with the current density being a monotonically increasing function of temperature. However, a larger disc requires more heating power because of the power losses due to radiation. Instead, a smaller disk is suitable in order to have more a uniform temperature distribution, which results in a more uniform emission. The model ES-015 utilizes a 0.84 mm diameter refractory metal disc coated with barium oxide, attached to a 0.08 mm diameter tungsten 3% rhenium heater wire [56].

3.2.1.2 Cathode activation

If the cathode is sold apart from a factory electron gun, it is sent with a carbonate covering. This is in order to protect the coating on the emission surface during storage and shipping by the manufacturer. A one-time activation by the user will be required.

The activation procedure consists in keeping the cathode at high temperatures for a number of steps of defined time. This allows the conversion of carbonate to oxide, the release of barium from the metal-barium oxide interface, and the diffusion of the free barium. The electron gun activation is usually carried out during the setting up of the apparatus and out of the data-taking period, to avoid any risk to the vacuum of the chambers. The electron gun activation requires an initial vacuum better than $10^{-6}$ mbar. A vacuum worse by an order of magnitude than that indicated would poison the cathode. Vacua in AEgIS should be at least three orders of magnitude better than required for the electron gun. If the extraction voltage is not applied (see Sec. 3.2.2), the cathode heating current should be gradually increased from 0 to 1.15 A. These conditions have to be kept for 5 minutes to allow the formation of the BaO. The release of the excess Barium requires a slow increase of the temperature of the cathode. This is achieved with a slow increase of the heating current up to 1.24 A to release the free Barium. Otherwise, the cathode is to left untouched for half an hour. Finally, to get working cathode conditions, an extraction voltage has to be applied for one minute. The heating current has to be slowly reduced to a value within 1.0 and 1.13 A. The exposure to air of an activated cathode would result in the oxide to form hydrates which could cause flaking of the barium oxide. More details on the cathode activation are contained in the data-sheet from Kimball Physics [57].

The AEgIS vacuum chambers need vacuum values several orders of magnitude better than those required for the electron gun. For such reason, electron gun is typically tested during the setting up periods only, while vacua inside the AEgIS apparatus are still far from those required as working condition. This can be done since several days are needed to reach vacua better than $10^{-13}$ mbar, the working condition in AEgIS.

3.2.2 Working scheme

Figure 3.4 sketches the working principle of the electron gun installed in AEgIS. The cathode (emitter) is housed inside a hollow cylindrical electrode, the extractor, which is connected to a configurable current source. The two cathode pins, the heating wires (hw), are also connected to an adjustable current source. The current set on the heating wires is the heating current. Electrons are emitted by the thermionic effect in all directions and they form a dynamic space-charge that is almost fully contained inside the hollow of the extractor. The application of an external potential moves them out of the collimator. When such a potential is not applied, the probability for an electron to overcome the cylinder is almost zero. In this case it is said that there is no extracted current.

The extractor is connected to a custom power supply that allows it to be biased up to $\pm 200$ V. The electric field between the extractor and the emitter allows the extraction of an electron current. As the heating current is turned on with a value of $I_{hw} = 1.0 \div 1.3$ A, the emitter takes some seconds to reach the right temperature. After that time, a potential is applied to the extractor in order to obtain a stable current of extracted electrons. To have a stable extracted current, the application of the potential to the extractor is usually delayed.
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In principle, since electrons are extracted by the difference of potentials, it is possible to set the cathode at ground such that only the extractor is biased. However, in AEgiS both the extractor and emitter are electrically insulated from ground so that they can be independently biased. This enables the measurement of the potential difference between the cathode and the extractor, that results in the measurement of the extracted current coming from the electrons that hit the extractor.

For typical operating conditions, a potential difference of \( \sim 50 \text{ V} \) is sufficient, yielding an emitted electron current \( I_{\text{Emit}} = 50 \pm 150 \mu\text{A} \). This current is also called the primary current. The electron gun shows operation memory and substantial hysteresis. In AEgiS, the electron gun is not operated in a standard steady-state regime i.e. for cycles longer than 30 minutes, but rather in few seconds long on-off cycles. For this reason, the emitted current does not only depend on the potential difference between the filament and the extractor. It also depends on the previous operation cycles of the filament [38].

While in operating conditions, the AEgiS vacuum chambers are immersed in their uniform magnetic fields. However, the field is no longer uniform in the outer region of the apparatus. In particular, in the region of the sun flange where the electron gun is placed, the intensity of the magnetic field is some hundreds of gauss. The design of the AEgiS apparatus makes sure that the emitter is on axis with the centre of the magnetic field with a \( \pm 1 \text{ mm} \) precision. Electrons are extracted from the cathode by the electric field applied to the extractor and radially confined by the magnetic field \( (r_L \sim 10^{-5} \text{ m}) \). The sum of the two effects, drives electrons into the 5T traps, passing through the 3 mm hole in the front extractor face.

3.2.3 A check before operations

It is possible to determine the number of the extracted electrons by performing a charge measurement on the Faraday cup situated between the two magnets. This will give the value of \( I_{FC} \) as the current that both leaves the extractor and reaches the end of the 5T magnet. Due to the spatial confinement of charges, this value is highly reliable.

While staying inside the extractor cylinder, the electron cloud induces a current that is detected by the electrode. It is then possible to infer the current that reaches the extractor, as the difference between the current set on it and the current measured on the electrode. The different currents can be defined as:

- \( I_{E^{\text{tr}}} \): the electron current reaching the extractor, given by the difference between the current applied to the extractor and the current induced by the electron cloud and measured via the electrode;
• \(I_{FC}\): the current crossing all the \(5\)T trap that reaches the Faraday cup;

• \(I_{Emit}\): the total emitted current, also said \textit{Primary Current}, given by the algebraic sum of the other two.

In the ideal case \(I_{Extr} = I_{FC}\). In configurations close to this, \(I_{FC}\) is few tens of Amperes. Such a current is tunable by properly setting the electrode potentials. It is also possible to check the primary current on a degrader between the two magnets without using the Faraday cup. This procedure is useful when FC is not working, or its signal becomes not reliable. If the FC is removed from its position by the piston, then the primary current is free to cross the whole detector and to reach the \(5\)T MCP. Such current in fact can be dangerous for the MCP. Actually, a 10 \(\mu\)A current is equivalent to \(6.25 \times 10^{13}\) electrons. This value is 5 orders of magnitude greater than the typical \(10^8\) electrons that are confined in the trap and usually dumped on the MCP. This can give an estimate to the damage of the MCP – even when turned off – caused by receiving the primary current.

### 3.3 Antiproton manipulation in AE\(\text{\={
\dagger}}\)S

The core of the AE\(^{\text{\={
\dagger}}\})S trap system is a multi-ring structure (~2.5 m long) mounted in a cryogenic environment with two different homogeneous magnetic fields (5 T and 1 T) and a transition region in the middle. This is the entire trap used to confine, manipulate and cool antiprotons, positrons and electrons in AE\(^{\text{\={
\dagger}}\})S.

In this respect, a main activity over the past few years was to continue to develop and commission the steps towards antihydrogen production. A stable and reliable procedure was defined and improves with an increase of the production rate and an enhancement of the reaction efficiency. This was achieved by refining the plasma manipulation techniques to reach an outstanding compression of antiproton clouds and via the full implementation of a stacking procedure. The technique was thus extended to several AD shots of antiprotons, resulting in the possibility to store up to \(10^6\) antiprotons for many thousands of seconds in stable conditions without any further manipulation, overcoming the limitations induced by the unusual design of the production trap. Cooling techniques are of fundamental importance for antihydrogen production as well as all other plasma manipulation techniques which are used to capture and compress clouds of antiprotons and to manipulate positrons and electrons.

In this section, I will describe the overall procedure developed to efficiently capture, compress and cool down several AD bunches of antiprotons, to transfer them to the production trap in suitable conditions for antihydrogen production and to keep them at stable conditions for macroscopic times.

#### 3.3.1 \(5\)T operations

Antiproton trapping is performed in the \(5\)T region using a trap of about 35 cm length, 1.5 cm radius with 9 KV applied to the high-voltage, end electrodes with a voltage rise time of \(\sim 10\) ns. Trapped antiprotons need to be cooled down and compressed before being transferred to the \(1\)T traps for further manipulations to prepare them for efficient charge exchange reaction. A multi-stack procedure consists of capture and storing several antiproton bunches from AD. A good trade-off between the number of stored antiprotons and the cloud expansion in the production trap was found with the stacking of 8 AD shots.

##### 3.3.1.1 Antiproton trapping and cooling in \(5\)T

The AD injection energy exceeds the energy of trappable particles by two orders of magnitude. For this reason, a silicon-aluminium degrader is used to decelerate particles to 5-10 keV. Antiproton catching is performed at the entrance of the \(5\)T traps, in the C-trap. A first cooling stage takes place in the same trap and then the antiprotons are moved to the following P-trap for compression. A different
approach would involve electrodes from both C- and P-traps for capture, and the P trap electrodes only for compression, after potential well reshaping.

The capture procedure consists of in-flight trapping of a fraction of the high-energy antiprotons from the AD by applying a constant negative bias voltage to the downstream end-cap and raising the negative voltage to the end-cap at the beginning of the trap. Electrode bias timing plays a crucial role at this stage and needs to be optimised at the beginning of the run every year, as well as at any time the AD conditions undergo variations. Capture efficiency depends on degrader thickness, trap closing time, value of the potential applied to the trap end-cap electrodes and beam steering. Thickness and composition of the degrader were optimised \cite{40} to provide an overall capture efficiency of 1.3%, thus giving 3.7 \cdot 10^5 trapped antiprotons from one AD bunch of 3 \cdot 10^7 particles.

The estimation of the number of trapped antiprotons can be done by lowering the upstream end-cap to let them annihilate to the degrader and check the recorded signal on the external scintillators. To get an absolute value, the number of counts on the external scintillator slabs has to be converted by a factor computed on the basis of the annihilation position, the detector solid angle and its efficiency. Antiproton annihilations on the degrader result in the production of an odd number of charged pions (typically from three to seven) which can be detected by the external scintillators with a \sim 100\% efficiency. The annihilation process also produces neutral pions, photons and sometimes nuclear fragments (Chapter 5). However, only charged pions are relevant for \bar{p} detection in AE\textsc{gi}s. The number of minimum ionising particles expected to be detected per \bar{p} annihilation in AE\textsc{gi}s is determined by a simulation which also takes into account the levels of nitrogen and helium in the chambers surrounding the traps for the evaluation of the material budget between the annihilation point and the detector.

As cyclotron emission is highly inefficient as cooling mechanism for antiprotons, a first round of sympathetic cooling is carried out, at this stage, through collisions with a preloaded electron plasma with some 10^8 electrons, which in turn efficiently cool down by emitting cyclotron radiation in a high magnetic field. The technique is now well-established and it allows cooling of the trapped antiprotons to the \sim 1\,eV energy range and lower within \lesssim 50\,s by collisions with the preloaded cloud of electrons. The electron trap is 3 cm long giving an electron density in the range of some 10^8 e^+ /cm^3. Electron number is reduced by 40\,V steps of the potential wells. Then, the trap is adiabatically reshaped to a flat Malmberg trap with its bottom level at 140\,V. Antiprotons are then captured in a physical region surrounding the electron trap and they start losing energy by collision. After a few tens of seconds, the hottest \bar{p} fraction is dumped by lowering the trap edge towards the AD and it annihilates on the degrader surface. Such signal is monitored and recorded as an on-line reference of the number of antiprotons trapped. To directly measure the cold \bar{p} fraction, the trap is opened towards the degrader in multiple steps in order to avoid any pile-up effect on external scintillators. To measure the antiproton spatial distribution, electrons are first removed by the application of a number of short pulses to the end-cap. What remains inside the trap is dumped towards the downstream MCP. The measurement is highly reliable since charged particles are known to stay bound to their field line. If the MCP is in the same magnetic field condition as the plasma, the image can be assumed as the exact representation of the plasma condition. If the \textsc{tMCP} is used for such measurement, radial distribution will be larger by a factor depending on the difference between the two fields, \sqrt{B_1/B_2} which is \sim 2.2, in AE\textsc{gi}s.

It is possible to easily cool more than 90\% of the trapped antiprotons by properly tailoring the electron plasma. Interestingly, a considerable fraction of antiprotons are trapped at large radii and if the electron plasma is large enough, they can be cooled.

In the multi-stacking scheme, once the hottest fraction of particles in the plasma is removed, it is possible to catch another AD shot, sympathetically cool it down with the plasma already trapped and release again the most energetic particles while waiting for the next shot. In principle, this procedure can be endlessly repeated and a great number of shots can be stored in the 5T traps. However, a good trade-off between the number of stored antiprotons and the cloud expansion in the production trap was found with 8 AD shots, which corresponds to a number of \sim 10^6 \bar{p} per H trial, about 10 times larger than expected in the original AE\textsc{gi}s proposal \cite{1}. 

\section{3.3. ANTI PROTON MANIPULATION IN AE\textsc{gi}s}
3.3.1.2 Antiproton compression

The captured and cooled plasma has to be compressed before being transferred to the production trap, in the $1T$ region of the apparatus. This is a decisive step for antihydrogen production in AEgIS.

Firstly, a good $\bar{p}$ plasma compression is required for the transfer itself. In fact, the capture and cooling procedure are done in the $5T$ region, while the production trap is immersed in a $1T$ magnetic field. As highlighted in previous sections, the plasma cloud transfer towards the $1T$ traps would necessarily imply an expansion. In addition, the magnetic field in the transfer region can drop down to 0.8 T (Sec. 2.4), resulting in an even more significant expansion in the transfer region. Furthermore, it must be remembered that the $5T$ and $1T$ traps are intrinsically misaligned, as described in Sec. 2.2.1. Hence, a better compressed plasma results in less antiproton loss during transfer. Another argument for $\bar{p}$ plasma compression resides in the design constrains of the production region. Although the Ps converter is mounted outside the trap, it would be good if it was as close as possible to the $\bar{p}$ cloud in order to maximize the antihydrogen production rate. Therefore, a radially small antiproton cloud allows for a radially small antiproton trap, thus enabling placement of the positronium formation target as close as possible to the antiprotons. Finally, driving antiproton clouds in the production trap already with a small radius, helps tackling the radial expansion issues and it allows to develop procedures with longer $\bar{p}$ storing times thus increasing the production efficiency. Instead, deferring the plasma compression to the $H_{\text{trap}}$ would have implied a plasma with initial radius comparable with the trap size. Compression attempts did not give satisfactory results. Therefore, the choice was to work with an electron plasma that only cools a fraction of 50-60 % of the trapped antiprotons but with an initial radial size that allows a very efficient radial compression.

The density and shape of a plasma of particles confined in a Penning trap can be controlled by the so-called rotating wall technique (RW), which consists of a specific, non-resonant excitation of the plasma rotation. A strongly correlated plasma confined in a Penning trap is forced into a global rotation by the presence of the magnetic field with the rotation frequency depending on initial conditions. The application of a torque to the plasma by a rotating external field around the central axis $z$, permits control of the particle density of the plasma [48]. To reduce the radius of the distribution of a charged plasma, radio frequency voltages are applied to radial sectors of some trap electrodes designed for such a purpose. The RW technique is common in experiments with single-component non-neutral trapped plasmas and across the antimatter community. The theory behind the dynamics of the compression of single or multi-species plasmas with the RW technique is quite limited. There is little theoretical work, mostly done in a descriptive manner, that would allow the experimentalist to use a simple set of formulae to predetermine the compression rate and efficiency inside a trap [58]. In the first reported antiproton compression study that used the RW technique on antiprotons and electrons [59], it was shown that the compression of a mixed $\bar{p}$ and $e^-$ plasma is achieved at a fixed frequency, if the compression of the electron cloud is slow enough.

Instead, with the results obtained in AEgIS (a paper was published in 2018 [60]), it was shown that the speed of compression is not a key parameter, and the full compression of the electron cloud, including its low density radial tails, is central in achieving high radial antiproton compression. It was observed that the compression dynamics for a pure electron plasma acts in the same way as that of a mixed antiproton and electron plasma. The antiproton compression dynamics seems to be solely dependent on the electron dynamics and it can thus be optimized outside of the antiproton beam time. Operations concerning compression at this stage are performed in the P-Trap, a 12-electrode Penning–Malmberg multi-ring trap, with an inner diameter of 30 mm composed of ten 13.5 mm long electrodes and two 30 mm long end-caps at each end. Two of the central electrodes are cut into four azimuthal sectors onto which the RF compression signal is superimposed on top of the respective DC bias potential. The applied RW drive is a sinusoidal voltage signal, $V(t) = A_{\text{RW}} \sin(\omega_{\text{RW}} t + \phi)$, of a given frequency, $f_{\text{RW}} = \omega_{\text{RW}} / 2\pi$, and an amplitude, $A_{\text{RW}}$. The sine signal is shifted in phase, $\phi$, by 90° on each azimuthal sector of the electrodes, thus creating an approximation of a rotating radial dipole field. The particle diagnostics is performed destructively by lowering the end-cap voltage, by
allowing the particles to escape, and by recording the resulting signal on the external scintillator slabs to count the \( \bar{p} \) number, on the 1T MCP to measure the radial profiles of electrons or antiprotons and to the 5T FC to measure the total electron number.

According to Eq. 3.22 in Sec. 3.1.8, an efficient compression would require either the reduction of the electron plasma density or an increase of the plasma temperature. In fact, a centrifugal separation would be responsible for a drift of antiprotons towards larger radii, thwarting any effort for compression. While a high electron density is needed for fast antiproton cooling from keV to eV, temperatures below 1 eV are not required for compression. Hence, for AEgIS conditions, it is preferable to apply a plasma heating signal to overcome the centrifugal separation effect during the compression stage. To this purpose, the RW drive itself turned out to be a viable option. The drive was kept at \( f_{RW1} = 300-400 \) kHz and \( A_{RW1} = 2 \) V since the trap loading time, preventing the two populations from expanding.

The compression procedure starts soon after the release of the hottest \( \bar{p} \) fraction from the mixed \( \bar{p} - e^- \) plasma with the application for 20 s of a RW drive with \( f_{RW2} = 1.5 \) MHz and \( A_{RW2} = 2 \) V. The compression dynamics of a pure electron plasma behaves the same way as that of a mixed antiproton and electron plasma. Figure 3.5, on the left side, shows the compression under the \( f_{RW2} \) drive of two pure electron clouds differing in initial number and size. The plot on the right side reports a systematic study of the compression as a function of the RW frequency \( f_{RW2} \) for two \( e^- \) loading conditions, \( N_{e^-} = 2 \cdot 10^8 \) and \( N_{e^-} = 4 \cdot 10^8 \) loaded in the trap. The behaviour of the \( \bar{p} \) radius follows that of the electrons, which are compressed in a similar way as for an electron-only plasma. The maximum \( \bar{p} \) compression is reached at \( f_{RW2} = 2 \div 4 \) MHz for both the \( e^- \) loading conditions, with comparable compression values. Antiprotons get compressed since the moment in which the RW drive frequency starts to be increased. This lets the electron plasma enhance its rotation frequency with a consequent decrease in radial size. The \( \bar{p} \) follow the electrons as long as the compression remains slow. Then, part of the cloud expands to larger radii.

In the end, the single step procedure shows a limit in the electron density rather than in the radius of the particle distribution. The compression achieved is not sufficient to obtain a cold antiproton plasma where higher densities are necessary. Therefore, a multi-step \( \bar{p} \) RW compression method was developed, based on the application of different frequencies of RW signal with progressive reduction of the number of electrons. A ten-fold antiproton radius compression has been achieved, with a typical antiproton radius of only 0.17 mm, in the 5 T trap. The most important condition to achieve maximal antiproton compression is to reduce the electron cloud tail density to a minimum, regardless of the frequency applied. Importantly, to minimize the tails of the electron density distribution, one key experimental condition consists to perform the mixed plasma compression in which the antiproton density distribution follows that of the electrons.
CHAPTER 3. ANTIPROTONS MANIPULATION FOR ANTIHYDROGEN PRODUCTION IN AEGIS

Figure 3.6: Radial density profile of $e^-$ and $\bar{p}$ after two cases of RW compression. Dotted lines show unsuccessful compression of the electron plasma tail while the full lines show the high density $\bar{p}$ compression accompanied by the successful compression of the tails of the electron plasma. [60].

This effect can be quantified defining a peak-to-tail density ratio $n_{p/t}$ as $n_{z}(0)/n_{z}(r_{t})$, with $r_{t} \equiv 3r_{HWHM}$, being the radial tail position defined as three times the HWHM radius. The peak-to-tail density ratio for electrons was found to be of the order of $n_{p/t} \approx 150$ or higher for efficient antiproton compression achieving a high core density $\bar{p}$ plasma. Figure 3.6 shows the radial density profile in two different RW compressions of a mixed plasma. The antiproton radial density profiles follow quite accurately those of the electrons. In the case of one of the best compressions, the electron ratio is $n_{p/t} \approx 190$, whereas the corresponding antiproton profile shows $n_{p/t} \approx 47$. At RW amplitudes higher than 0.5 V, the $e^-$ core are well compressed although some electron tails remained. The antiprotons were then more evenly distributed and in some cases, like that shown in Figure 3.6 (dotted lines) there was practically no antiproton compression, with $n_{p/t} \approx 3.6$ and $n_{p/t} \approx 23$. As a possible interpretation, the necessity to compress the mixed plasma slowly (with low amplitudes) is dictated by the need to compress electrons without creating tails. The observed electron tails could be the remnants of the original electron cloud distribution prior to the RW application. In fact, such tails are visible also in the case of a pure electron plasma compression and in some cases tails take the form of a pedestal or a ring that have approximately the radius of the original uncompressed electron plasma (prior to the RW drive application).

The compression results achieved for a single $\bar{p}$ bunch, i.e. small dimension ($r_{\bar{p}} = 0.17$ mm) and high $\bar{p}$ number ($\approx 70 \text{,}000$) available, well scale with multiple AD shots allowing for a lossless transport into a lower magnetic field. Once compressed, in fact, antiprotons have to be moved to the 1 T region to reach the antihydrogen production trap.

3.3.2 Antiproton transfer from the 5 T region to the 1 T region

As introduced in previous sections, antiprotons in AEgIS are moved from 5T region to the 1T region with a procedure, called ballistic transfer, which consists of opening the P-trap towards the transfer region, moving the potentials to favour the cloud shift, in-flight centring the antiprotons and recapture them in the 1T traps.

This is not the only one option for such operation. In fact, until 2016, antiprotons were adiabatically moved across the magnets in the adiabatic transfer procedure by extending the compression trap to a larger one which included the P-, T-, B- electrodes. Such large trap was then reshaped to the B-trap electrodes only. Once the shift was complete, the antiprotons were moved to the production trap and cooled down again. The presence of electrons helped to compensate for some heating that unavoidably
happens during the trap movement and allows to place the two species in the final trap, where the final cooling could take place. However, in practical conditions, the efficiency of this procedure was limited by the residual misalignment between the ST and TT magnets that induced a diocotron mode due to field instabilities, and that contributed to the increase of the radial size of the plasma. Indeed, the observation of radial expansions itself was a kind of big deal.

Instead, the ballistic transfer procedure allows for the application of a controlled shift of the radial position of the antiproton cloud by setting static voltages ranging from -180 to +180 V to the 4 radial sectors of one cylindrical electrode mounted in transition region between the two magnets, the Bo electrode. The resulting velocity acquired by the antiprotons in the $\vec{E} \times \vec{B}$ direction is sufficient to shift their position by few millimetres while moving inside this electrode, and therefore to compensate for the misalignment between the two magnets and trap structures. This procedure allows to place the antiproton cloud directly in the antihydrogen formation trap with the same radial extension as that obtained in the ST trap, with the only unavoidable expansion due to the decrease of the magnetic field.

Typically every year, the vacuum chamber has to be opened for maintenance or to allow upgrades. As a consequence, the two traps won’t have the same position with respect to each other after the closing procedure. The best value for the shifting electric field has generally to be recovered. A calibration procedure to compensate for such changes and to adjust the residual misalignment has thus to be performed every year, at the beginning of the run, or at any time the conditions inside the apparatus undergo variations.

To check the radial distribution of antiprotons, the cloud is dumped from the ST trap towards the TT MCP without any recapture in between. The coordinates of the centre of the plasma are obtained by analysing the images acquired with the TT MCP downstream the antihydrogen formation trap. As a reference, at the beginning of 2017, the position displacement with respect to the best centring of the previous year was only 2.16 mm and the Bo electrode parameters were kept to the same values as the year before. In 2018, instead, the procedure needed to be repeated several times. It is worthy to note that, by means of ballistic transfer procedure, it is possible to centre the antiprotons in the final trap with an accuracy of few tens of microns.

However, antihydrogen production procedure requires antiproton recapture in the HT trap. Once antiprotons are recaptured, they undergo several steps of further compression and cooling down. At this point, to check their radial distribution they have to be dumped on the TT MCP. The technique for the temperature measurement will be described in Section 3.3.3.

Figure 3.7 shows different $\bar{p}$ clouds dumped of $\bar{p}$ clouds from the antihydrogen formation trap to the TT MCP. This measurement is performed after recapture of the $\bar{p}$ cloud, 1 ms storage and dump via ballistic transfer technique. In the case of non-perfect centring, the plasma injected off axis starts a diocotron motion and it forms a ring around the centre of the trap. The size of the plasma cloud is closely related to the thickness of the ring and it slowly starts to fill up its whole volume, ultimately rearranging in a large cloud. It is also possible to note (Fig. 3.7, bottom right) that a well-centred plasma may still achieve compressions as good as those in ST.

The recapture procedure requires synchronised pulses with programmable amplitude (1 ns to 64 $\mu$s), length and delay with respect to the trigger. These are provided by custom electronics (Sec. 2.5). Pulses are electrically summed to the trap bias and used to launch the antiprotons (trap opening) or recapture them (trap closing). In order to minimize the energy and time spread of antiprotons, the HT trap is shaped into a pure Malmberg configuration before the $\bar{p}$ arrival time. Antiprotons are then released by the ST trap and fly along the 1.2 m distance at the maximum energy available with the present hardware, ~100 eV, and get recaptured by the pulsed opening of the HT trap. The arrival trap is biased in order to slow down the incoming antiprotons. Trap length and closing time are determined by the energy and time spread of the recaptured $\bar{p}$ cloud as well as number of particles and losses on the external scintillators. Recapture efficiency is typically ~90%, corresponding to $\approx 2 \cdot 10^5$, with all the considerations on the capture efficiency taken into account and assuming an AD intensity of $3 \cdot 10^7$ $\bar{p}$/shot.
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Figure 3.7: Antiproton cloud moved from 5T traps to \( \hat{H}_{\text{Trap}} \), stored there for 1 ms and dumped on the MCP. Calibrations data taken at the beginning of 2017 run. Axis units are in pixels. Conversion: 43 pixels = 1 mm. The intensity is in arbitrary units. Top left: image without any \( E \times B \) correction. Top right: a partial trajectory correction. Bottom left: correction voltages optimized before the end of the 2016 run. Bottom right: the best setting for 2017.

Remarkably, \( \bar{p} \) losses happen around the catching time rather than at any other time during the flight. This appears clear from Figure 3.3.2 which reports the time distribution of the signals detected by the slabs surrounding the \( \bar{T} \) magnet while the \( \bar{p} \) transfer from 5T to 1T traps is performed. Left side of the figure shows long time recording before the moment of the transfer. A detail of the transfer is reported in the right panel. The first red mark, around \( t = 242.0 \) s, indicates the time at which the recapture pulse is applied, while the second at \( 243.5 \) s, marks the beginning of the voltage ramp used to dump the antiprotons for counting. The peak corresponds to about \( 2 \cdot 10^5 \) antiprotons. The figure also shows that \( \bar{p} \) tiny losses (some % of the final peak) occur around the re-catching time.

3.3.3 Antiproton cooling in 1 T

Cooling of the antiprotons recaptured in the \( \hat{H}_{\text{Trap}} \) requires electrons. Nevertheless, the electrons used in the compression procedures are lost during the ballistic transfer because of their velocity which is higher than that of antiprotons. The simplest fix to drive a mixed plasma in the production trap could have then been a new electron loading. However, the already mentioned shift between the 1T and 5T
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Figure 3.8: Time distribution of the annihilation of antiprotons as seen by scintillators surrounding the 1T region. The red marks indicate antiproton movements as they are set in the trap electrodes control code. On the left: long time recording. No significant $\bar{p}$ losses can be spotted. Antiproton transfer occurs between the two last marks around 240 s. On the right: zoom around the transfer time region. The red mark around 242 s indicates the moment when the pulse used to re-catch in-flight antiprotons is applied. The second red mark indicates the beginning of the potential ramp applied to dump and count the antiprotons. The peak corresponds to about $2 \cdot 10^5$ antiprotons. The plot shows that some losses (some % only of the final peak) of antiprotons occur around and after the re-catching time. No electrons are loaded in the 1T trap.

region makes it difficult to direct load electrons in the 1T traps. This is since the electron gun is located in the fringe field of the 5T region and the resulting plasma showed a quite large radius. Hence, a procedure was developed with the electrons loaded in the production trap before the beginning of the antiproton manipulations. When all the $\bar{p}$ operations have been completed, the H$_{\text{Trap}}$ is opened and the antiproton cloud reaches the electrons. In detail, the electrons were first loaded and compressed in the 5T trap before the AD extraction time, then adiabatically transferred in the B-trap and recompressed by use of RW technique. At that point they were finally ballistically moved to the anti-hydrogen formation trap. The e$^-$ storage time in the B-trap is extremely long with the application of the compression technique and the charge collected on the 1TMCP (operated in charge collecting mode) remains constant even after many hundreds of seconds. However, the non-standard design of the anti-hydrogen production trap induces some effects in the dynamics of the trapped plasma. Rotational symmetry is an important parameter to limit radial transport and confinement time as an imperfect electric field would generate an induced radial transport. Imperfections in the realisation of the electrodes might affect the conditions of the plasma inside. In particular, the symmetry of the production trap of AE\textgreek{g}IS is broken by design. This is due to the opening in the electrodes due to the gap needed for the passage of positronium. Despite the addition of a mesh to cover the opening, the plasma expansion can be considerable. Clouds of electrons have been stored in traps with different lengths (i.e. involving different numbers of electrodes) and centred in different positions along the H$_{\text{Trap}}$, like, for instance H$_{\text{Trap}}^{6\text{-}10}$, H$_{\text{Trap}}^{25}$, or OnAx28-H$_{\text{Trap}}^{25}$. The design of the trap is modular so that the plasma can be trapped in different regions by properly shaping the electric field on the electrodes. In particular, the latter configuration is the least affected by the asymmetry and that one with the most stable plasma behaviour in the H$_{\text{Trap}}$. Nevertheless, with $3 \cdot 10^7$ e$^-$ stored in such trap and potentials shaped in order to arrange a square well (Malmberg-like trap), the pure e$^-$ plasma expands in few minutes and the first particle losses start in 300-400 seconds (Figure 3.9). Longer traps (i.e. shaped with a larger number of electrodes) or traps located in different positions were more affected by the field inhomogeneity. Pure electron plasmas stored in such traps showed qualitatively similar behaviours, typically with faster time scales. This observation alone, rules out a major contribution in the plasma instability in the production trap due by electrical issues, non-perfectly insulated connections or sources of electrical noise reaching the H$_{\text{Trap}}$ electrodes.

The replication of the well-established cooling scheme implemented in the 5T traps was expected
to succeed in sympathetically cooling the antiprotons down with a preloaded cloud of electrons. To do this, once the electrodes for the \( \bar{p} \) manipulations in the \( H_{\text{Trap}} \) were selected, electrons were to be stored in a trap nested into the selected \( \bar{p} \) trap. The \( e^- \) clouds were stored in a trap shaped using some of the electrodes among those of the \( \bar{p} \) trap. For instance, for a \( \bar{p} \) trap shaped between OnAx28 and \( H_{\text{Trap}}^{14} \), a reasonable choice for the preloaded electrons could be \( H_{\text{Trap}}^{14} \). Such scheme, however, did not produce the expected results. The cooling was inefficient and significant antiproton losses were systematically observed. A most reasonable explanation could be that the stability of the trapped antiproton cloud was affected by the electric field generated by the inner electron trap, regardless of the presence of the electrons.

The only way to overcome the issue was to come up with a reversed procedure, with the electrons preloaded in the same trap as that designed for antiprotons without creating an inner potential well. Hence, in the final procedure, first the antiprotons are ballistically captured in the designed trap (e.g. \( H_{\text{Trap}}^{14} \)) and then the electrons in the same trap, again ballistically, from the reservoir B-trap. Electrons (\( \sim 2 \times 10^7 \)) are captured in the \( \bar{p} H_{\text{Trap}} \) by lowering the potentials on the upstream electrodes for such a short time as to prevent significant losses of antiprotons. Electrodes are then pulsed to raise up again potentials to previous values and get the trap shape restored in \( \sim 40 \) ns since the opening time. With \( \sim 10^7 \) electrons, antiproton cooling is observed in few seconds. After this time, the number of electrons is reduced to limit the expansion rate of the mixed plasma and to allow an estimation of the plasma temperature. However, a small fraction of the electrons is needed to remain inside the trap to further cool \( \bar{p} \) down after next operations.

The axial temperature of the antiprotons is measured by using a procedure similar to that developed in [61] and [62]. Once the initial cooling stage is completed, a large fraction of the electrons is dumped by applying fast short pulses to one electrode as to prevent the electron space-charge potential to influence the temperature measurement. The number of electrons remaining inside the traps, typically \( \sim 10^5 \), is so small that it cannot be measured by the FC. However, their number is sufficient to continue to cool antiprotons down after the electron kick-out. This second cooling stage is needed since antiprotons are heated by the pulses and by the variation of the space-charge potential in the trap and it lasts in a short time, \( \sim 10 \) seconds. Electrons and antiprotons are then moved adiabatically into a different region of the \( H_{\text{Trap}} \) with a better overlap with the Rydberg Positronium for the antihydrogen formation experiments.

To allow reaching the equilibrium temperature, it was necessary to wait for a time of the order of several tens or up to 100 seconds. Then it is possible to measure the temperature by slowly ramping down one of the end-cap electrodes and fitting the time distribution of the first few antiprotons escap-
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Figure 3.10: Antiproton temperature measurement in the $H^\text{p-6}_\text{Trap}$ obtained after a 100 seconds cooling time with a small number of residual electrons left in the trap. The plot shows the counts on the scintillator due to annihilation of antiprotons as a function of the vacuum potential well on axis. The fit indicates the temperature, as described in the text. No correction for space-charge potential has been applied.

The first escaping particles are those trapped close to the trap axis and, under ideal conditions considering a Maxwellian axial velocity distribution, the following relation holds

$$dN \propto e^{-\frac{W_0 + q\Phi_p}{k_B T}} \frac{1}{\sqrt{W_0 + q\Phi_p}} dW_0,$$

(3.23)

where $W_0$ is the trap depth on axis due to the applied voltages (the so called vacuum trap) and $\Phi_p$ is the potential on axis due to the space-charge. In a first approximation, the temperature is typically obtained under the assumption that the number of extracted particles is so low that the variations of the space-charge potential are negligible and by neglecting the variation of the divisor in the equation above. Under this simplified hypothesis the first few particles escaping the trap are counted as a function of the trap depth and an exponential fit is performed. However, it is known that this method needs many corrections due to the plasma space-charge effects. A more refined analysis must include the variation of the space-charge potential. Note that in the simplified model the temperature results overestimated. In addition, pickup of electronic noise was proven as a source of plasma heating. In fact, temperature measured were significantly higher (above 1000 K) whenever the crate hosting the RW electronics was on or switched off. For such reason, a modification in the electronics was introduced to automatically switch off the RW crate before the antiproton entrance in the production trap.

Measurements performed under the same plasma conditions in different positions inside the $H^\text{p-6}_\text{Trap}$ showed slight different temperature values confirming that plasma temperature in the production trap depends on the trap region. The lowest temperature value, $237 \pm 21$ K, is achieved in the $H^\text{p-6}_\text{Trap}$ (Figure 3.10), which, however, does not offer a good solid angle for the interaction between antiprotons and positronium atoms from the above target converter. For such reason, the $H^\text{p-8}_\text{Trap}$ (hereinafter $H^\text{p-8}_\text{Trap}$) was selected as antihydrogen production trap in 2018. Upper limit for the antiproton temperature in $H^\text{p-8}_\text{Trap}$ was measured in $440 \pm 80$ K, with all the above assumption still holding.

3.3.4 Single $\bar{p}$ bunch storage for $H$ production in the $H^\text{p-8}_\text{Trap}$

The cross section for antihydrogen production also depends on the relative velocity between $\bar{p}$ and Ps, besides other parameters. However, the major limitation induced by a too high temperature is connected to the detection of the formed atoms rather than to the reaction itself. Antihydrogen
temperature is mostly given by antiproton temperature and the $\bar{H}_{\text{Trap}}$ has a 5 mm radius. Hence, for a 1000 K $\bar{p}$ temperature, the $\bar{H}$ signal would be expected later than 1 $\mu$s after the $e^-$ arrival time on the target, for a $\bar{p}$ cloud narrowly distributed around the trap centre. A grace time of 1 $\mu$s is sufficient to allow the detectors to recover from the $e^-$ burst. A $\bar{p}$ temperature of 1000 K, corresponding to 0.13 eV, is then assumed as the temperature limit for $\bar{H}$ detection.

A single $\bar{p}$ bunch reaches the $\bar{H}_{\text{Trap}}^f$ with fairly reasonable temperature, $\sim 440$ K, and radial distribution, 0.2 mm. As discussed above, during the compression procedure of a mixed $\bar{p}$-$e^-$ plasma, the dynamics is driven by electrons, whose compression induces that of antiprotons. A similar effect is observed for the plasma expansion during the $\bar{p}$ storage. If no RW drive is applied, a relatively fast expansion of the electrons induces expansions for the antiprotons too, with consequent losses. A reduction of the $e^-$ number (from $\sim 10^3$ to some $\sim 10^2$) allowed to achieve a suitable temperature and a satisfactory storage time of the mixed plasma in spite of the non standard design of the trap. As an example, Figure 3.11 show the number of surviving antiprotons as a function of the trapping time in the $\bar{H}_{\text{Trap}}^{c-9}$ with all the electrons initially used for the initial stage of the cooling and with reduced numbers of electrons as used during the final stage of the cooling.

At this point, a protocol for antiproton manipulation for antihydrogen production was defined with satisfactory performances and good reliability.

### 3.3.5 Working with multiple $\bar{p}$ bunches

The major advance in the antiproton manipulations achieved during the 2018 data-taking run was the full implementation of the antihydrogen formation procedure with an increased production rate as a result of improvements on plasma conditions and an increased production efficiency due to the introduction of a multi-stacking technique.

Multi-stacking permits to store an increased number of antiprotons in the production trap, thus enhancing the production efficiency given the same number of Ps* atoms per unit time reaching the trap and a constant reaction cross section. The number of antiprotons gets increased by stacking and
compressing several \( \bar{\text{p}} \) bunches in the \( \text{5T} \) traps. In fact, at the capture of a first AD shot, the hottest fraction of particles in the mixed plasma is removed for a first cooling down stage (Sec. 3.3.1.1). At that point, it is possible to capture another AD shot, sympathetically cool it down with the chilled plasma and, again, release only the most energetic particles before to start a new cooling down procedure with the new plasma. In principle, the procedure can be extended to any reasonable number of AD shots (up to ten or even more), with a good compression and a fine linearity between the number of captured antiprotons and the counts registered at the release of their cold fraction, without significant losses. However, geometrical limitations of the production trap substantially curtail the number of storable antiprotons, establishing 8 AD shots as working condition. The resulting plasma, containing up to \( 10^6 \) antiprotons, could be stored for several thousands of seconds in the production trap in stable conditions without any further manipulation. Notably, in the above mentioned conditions and once the plasma inside the trap is a regime, the number of antiprotons was higher than that of electrons used to cool them down.

Such improvement of plasma conditions, with the possibility to store antiprotons for such a long time in the production trap, gave the opportunity to run multiple cycles of antihydrogen production with the same \( \bar{\text{p}} \) cloud in the production trap. In typical conditions, positrons are accumulated, compressed and sent to the target converter every \( \sim 90-100 \) seconds. A fraction of formed Ps cloud is then laser excited to Rydberg states and enters the production trap to encounter the \( \bar{\text{p}} \) cloud. The possibility to use the same \( \bar{\text{p}} \) cloud for several \( \bar{H} \) production cycles allowed to get rid of the \( \bar{\text{p}} \) dead times, including the AD cycle and the standard manipulation times. In addition it made possible to cut down the number of positrons for each \( e^+ \) shot to reduce the background due annihilation photons from the \( e^+ \) burst and the consequent reduction of the recovery time for detectors. This resulted in a considerable simplification of the \( \bar{H} \) data analysis, providing more straightforward normalisation conditions.

In working conditions, with 8 AD shots stacked and compressed in the \( \text{5T} \) traps, \( 3 \cdot 10^7 \) electrons still suffice for cooling down the plasma in the production trap in few tens of seconds. To keep the plasma stable for such a long storage time, the plasma expansion rate must still be balanced with the application of the compression technique. The procedure developed for a single shot remains valid and the number of electrons used for cooling has to be reduced by applying fast voltage pulses on one end-cap electrode to get the plasma in condition to be shifted of few electrons into the final production trap, \( \text{H}_{\text{Trap}} \) shaped as an harmonic trap centred in the \( \text{H}_{\text{Trap}} \) electrode. At this point, stacking 8 AD shots, \( \sim 8-9 \cdot 10^5 \) were trapped with \( \sim 5 \cdot 10^5 \) electrons in the \( \text{H}_{\text{Trap}} \). The plasma was kept in the trap while waiting for positronium without moving voltages potentials. Then, few ms before the positron injection on the target, the trap voltages were adiabatically lowered, from \( -180 \) V to \( -32 \) V on the edges whilst keeping the trap harmonically shaped, to prevent the positronium atoms to be affected by the electric field while moving (see Chapter 4). Under these conditions, when the positronium is produced, the plasma shape at equilibrium is almost spherical, with a semi-axial extent of about 1-2 mm and a typical radius of 1-2 mm. Figure 3.12 shows the comparison between the radial profile on the 1T MCP of a mixed \( \bar{\text{p}}-\text{e}^+ \) plasma in typical conditions for \( \bar{H} \) production.

The radius of a 8 AD shots plasma stored for 20 \( \bar{H} \) cycles (more than half an hour) is still \( \sim 2 \) mm only. In the picture the electrons are displayed. However, the \( \bar{\text{p}} \) distribution follows that of the electrons.

Out of the Ps arrival time, instead, the trap was kept at higher voltages and the antiproton plasma was thus shorter. The length and the radius of the plasma were key parameters to tune in order to obtain stable conditions. As already mentioned, the rotational symmetry in the \( \text{H}_{\text{Trap}} \) is broken by construction because of the semi-transparent grid needed on top of the central electrodes to let the positronium enter the trap to encounter the \( \bar{\text{p}} \) cloud. Therefore, the length and the radius of the plasma are key parameters that it was necessary to adjust in order to obtain stable conditions.

Antiproton losses have been observed due to unavoidable collisions with residual gas. A fraction of about \( \approx 75 \% \) of the initial number of antiprotons is still detected after more than 3000 seconds with a negligible plasma expansion and this can be considered an estimation of the maximum losses due to collisions with residual gas. Occasionally, larger losses related to plasma dynamics and correlated
Figure 3.12: Electrons released from the antihydrogen production trap to the 1MCP. The circles indicate the trap inner profile. On the top: electrons needed to compress a single AD shot plasma stored for one production cycle only. On the bottom: electrons for a 8 AD shots plasma stored for about half an hour. MCP image is reported on the left side of each row, radial profile distribution on the right side. Antiproton distribution follows that of electrons.

with larger antiproton radial size were observed, most probably caused by the fluctuating conditions of the electron cloud stored in the 1 T production trap together with the antiprotons.

Taking all this into account, in a preliminary manner it was estimated that the mean number of antiprotons available during the antihydrogen procedure is \( \approx 5 \cdot 10^5 \). This pulsed production procedure can operate for up to 50 production cycles, which corresponds to 75 minutes without significant antiproton losses or significant radial expansion. Under standard conditions a production procedure of 24 cycles guaranteed a good compromise between reliability and efficiency.
Chapter 4

Positronium for \( \bar{H} \) production in AEGIS

Positronium, the intermediate system for antihydrogen production via charge exchange reaction with antiprotons in AEGIS, is a purely leptonic hydrogen-like bound state composed of an electron and a positron.

When positronium is formed, it has to be laser excited to Rydberg states to allow for an efficient charge-exchange reaction. Rydberg-excited positronium clouds get to the \( \bar{H}_{\text{trap}} \) while cold antiproton plasmas are stored in suitable conditions for antihydrogen production. The time when the laser is fired is the reference time for the pulsed production scheme and it is known with few ns accuracy. The positron sequence for antihydrogen production starts with accumulation of positrons. The positrons are then extracted from the positron trap system and driven in form of bunches through the transfer line to get to the main apparatus where they are accelerated on an off axis trajectory towards the sensitive region of a nano-channelled aluminium target converter. Nano-channels are produced via electrochemical etching and thermal oxidation in air. In multiple-cycles production scheme, positron procedures are repeated several times, up to 60 cycles, while keeping the same \( \bar{p} \) plasma in the \( \bar{H}_{\text{trap}} \). The repetition number depends on the antiproton expansion rate in the trap, which is sensitive to several factors. In typical production runs, 20-30 cycles were considered a safe number of repetitions.

Several novel detection techniques were implemented in the positronium diagnostics, also with my contribution. In particular, the use of a kicker pulser to detect the charge induced by the passage of the positron bunch was developed, tested and used as a main technique to monitor the condition of the positrons entering the main apparatus. On the top of this, the conversion of the MCP into a position sensitive detector for slow positronium allowed to characterise the Rydberg state of this unstable atom in magnetic field. The work for the fine tuning and characterisation of the new detection techniques was part of the activities I carried out during the data taking period.

After a short introduction on positronium and its detection techniques, in this chapter I will describe the steps for the Rydberg-Ps production in the \( \bar{\Lambda} \bar{t} \) production region with special attention to its detection and recent improvements in the detection techniques in the AEGIS apparatus.

4.1 Positronium and detection techniques

Decay modes and atomic structure of positronium are determined by the electromagnetic interaction. However, the decay itself is not a radiative process, but rather a mutual annihilation of the e\(^{-}\)-e\(^{+}\) pair. The overall lifetime of an excited Ps atom may depend on annihilation and radiative decay rates as annihilation process can only occur from certain states, which might only be accessible via radiative transitions [63].

Ground state of positronium has two possible configurations depending on the relative orientations of the spins of the electron and the positron. The number of gamma rays emitted in Ps decay is determined by the charge conjugation invariance. An exhaustive discussion and the selection rules can be found e.g. in [63], Sec. 2.1.2 and references. The singlet state (\( \text{para}-\)positronium, p-Ps), with anti-
parallel spins \((S = 0, M_S = 0)\) may decay into any even number of photons. However, typical decay is into two 511 keV photons in 125 ps. The decay branching ratio drops with the number of photons and a 4\(\gamma\) decay may happen every \(\sim 10^6\) events. In the triplet state (ortho-positronium, o-Ps), the electron and the positron have parallel spins, resulting in \(S = 0, M_S = -1, 0, +1\) quantum numbers. Ortho-positronium has a decay time of 142 ns with three photons produced. Rates for higher number of photons are negligible as their branching ratios are in the order of \(10^{-6}\). The photon energy distribution is continuous (multiple-body decay) between 0 and 511 keV \([64]\). Ps excited to higher levels has a longer lifetime. In particular, Rydberg states refer to a very high principal quantum number \(n\) \((n \geq 10)\), close to the continuum.

Positronium is formed following positron bunch annihilation on the target converter. Most of the positrons annihilate with surface electrons of the target immediately producing two 511 keV photons emitted back-to-back because of momentum conservation. Photons produced in Ps decay interact with scintillators and the correspondent produced light is converted into an analog signal by photomultiplier tubes.

The choice of a scintillator for Ps detection is crucial for a good quality of data. A suitable scintillator for Ps detection should present fast rise time (ns or few tens of ns), good conversion efficiency, good light yield and low delayed light component (Birk’s law, e.g. \([65]\)).

The Single Shot Positron Annihilation Lifetime Spectroscopy technique (SSPALS) is the technique used to detect the Ps formation and variations in its lifetime spectra. It allows for an extraction of the lifetime of positronium from the spectrum of the annihilation counts as a function of time referenced to the time of the positrons release. The technique is based on monitoring the lifetime of Ps, which varies depending on its internal quantum state. The idea is to analyse the time profile of the analogue signal of a photomultiplier tube (PMT) connected to the scintillator detecting the gamma produced in the annihilation of e\(^+\) and Ps in different experimental conditions. With the SSPALS technique, the analog signal from the PMT is acquired. The signal time profile describes the time distribution of photon annihilations from positronium decay, as the annihilation rate would be too high for counting experiments with typical bunches of \(10^6\)-\(10^7\) positrons. The signal due to the annihilation of the e\(^+\)-e\(^-\) pair is digitised and acquired with ns resolution. The resulting averaged and normalised curve is dominated by a prompt peak corresponding to the time of implantation of the positrons in the converter. When Ps is formed, this peak is followed by a slow decay corresponding to the annihilation of freely-propagating\(^1\) Ps atoms in the ground state with ortho-spin configuration. However, the slope of the signal depends also on the secondary light component of the scintillator itself. Therefore, an exponential fit on the tail of the signal will typically have a time constant greater than 142 ns. Significant variations in the Ps population are reflected in the SSPALS spectrum and the formation of Rydberg-Ps atoms, in general, can be established by this technique \([66]\). As the variations have to be searched in the tail of the signal, to improve the detection precision, the output of the photomultiplier tube is typically split and it is acquired also in high resolution. This allows a better precision in the detection of tail of the signal, where the tiny differences should be searched. In AE\(\bar{G}\)IS, this is performed with a 12 bits, 4 GS/s fast digitizer and the trace is then reconstructed off-line for the analyses. Typically, traces are summed up, averaged and normalised to 1 nominal Volt for comparisons between data series.

### 4.2 Positrons preparation for \(\bar{H}\) production

Processes of positronium formation and its excitation take place during the antiproton preparation time for \(\bar{H}\) formation. Positrons are emitted from a 25 mCi \(^{22}\)Na source and moderated by solid neon to kinetic energies of few eV to be trapped in a Surko trap \([67]\) where they are cooled down by collisions.

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\(^1\)This is only true if Ps is emitted into vacuum; in fact, the decay time extracted from the SSPALS measurement critically depends on whether Ps is formed in closed voids, the electron density of the surface of the voids, the fraction emitted into vacuum. For such reason, the experimental apparatus was designed so that the Ps atoms have an obstacle-free trajectory, allowing them to decay while in-flight.
with a buffer gas. The accumulator is connected to the trap. It is a cylindrical Penning trap in a 0.1 T magnetic field where positrons are moved in pulses and radially compressed by mean of RW technique before being finally extracted in bunches of tunable intensity and length.

For \( \text{H} \) production experiments, bunches of \( \sim 2 \times 10^6 \) e\(^+\) with \( \sim 300 \) eV mean axial energy are accelerated in flight to 4.6 keV and magnetically transported along an off-axis trajectory towards the nanoporous target converter placed above the \( \text{H}^\text{\text{f}} \) Trap. Positrons are guided towards the main magnetic field of the experiment through a pulsed magnetic transfer line [38] which allows vertical and horizontal tuning of their injection position. A representation of the transfer line is given in Figure 4.1. In particular, there are two openings for the Faraday cups used as destructive beam monitor for positron bunches. Along the transfer line, positron bunches get their axial flight energy increased by the passage in a 70 cm-long electrode pulsed to 4.6 kV [40], the kicker tube, which can also be used as a non-destructive beam monitor for e\(^+\) bunches. The technical drawing of the kicker tube is shown in Figure 4.2. The positron transfer non-destructive diagnostics is discussed in Sec: 4.3. The electrode is pulsed synchronously to the passage of the bunch in order to have the full bunch contained inside the electrode at the pulse arrival. This process, on one hand, tightens the time distribution of the positron bunch and, on the other hand, leads to the energy suitable for efficient Ps formation by implantation in the converter.

Figure 4.1: Technical drawing of the AEgiS positron transfer line from the accumulator to the main apparatus [38].

Figure 4.2: A depiction of the kicker tube assembly. The electrode installed in the transfer line is marked in blue. The vacuum chamber section of the transfer line is represented in grey.
4.3 Non-destructive detection of positrons

Of particular relevance to the concern of this section is the description of the induced signal on the kicker tube. The kicker tube is shown in Figure 4.2. It is a cylindrical AISI316L Stainless Steel pipe with 70 cm length, 3 cm outer diameter and 0.15 cm thickness mounted along a vacuum chamber of the transfer line. Figure 4.3 shows the technical drawings of the kicker tube with some details.

The characterisation of particle beam passing through such electrode requires some considerations. According to the Shockley-Ramo theorem \([68, 69, 70]\), the current induced on an electrode by moving charges is obtained as a simple consequence of basic electrostatic laws for the particular geometry of the detector. The method is based on the Ramo’s equation

\[
i = qvE_z,
\]

where \(i\) is the instantaneous current deposited on the electrode due to the motion of the single charge, \(q\) is the charge and \(v\) its instantaneous velocity. In the original formulation, \(E_z\), the weighted field, is the component of the electric field in the direction of particle’s motion \(z\) at the instantaneous position of the charge, under the following conditions: the charge removed, the considered electrode raised to unit potential, and all the other conductors grounded. The weighted field depends only on the geometry of the detector and on the position of the charge inside the sensor. Considering a single particle moving with a velocity \(\vec{v}\) towards the kicker tube, the charge induced by the particle can be expressed as a function of the particle’s position as

\[
Q(t) = qw(\vec{r}(t))
\]

where \(W\) is the weighted potential of the electrode which information about the geometry of the conductor \([69]\). The gradient of the weighted potential is the weighted field. The weighted potential shouldn’t be considered as a proper potential but rather a tool function for the calculations, consisting in the potential obtained when solving Poisson’s equation with the assumptions stated above taken as boundary conditions. Imposing \(W = 1\) on the kicker surface and \(W = 0\) on the remaining conductors, the solution of the equation

\[
\nabla^2 W = 0
\]

in the whole space gives the expression for \(W\). The weighting function obtained for the kicker tube in the AEGIS positrons transfer line is shown in Figure 4.4, top left panel, as a function of \(z\), with \(x, y = 0\), i.e. along the kicker axis \(z\), with \(z = 0\) indicating the kicker entrance. The current induced on the electrode and thus on a circuit connected to the kicker is obtained through

\[
i(t) = q\vec{v} \cdot \nabla W(\vec{r}(t)) = qv_z \frac{\partial W}{\partial z}.
\]

When many particles are considered, the total induced current is the sum of all the currents due to the single particles. The function \(W\) calculated for the kicker tube geometry returns \(W = 1\) when all the particles are fully contained in the tube and the moving charges act as a current generator

\[
I_{ind} = \Sigma q\vec{v}_i \cdot \nabla W(\vec{r}_i(t)).
\]

While travelling in the tube, positrons produce a variation of the current by changing the charge induced in the conductive kicker tube. If the time length of the e⁺ cloud is shorter than its transit time in the tube (short bunch), a signal is expected when the cloud enters as well as when it exits the tube, while no significant variation of the induced charge is expected during the time interval in which the cloud is fully contained inside the tube. The two pulses will be separated by the bunch transit time inside the tube. Remarkably, the induced charge is zero when the cloud is very far away from the tube and it is equal to the total charge of the bunch when it is fully contained inside it. Consequently, the integral of
Figure 4.3: Two technical drawings of the kicker tube installed in the AEgIS e⁺ transfer line. On the top: the full system. On the bottom: one of the main components, the kicker tube itself. Drawings are provided by the Genoa Division of the INFN.
Figure 4.4: Top left: the weight function $W$ as a function of $z$ with $x = y = 0$ along the kicker axis. The kicker entrance is at $z = 0$. As expected $W = 1$ inside the kicker. Bottom left: result of the calculation of the signal expected in the ideal case of $10^7 e^+$ entering the kicker with no time spread and 300 eV axial energy. The signal is calculated using the real values of the circuit element and gain of the amplifier. On the right: Measurement of a bunch of $3 \times 10^6$ positrons. The horizontal red line indicates the baseline for the calculation of the integrals and is computed in a region far from the signals, not shown in this plot. Perturbations before the entrance signal can be interpreted as electrical noise. The measured time between the entrance and the exit of the bunch in the kicker is 70 ns. The exit peak is wider because of the broadening of the $e^+$ bunch.

Each pulse is proportional to the number of positrons with a proportionality factor dependent only on the circuit connected to the electrode and on the gain of the amplifier.

Figure 4.5 shows the scheme of the connections for the detection of the signal induced by the passage of the particle bunch across the kicker. As it can be seen, a single feed-through exclusively connects a non-destructive detection circuit or the high voltage pulser. At the moment, the two systems cannot be connected at the same time.

As the current is injected in the circuit shown in Figure 4.5 it produces an output signal $V_{\text{out}}(t)$ at the output of the amplifier which is acquired in AEgis on 50 $\Omega$ impedance and amplified using a commercial
amplifier ZPUL-30P from Mini-Circuits company [71] with 50 Ω input resistance. The assembly made by the kicker tube and the vacuum chamber is a transmission line with 30 Ω impedance. The network of resistors between the tube and the amplifier shown in Figure 4.5, has the purpose of adapting the impedances. The voltage at the output of the amplifier is

\[ V_{out}(t) = G_A I_{ind}(t) \frac{R_1 R_3}{R_1 + R_2 + R_3}, \]  

where \( R_3 \) is the input resistance of the amplifier and \( G_A \) is the amplifier gain. Hence, for the circuit in Figure 4.5, the number of particles can be determined as

\[ N = \frac{1}{q G_A} \frac{1}{R_1 R_3} \int V_{out}(t). \]

4.4 Characterisation of positron bunches reaching the target converter

Positrons reach the converter by following an off-axis trajectory through the two magnetic fields inside the apparatus and practically conserving the time spread they have inside the accelerating electrode. In typical conditions for \( \bar{H} \) production, this is estimated to be below 10 ns FWHM, as shown in Figure 4.6. The picture shows the averaged normalised response of three different detectors discussed in detail in Chapter 7 and exposed to annihilation of positrons on the target in typical conditions for \( \bar{H} \) production. The FWHM of the narrowest of them (blue line) is well below 10 ns, suggesting that the \( e^- \) bunch is shorter than 40 cm.

The number of positrons reaching the target during each \( \bar{H} \) production cycle is measured through the charge collected by one of the PMTs of the ESDA scintillators, in favourable position and known to provide a non-saturated signal for this measurement. It is not possible to slowly dump the positrons in the bunch in the same way as it is done for antiprotons. The conversion procedure, instead, is similar to that introduced in Chapter 3 for captured \( \bar{p} \) counting in \( \bar{T} \), and it requires a normalisation with the Geant4 Monte Carlo prediction developed for the \( \bar{T} \) traps at the \( \bar{H} \) production parameters. The results are in agreement with independent control measurements obtained by dumping the positron bunch on-axis on a Faraday cup close to the target region (rather than off-axis on the target itself) and detecting the collected charge. For precise alignment and diagnostics purposes, positrons can be sent on-axis on the MCP imaging system. For all cycles, there are \( 2 \cdot 10^6 \) \( e^- \) available on average, with a FWHM of 45% corresponding to 1000 pC, as shown in Figure 4.6. The plot shows the charge collected by one of the scintillators of the ESDA at the positron dump. In particular, one of the slabs of the ESDA is used for this measurement, which is in a favourable position and does not saturate for this measurement.
Ps conversion and laser excitation to Rydberg states

Positron bunches are typically magnetically steered and aligned with respect to the target holder surface by extrapolating the currents in the coils as the positrons were steered on-axis. A fine vertical and horizontal ~0.1 mm position adjustment was carried out by looking at the positron image on the MCP. This was possible by redesigning of the target holder and the vertical shift of the detector.

To produce positronium, a positron spill from the accumulator is bunched and accelerated to 4.6 keV on the Ps converter using the direct e⁺ injection scheme developed in 2016, as previously introduced. The e⁺ to Ps target converter is constituted by a Si(111) p-type crystal with nano-channels produced via electrochemical etching and subsequently oxidised in air. Positronium atoms have ~3 eV energy inside the nano-channels of the converter [72] and slow down by collisions with the nano-channel walls before being emitted into vacuum. Positronium formation in 1T is assessed by detecting the annihilation photons on ESDA detector with SSPALS technique, by detecting the time distribution following the e⁺ implantation with one of the scintillators of the ESDA. The measurement is performed by comparing signals produced steering e⁺ bunches on the formation target and on a non-Ps forming surface. Left side of Figure 4.7 shows the averaged time profile of signals from Ps annihilation, the SSPALS spectra, in the Ñ production region. The two curves show the averaged signals for positrons steered on the target, i.e. with Ps production and for positrons steered on a non-converting surface. The production of Ps is inferred from the difference between the two curves, better visible in the inset with a decay time compatible with 1S Ps annihilation in vacuum. The yield of Ps emission over the total number of e⁺ impinging on the target can be estimated from the reduction of the e⁺ annihilation peak (lower bound estimate) and the amplitude of the exponential tail, giving (7.0±2.5)%.

Subsequently, laser excitation to Rydberg states is performed in two steps. First, the n_ps=3 level is reached by means of a broadband UV laser pulse with 205.045 nm wavelength, 1.5 ns duration and ~40 µJ energy. Then, a second synchronized broadband IR laser is used, with pulses 3 ns long, and wavelength tunable from 1680 to 1720 nm, 1.6 mJ energy for the subsequent excitation to Rydberg levels (with n_ps ranging in the interval 14-22). In the conducted SSPALS measurements data acquired with the lasers are compared to those without the lasers, both in presence of Ps. A 3% relative Ps reduction signal is detected when the lasers were present, as shown on the right panel of Figure 4.7. This relative reduction, normalized to the measurements taken without Ps formation, indicates that ~9% of the total available Ps was excited and ionized. The detection of Rydberg-Ps states in magnetic
positronium diagnostics in the 1T region

In 2018, the ability of observing and manipulating positronium was significantly improved by the re-design of the target converter geometry which allowed for the development of a fast and reliable Ps diagnostics.

Figure 4.8 shows the $\tilde{H}$ production region where 4.6 keV positrons reach the target converter to generate a Ps cloud. The idea behind the upgrade of positronium diagnostics is the repositioning of the target holder and consequently the target itself a few millimetres upwards to allow the MCP to collect the positrons emitted from the converter in Ps atoms once detached by laser photo-ionization. The detection of such positrons by the MCP allows to image them and infer the information about position, velocity and evolution of the Ps cloud. The availability of such a technique for Ps study in the production region turned out to be of a fundamental importance for the characterization of positronium during the 2018 data-taking run in which the pulsed production of antihydrogen was demonstrated. Even though a similar idea was proposed in 2017, it could not be implemented at the time because there was no overlap between the MCP visual range and any region of space concerned by the flight trajectories of Ps atoms, where the detached positrons could be collected. The upgrade was fully implemented before the beginning of the 2018 run. As a drawback, however, moving the target upwards to allow the Ps cloud...
to be visible from the MCP reduced the solid angle for the overlap between Ps and $\bar{p}$ clouds.

Importantly, the MCP is capable of detecting particles of both charge signs. For such reason, in addition to antiproton plasma diagnostics and the possibility to detect positrons detached from ionised positronium atoms, the same MCP allowed to take a picture of the hardware surrounding the production region by collecting electrons produced by photo-emission from the surfaces of the metallic structures inside the UHV. Such picture is taken as a reference for the analysis of the Ps cloud. This new detection scheme, dramatically faster and more sensitive than the previously-used external scintillation detectors, allowed us to fully characterize the emission of Ps from our target, to steer the excited portion of the Ps cloud into the trap for interaction with the antiproton plasma and provided a highly efficient background-free shot-to-shot in situ diagnostic of Ps excitation for $\bar{H}$ production.

4.6.1 Positronium converter setup upgrade

Positronium production in 1 T magnetic field and from the 15 K converter was established in AEgIS in 2017 using the SSPALS technique acquiring the digitalised signal of one of the scintillators in the ESDA detector, split in high and low resolution. However, the technique turned out to be quite inefficient and highly time consuming for the detection of Rydberg states of positronium because of significant lacks in diagnostics in the original design of the apparatus, with a reduced solid angle covered by the detector and because of the short time of flight of the photons imposed by the geometry of the experiment. In fact, the acquisition of an amount of data sufficient to establish the presence of Ps*, typically took thousands of runs of perfectly stable Ps production and excitation conditions. Under such conditions, the optimisation and quick diagnosis of Ps excitation for $\bar{H}$ production attempts were quite unimaginable. Furthermore, there was no diagnostics available to detect that the Ps atoms addressed by the laser and excited into Rydberg states were heading towards the $\bar{p}$ plasma. Given the geometry of the experiment, SSPALS technique is not appropriate to diagnose the direction of the fraction of the Ps cloud that has been excited into Rydberg states. The shape of the Ps cloud produced by implantation of positrons in the cryogenic converter is close to a semi-sphere and the geometry of the experiment is such that the cloud is larger than the slit through which the Rydberg-Ps atoms can enter the trap where antiprotons are stored. A small laser bandwidth relative to the Doppler broadening is critical to carefully select the wavelength of the laser to use for excitation and to tune it in order to allow the excited fraction of Ps to enter the slit. In addition, due to the Doppler effect, a small detuning of the laser wavelength could have easily excited Ps atoms that are not heading towards the slit in the production trap. In these cases, no Ps* is able to reach the $\bar{H}$ Trap.

To overcome all these limitations, the Ps target holder was modified to create a gap between the bottom of the converter and the top of the trap’s electrodes so that positrons emitted by photo-ionization of Ps could be accelerated towards the MCP. To make this possible, the MCP was moved 2 mm upwards to match the Ps* flight path where the positrons emitted by photo-ionisation can be collected, making the overall gap 5 mm wide. Visible on the left side of Figure 4.9, a phosphor screen was added on the side of the converter inclined of $45^\circ$ angle to reflect the laser light towards the same external camera that was used to diagnose the laser position. This allowed the development of a technique for measuring the spatial distribution of the Ps cloud in the plane transverse to the magnetic field and parallel to the MCP surface (Sec. 4.6.3). On the other side of the converter, an aluminium FC was added to improve the e’ beam steering. In addition, the target holder was further modified to enlarge the view on the MACOR screen on the background from the camera and a 1.2 mm $\times$ 1.2 mm metallic mesh was added to guarantee electrical neutrality on the ceramic’s surface and to improve the precision in laser positioning.

Finally, minor mechanical modifications were implemented to improve the laser operations. Before the 2018 run, the optical line used to transport the laser light on the Ps excitation area was affected by cryogenic residue growing on the view-ports, preventing a good view of the interaction area, the prisms for laser transport were undersized and no precise diagnostics for the laser position with respect to the trap or the converter was possible. The ordinary view-ports were changed for wedged view-ports
4.6. POSITRONIUM DIAGNOSTICS IN THE 1\text{T} REGION

Figure 4.9: On the left: picture of the modified Ps excitation region as taken with the new CMOS camera from outside vacuum. The two green circles mark the position of two fibres used to complement the laser diagnostics. The lower one is coupled to a photomultiplier whose signal is digitized and used for laser timing diagnostics. On the right: Sketch of the Ps-excitation area. The two-coloured spot marks the laser position of an UV-beam (purple), superimposed with an IR-laser (red) used for Ps excitation. Picture from [75].

to avoid disturbances caused by back reflection on the entrance surface and equipped with heating systems to keep them free of cryogenic deposits. The camera used to image the Ps excitation area was changed for a 12 bit CMOS 1.67 \mu m \times 1.67 \mu m pixel size camera, equipped with a low pass filter cutting everything above 500 nm (for low enough intensity) to avoid damaging the camera and to cut out parasitic reflections.

4.6.2 Development of an imaging technique for fast diagnostics of slow positronium

The main limitation of SSPALS used to diagnose Ps laser excitation in the \( \bar{\text{H}} \) production region is the long measurement time required to reach a signal-to-noise ratio adequate to distinguish the effect of lasers on the Ps sample. This motivated the development of an alternative, faster diagnostic for Ps laser excitation, based on the MCP detector amplifying the charged positrons produced from photo-ionization and field-ionization processes of Ps and guided by the 1.0 T magnetic field. A representation of the working principle of the technique is given in Figure 4.10.

Positronium can be dissociated in two different ways in AE\( \bar{\text{G}} \)IS. Positronium excited to \( n=3 \) level can be laser photo-ionised using both 205.045 nm and 1064 nm pulsed lasers. High Rydberg-Ps states, with \( n>17 \), can be ionised by self-ionization in high magnetic field by self-induced motional Stark electric field acting on the atoms in their co-moving frame of reference [63]. The dissociated positrons and electrons are bound to their magnetic field lines, perpendicular to the MCP surface in the AE\( \bar{\text{G}} \)IS geometry. Positrons are driven to the front face of the MCP with half of the energy difference between that of the photons used for photo-ionization (1.165 eV at 1064 nm) and the binding energy of the ionised state, defined by 6.8 eV/n\(^2\). The initial kinetic energy of the Ps atom, \( \approx 60 \) meV for 10\(^5\) m/s can be neglected in a first approximation. An intrinsic imaging resolution limit is set by the size of the e\(^+\) orbit, which is given by the gyro-radius \( r = \frac{m_e v}{e B} \approx 0.5 \) \mu m field of AE\( \bar{\text{G}} \)IS, much smaller than the intrinsic resolution of the two-staged chevron MCP assembly used here, which is \( \approx 80 \) \mu m according to the manufacturer.

The upgraded Ps target holder, modified with respect to the original AE\( \bar{\text{G}} \)IS configuration, minimized the distance between the lower end of the silicon target and the view volume of the MCP, allowing the lasers to be aligned at a lower position with respect to the positron implantation axis. A constant 10 V/cm axial electric field applied to the nearby production trap electrodes separates the positrons from the electrons in the resulting Ps atoms. To reach the nominal detection efficiency of the MCP for positrons, the MCP metallic front face was negatively biased to \(-180\) V. Instead, the application of an
Figure 4.10: Schematic of the position sensitive Ps detection scheme. Ps is photo-ionised via laser pulses. The photo-e\textsuperscript{-} drifts along the magnetic field lines towards the negatively biased surface of the MCP. This drift conserves the original position of the Ps in the plane parallel to the MCP surface. Picture from [76].

opposite voltage when UV laser is shined on the metallic surfaces of electrodes detaches secondary electrons due to photoelectric effect. Electrons are bond to their cyclotron orbits around the magnetic field lines which are perpendicular to the MCP’s surface. For such reason, they reach the MCP keeping their position in the transfer plane. The resulting picture is shown in the left panel of Figure 4.11. As it can be seen, it represents the production region from the MCP’s point of view in the exact conditions of data taking and, as a result, it can be used as a reference for e\textsuperscript{-} image analyses for Ps diagnostics. In fact, it provides a direct measurement of the size of the different elements, the distance between them and their relative position, under vacuum and at cryogenic temperature. On the right panel of the same picture an application of the secondary electron imaging technique is shown. The picture is made by combining two layers. An electron image (in red) analogue to that of the left panel is shown in background and the acquisition of positrons from Ps ionisation is added in green on top of it. The green layer is actually the result of an average over a scan of the UV wavelength throughout the Doppler profile of the Ps cloud, therefore revealing the whole cloud.

Results obtained with this technique show a signal-to-noise ratio of about $\sim 150$, corresponding to a $\sim 50$-fold gain with respect to the SSPALS technique applied to Ps n = 3 photo-ionization. A single Ps image is obtained averaging 5 images acquired with Ps exposed to UV and photo-ionisation lasers. Typically, the MCP front face is kept at $\sim 180$ V, the MCP back face at $-1.2$ kV and the phosphor screen at $-4.2$ kV. Remarkably, $\sim 10$ min of e\textsuperscript{-} accumulation are required to take one image and assess the presence of Rydberg-Ps, resulting in a 100-fold gain in terms of reduced measurement time compared to SSPALS.

4.6.3 Ps cloud positioning on the transverse plane to magnetic field

The spatial distribution in the plane transverse to the 1.0 T magnetic field of photo-positrons, as imaged by the MCP assembly, is determined by analysing the transition on the edge of the target holder. Top left part of Figure 4.12 shows a the schematic view of the detection system described in the section above and it defines the coordinate system used in this section. The position of the Ps converter, the Ps cloud, laser spot and MCP are indicated. The lasers pulses are shot along the y-axis, transverse to the MCP. An image of the spatial distribution in the plane transverse to the 1.0 T magnetic field ($xy$ plane) of positrons freed by Ps photo-ionisation is shown on the bottom left panel of the figure. The dark region in the upper part (negative-x) is due to the shadow of the target while the bright part below (positive-x) is given by photo-e\textsuperscript{-} reaching the MCP-assembly. The bright signal reproduces, along the y-axis, the distribution of the Ps velocity component $v_{\text{Ps},y}$. The sharp edge of the target is expected to generate a step transition between the two regions. However, in this measurement,
4.6. POSITRONIUM DIAGNOSTICS IN THE 1T REGION

Figure 4.11: MCP electron picture of the production area obtained by shining the UV laser on the trap electrodes. On the left: the simple electron picture, featuring the geometry of the production trap area. The upper square structure is the silicon target; the left white structure is the grid covering the laser alignment screen; the bottom ring structure is the inner radius of the production trap electrodes. On the right: image made of two layers. The red layer is an electron image analogue to that of the left panel. The green layer has been acquired for positrons. Picture from [77].

Figure 4.12: Top left panel: schematic side view of the detection system. A coordinate reference system is indicated. Bottom left panel: image of spatial distribution in the plane transverse to the 1.0 T field (x y plane) of e⁺ freed by Ps photo-ionisation. The border between the dark and the bright regions in the picture corresponds to the lower edge of the converter. The yellow arrow indicates the lasers direction. The intensity profile along the x-axis calculated in the indicated red perimeter is shown on the left of the image. Right panel: Derivative of the intensity profile of the image shown in bottom right panel as a function of x-position in the region indicated in the same picture. The continuous line is the best Lorentzian fit of the data. Pictures from [76].
such transition is smoothed by the spatial resolution of the detector. The spatial resolution can be estimated by analysing the transition from the dark region, with absence of signal, to the bright region, with maximum intensity. The intensity of the image has been integrated over $y$ in the marked region. The obtained plot of the intensity as a function of the $x$-position is reported in the left side of the bottom left panel. The derivative of the intensity profile and its best Lorentzian fit are shown in the right side of Figure 4.12. The transition from the no-signal region to the maximum intensity region has been found to occur in $(88 \pm 5) \mu m$ FWHM. This value is in very good agreement with the expected spatial resolution of the MCP-assembly of $80-100 \mu m$ [78] confirming that this is the main factor in the determination of the overall resolution of the detector.

### 4.6.4 Characterisation of positronium emission from cryogenic target

As an application of the Ps imaging system previously introduced, the results of a scan in UV laser wavelengths are reported on the left side of Figure 4.13. The picture shows horizontal slices of several photo-ionised Ps images acquired with UV laser wavelengths incremented by steps of 0.05 nm. A scan of this type requires only few minutes and it allows monitoring the main parameters necessary for the production of a Ps beam for antihydrogen production experiments with charge exchange reaction. Laser wavelength scan was performed in the range between 204.99 and 205.10 nm, from bottom to top in the picture, keeping the other experimental conditions as above. The left-to-right displacement of the photo-ionised cloud is a function of the selected wavelength. The selection of horizontal velocities is related to the laser linewidth. A limited laser linewidth can only select a fraction of the whole Doppler Ps distribution. Indeed, variations in the UV wavelength allow to perform Doppler selection of Ps with different $v_{Ps-y}$ ranges. The spatial distribution of the bright spots in the figure reflects this velocity selection. By setting the UV pulse on the $1S^{3}P$ transition resonance ($\approx 0$), Ps with roughly null $v_{Ps-y}$, and thus travelling along the $x$-axis, can be selected. The detune of the wavelength induces the selection of Ps with larger $v_{Ps-y}$ component that is imaged in the position $y = v_{Ps-y}t$. Notably, the possibility to make visible the direction of propagation of the fraction of Ps excited to the $3^{3}P$ state allows performing a fine tuning of the central wavelength of the UV pulse to select the velocity component aiming in a specific direction. On the right side of the figure, the evolution of the Ps cloud with respect to the delay time for laser firing is shown. The distribution of Ps velocities could be reconstructed by building a histogram of all the images in the scan of the selected velocities, with the assumption of a point Ps source both in space and time. Quantitative information on the velocity of Ps atoms can be extracted from measurement scans using the position of each pixel with respect to the Ps flight starting point and laser firing time with respect to the $e^{-}$ implantation time to calculate its associated velocity.

### 4.7 Steering Rydberg-Ps clouds towards the antihydrogen production trap

The right side of Figure 4.13 unveils that the population of Ps is selected by the UV laser travels with specific orientation angles with respect to a direction perpendicular to the target, depending on the time at which the laser reaches the Ps cloud. The Ps cloud originates from a point-like source and spreads in a $2\pi$ half sphere moving with a certain velocity distribution until its natural decay. Indeed, the directionality effect is due to the laser excitation - like any deviation from natural behaviour. The directionality observed in the emission of laser-selected Ps cloud is due to a chirp in the wavelength of the UV laser that spreads with $0.01 nm/mm$ over the whole beam profile. In fact, a monochromatic laser detuned off-resonance would have resulted in a straight line heading straight down and horizontally shifted from the emission point. Instead, a linear chirp of the laser in the $y$ direction results in the straight line apparently slightly inclined with an inclination angle depending on the laser firing time. Therefore, atoms in the Ps cloud can be excited to Rydberg states even though they have a non-negligible horizontal velocity component. While flying towards the $H_{trap}^{2}$ perpendicularly from the target, the effect of the transverse velocity components move them in the transverse plane. If the effect
4.8. Rydberg-Ps losses due to motional Stark effect

A reduction of the number of the Ps* atoms available for $^3\text{H}$ formation has to be accounted to the motional Stark effect. The effect is due to the presence of the 1 T magnetic field which causes field
ionisation of high principal quantum number Ps\(^*\) atoms. Due to their motion in the magnetic field, such atoms experience an induced electric field \(\mathbf{\Sigma}_{\text{MS}} = \mathbf{\nu}_{\text{Ps}} \times \mathbf{B}\) responsible for their immediate ionisation [79].

For \(\nu_{\text{Ps}} \approx 1.7 \times 10^5\) m/s the induced electric field reaches \(V_{\text{Ps}} \approx 1.7\) kV/cm and is sufficient to start field-ionizing the atoms with \(n_{\text{Ps}} = 18\) and to fully ionize those with \(n_{\text{Ps}} = 21\) [80]. For such reason, \(n_{\text{Ps}}\) was thus set to 17 during \(\bar{\text{H}}\) production trials as a compromise between field-ionization losses and the \(n_{\text{Ps}}\) gain in the \(\bar{\text{H}}\) formation cross-section [30]. However, field ionisation losses, amount to \(\sim 30\%\) of the total available atoms [75].

The velocity of produced Ps and the fraction of Rydberg-Ps surviving self-ionization caused by motional Stark effects in the magnetic field have been characterized in view of the optimisation of the charge-exchange cross-section. Given the typical time spread of the positron pulse hitting the target of \(<10\) ns, and the Ps cooling time in the target in the order of ten ns [81], the major uncertainty on the time when \(\bar{\text{H}}\) is formed is due to the spread in velocity of the Ps\(^*\) reaching the \(\bar{\text{p}}\) cloud, which corresponds to a spread in the Ps\(^*\) time of flight. With the Ps\(^*\) velocity distribution measured in our apparatus [75] this time is a few hundred ns.

Figure 4.14: Two different delays for the UV and photo-ionisation laser, 20 and 8 ns (yellow and red lines respectively), for two laser-wavelength configurations (left and right side, respectively). A chirp in the UV laser wavelength selects horizontal velocity components different from zero. After a laser-wavelength optimisation procedure (picture on the right), the converging point for all delays is positioned at the edge of the target and directly above the slit and thus the antiprotons, where the laser has its greatest excitation efficiency.
Chapter 5

Pulsed antihydrogen formation and detection

The work described in the previous chapters builds on the experience gained over years of efforts towards the first pulsed production of antihydrogen. This result was first achieved in AEgIS during the 2018 data-taking run, as a main result of this PhD work. The crucial aspect of this accomplishment lies precisely in its attribute of being pulsed. The knowledge of the instant when the antihydrogen is produced, with a few hundreds of ns resolution, is the key to carry out the measurement of gravity validating the proposed scheme [1]. Other methods in use for the production of antihydrogen, in fact, do not allow to trace this information back, only providing a quasi-continuous source of anti-atoms without the possibility to precisely tag the time of formation.

Antihydrogen produced in AEgIS does not get trapped so that after production it is free to drift towards the trap electrodes at the Maxwellian velocity given by the antiproton temperature at the formation time. Detection of antihydrogen formation is the detection of the annihilation of an antiproton on the surface atomic layers of the trap electrodes. Annihilation processes involve either protons and neutrons and result in the production of an odd number of charged pions, detectable by the ESDA and the FACT detectors. However, the latter is affected by the initial positron burst more severely than the ESDA, also due to its proximity to the Ps production region. For such reason, the detection of antihydrogen production is assessed by the ESDA, read out by photomultiplier tubes in a time window around the laser firing time. Nevertheless, the FACT detector provided a cross-check of the antihydrogen formation in the spatial distribution of the axial coordinates of the tracks reconstructed for the same events as those recorded by the ESDA.

In this chapter, I will describe the calibration of the ESDA for the detection of antihydrogen, the datasets acquired for this measurements and the determination of the result. I led most of the data-takings to get the results here presented, as shift leader and run coordinator. I also contributed providing raw analyses, on-line monitoring, detector cross-checks and reference measurements. In addition, I was in charge of the maintenance of the main apparatus during the whole data-taking period. Remarkably, a paper with the results here presented have been submitted to Nature Physics.

5.1 Detection of antihydrogen

Antihydrogen detection in AEgIS was assessed by the use of the ESDA detector, the system of external plastic scintillator slabs operating at room temperature surrounding the experimental apparatus. The scintillators are read out by photomultiplier tubes that are calibrated and equalised to be used as a whole detector with useful segmentation and redundancy to effectively detect single antiparticle annihilations. In addition to a study of the system in different operational conditions and an extensive Monte Carlo simulation, the ESDA periodically undergoes recurring calibrations with cosmic rays to efficiently identify antiproton annihilations over the constant background represented by cosmic rays and
over the strongly time-dependent background due to positrons/positronium annihilations. The energy released by the particle in each scintillator slab can be consistently estimated and with good accuracy by sampling and digitising the analogical signal produced by each photomultiplier tube and analysing the amplitude of the recorded events. As a consequence, an amplitude range for positrons/positronium annihilations can be univocally excluded allowing to exploit the array of external plastic scintillators for tagging antihydrogen annihilation signals.

5.1.1 Detector calibration method

The detection of antihydrogen in AEgIS is, to all intents and purposes, the detection of the annihilation signals produced by the interaction of an antiproton with the surface atomic layers of the inner walls of the trap electrodes. As introduced, the ESDA is devoted to the detection of cosmic rays, pions produced by the annihilations of $\bar{p}$ and $\bar{H}$, as well as $\gamma$ from $e^+$ and Ps annihilations. It is formed of 12 arc-shaped slabs made by EJ-200 (Eljen Technology) general-purpose, fast plastic scintillator. Each slab is 1 cm thick, 10 or 20 cm wide, $\sim$150 cm in length and installed as close as possible to the apparatus, i.e. in contact with the external surface of the cooling vessel at a distance of about 70 cm from the trap axis. This is necessary to maximise the overall solid angle, at about the 20% of the entire solid angle for annihilations inside the $H_{\text{trap}}$. The slabs are connected to independent, fast and high-gain photomultiplier tubes, at both side. Each of the PMTs has a triple magnetic field shielding and it was carefully positioned and tested with the aim of working properly in the external magnetic field. The double connection to photomultiplier tubes is needed to look for the coincidence of signals. This is essential to avoid spurious signals and to have good efficiency in spite of the light attenuation in the slabs.

A deeper analysis on amplitude of the signals was performed as the ESDA has to efficiently discriminate between signals from Ps/$e^+$ and $\bar{p}$ annihilations. Antiproton annihilations typically produce from three to seven pions, essentially minimum ionising particles. In the most frequent case, three charged and two neutral pion are produced (see e.g. [82]). Photons from Ps/$e^+$ annihilations, instead, produce Compton electrons in the material between the annihilation point and the scintillator, or inside the scintillator itself. The energy release in the scintillator is much smaller than the 511 keV taken as higher limit for simple $e^+$ annihilation. Hence, the application of a energy threshold could be considered as a simplest solution, relying on the proportionality of photomultiplier tubes. In fact, when the photomultiplier is in linear regime, i.e. far from the saturation as it was in the measurements here discussed, there is a direct proportionality between the energy released by the charged particle in the scintillator, the scintillator light yield and the PMT signal amplitude [65]. For the sake of completeness, however, proportionality does not hold for electrons below $\sim$100 keV and for other particles and energies irrelevant in our context. An attenuation length of 120 ± 10 cm was measured inside each slab implying a factor of $\sim$3 for the whole slab length. Such strong light attenuation causes a large uncertainty in the signal amplitude produced by the PMTs. The application any kind of method based on a threshold for single PMTs would turn out impractical.

For the reason above, a method based on the equalisation of PMT gains from the cosmic ray signals acquired in coincidence has been implemented and described in next sections. The average of the signal amplitudes collected by the two photomultiplier tubes connected to the same slab was adopted as the best proxy for the energy released in the scintillator to compensate for the light attenuation effect. Several dedicated data taking campaigns on intentional antiproton dumps on the trap electrodes and on Ps production allowed to establish a signal amplitude value to be taken as a threshold. For signal due to positrons, the full analogical signal produced by each of the two PMTs was acquired as a function of time, through a 12-bit-resolution 250-MHz-sampling-rate CAEN V1720 Flash ADC Waveform Digitizer [83] for a time window of 1 ms after the $e^+$ light burst. With the aim to identify events with an amplitude too high to be produced by $e^+/Ps$ annihilation, an off-line analysis was performed through the average method on positron annihilation data. Recorded events can be due to antiproton annihilations or related to the cosmic ray background. Considering that the latter is known and measured very well, the
number of antiproton annihilations could be inferred.

5.1.2 Cosmic rays background

Cosmic ray data were acquired by a CAEN V792 Charge-to-Digital Converter (QDC, [84]), integrating the PMT current over a ~70 ns window. The acquisition was triggered by the coincidence between two PMTs reading slabs in top-down configuration, i.e. one above and the other below the cryostat. Coincidence counts between two PMTs have been considered in order to have a better detection efficiency of cosmic rays. The corresponding distribution is shown in the left panel of Figure 5.1. The same configuration was reproduced in a Geant4 simulation and shown in the right side of the figure. The simulation demonstrates that the distribution of the energy deposited inside the scintillator is close to a Landau distribution with a maximum around 2.1 MeV.

Due either a few background events or some non-ideal behaviour not included in the simulation, the experimental spectrum corresponding to the top-down configuration (left side of Fig. 5.1) exhibits a second peak at low QDC counts. The spectra taken with the QDC with the coincidence of two PMTs reading the same slab are shown in the inset in the left side of the Figure 5.1. The peak due to the cosmic rays is clearly visible. A significant contribution at lower energies is also present. Remarkably, the latter is presumably caused by natural radioactivity in the experimental area. A number of calibrations was performed to assess that a signal with 1 mV peak amplitude gives around 0.2 pC of integrated charge in the ESDA. The charge collected by the QDC have to be doubled to get the real charge value as measurements with the QDC need an extra splitter at the end of photomultiplier. For example, 1 mV in the left sides of Figs 5.1 and 5.3 would correspond to 0.1 pC, i.e. 1 QDC count. From the distribution in the plot, it is possible to infer that ~70% of the events recorded are not due to real cosmic rays but rather to the natural radioactivity background, e.g. $^{40}$K - now under further investigation. Furthermore, this may also clarify why the rate of events recorded by a typical 10-cm-wide slab is ~65 Hz, while it is expected a flux of cosmic rays of ~20 Hz.

5.1.3 Positron burst and background from remnant positronium atoms

For the photon background, data were acquired just letting the positrons impinge on the $e^+$ to Ps converter without antiprotons in the apparatus.

As anticipated, when the positron bunch impacts the converter target to form positrons, a flash
Figure 5.2: Distribution of the average peak amplitudes simultaneously recorded in the coincidence of the two photomultiplier tubes connected to the same scintillator slab. On the left: experimental results. On the right: Monte Carlo simulation. Pictures from [85].

is generated from the annihilation of the positron fraction that is not converted. This is the reason why the detectors in the antihydrogen production region get blinded for a considerably long time. In particular, such a signal gives rise to PMT after-pulses for several tens of nanoseconds. The first hundred of nanoseconds are therefore skipped in the analysis of the measurements for this calibration.

Figure 5.2 shows the analysis of digitised data of the coincidence of the two photomultiplier tubes connected to the same scintillator slab, as in the antihydrogen production measurements. The plot on the left panel shows the distribution of the values obtained averaging the peak amplitudes measured by the two photomultiplier tubes connected to the same slab and summed up over all the slabs. Acquiring a large statistics, with $\sim 10^5$ annihilation signals per trial, the signal due to positrons never exceeds 250 mV on the ESDA. Cosmic rays passing through the slabs are accounted as one event over $10^4$ γ ray signals, in a conservative estimation. Results are in fair agreement with the Monte Carlo simulation, displayed on the right panel of Figure 5.2. Simulations for positronium have not been carried out as photons produced in the Ps decay cannot have energies higher than 511 keV. On this respect, the procedure adopted is conservative and the results are still valid.

5.1.4 Background from antiprotons

Data for the determination of the ESDA response to antiprotons are acquired in runs in which antiproton were intentionally dumped on the electrodes of the production trap with controlled losses induced on the trapped plasma. Losses were produced by means of the RW technique with an adequate choice of parameters. Antiproton annihilations are recorded at a rate much higher than cosmic rays. Special attention was given in preventing the PMTs from discharge effects. This is done avoiding too high rates, with simultaneous annihilations of more than one antiproton on a 10 ns time scale. In a typical run dedicated to this measurement, all the antiprotons available from a single AD shot ($10^5$) annihilated in a fraction of a second, giving rise to an annihilation rates per slab of some hundreds of kHz, corresponding to some tens of kHz per slab. At higher rates non-linearities in the detector response started to arise.

Like for positrons, the measurement was carried out with the digitiser. In the case of cosmic rays, instead, data were acquired using a QDC. A compatibility check with the QDC was performed in the measurement of antiprotons, confirming comparable results. The distribution of the average of the peak height amplitudes for signals recorded in coincidence by the two photomultiplier tubes connected to the ends of each slabs is shown in Figure 5.3, left panel. Remarkably, the distribution obtained averaging the signal of each couple of PMTs was checked to be compatible with the overall distribution,
confirming the validity of the calibration-equalization procedure. The right panel of the figure shows the result of a simulation on the same measurement. The experimental and the simulated distributions are in very good agreement. The low-amplitude component, present both in data and simulation, is probably due to a background present in the AD hall and quite similar to that already visible in the distribution for cosmic rays. The structure at higher energies, instead, is most likely due to MIP interactions.

5.2 Antihydrogen signal

Antihydrogen signal is only expected with the combination of all the ingredients in place for the formation as described in the above chapters, i.e. antiprotons stored in the $\bar{H}_{\text{f}}$ Trap in good conditions for the production, positrons hitting the target at each production cycle and laser fired at the right timing. Typically, 20-30 positron pulses are sent on the $e^+$ to Ps converter. A $\bar{p}$ plasma is trapped in the $\bar{H}_{\text{f}}$ Trap for macroscopic times, over several positron implantations. Every positron implantation in the converter corresponds to a production cycle, $\bar{H}_{\text{cycle}}$. Antihydrogen production runs have been acquired keeping the same antiprotons cloud in the production trap while sending positrons to the target at each cycle.

Data have been acquired in production and background data sets divided in turn in several data subsets, as indicated in Table 5.1. Nomenclature for the distinction of subsets is the dataset name followed by a three digits index indicating the $\bar{H}$ components in place for the measurement, that is $\text{DatasetName}[\text{ifAntiprotons, ifPositrons, ifLasers}]$, in descending order of mass at rest of the particle. The only one data subset where a antihydrogen signal should be found is the Prod$[111]$, acquired in $\bar{H}$ production runs, with antiprotons, positrons and lasers in place. Ordinary $\bar{H}$ production run includes a number of cycles determined according to several factors previously described. Every positron implantation in the converter corresponds to a production cycle, $\bar{H}_{\text{cycle}}$. Antihydrogen production runs have been acquired keeping the same antiprotons cloud in the production trap while sending positrons to the target at each cycle. Laser in nominal conditions for Ps excitation was fired alternated between cycles Prod$[111]$ data set refers to data acquired in cycles when laser was shined, Prod$[110]$ data set are acquired without the laser. A background data set (Bkg$[101]$) was acquired keeping antiprotons stored in the trap and firing the laser without sending positrons. All other data subsets indicated in Table 5.1 have been acquired and resulted negligible.

A candidate $\bar{H}$ signal is defined by the time coincidence of two pulses detected at the two ends of any of the scintillators composing the ESDA. Two time coincident pulses are a candidate $\bar{H}$ signal if
their mean amplitude is above a given threshold \( V_{min} \). The laser firing time is defined as \( t=0 \) The time window for the coincidence is indicated as \( \Delta T^{\text{signal}} \). It begins after a time \( T_{min} \), since the \( t=0 \). The distribution of such signals is given in Figure 5.4. Figures 5.5 and 5.6 indicate the most background detected corresponding to datasets Prod[110] and Bkg[101] respectively. Figure 5.7 shows the comparison between counts corresponding to the Prod[111] and Bkg[101] data sets, with the counts normalised to the number of antiprotons available in Prod[111].

The values for the thresholds \( T_{min} \) and \( V_{min} \) are selected as a compromise between the detection efficiency and the level of the background due to the positron induced signals. The number of candidates in the Bkg[010] data set is statistically consistent with that expected from cosmic rays, i.e. \((1.94\pm0.03)\cdot10^{-4} \) counts/\( \mu \)s, for \( T_{min}=1 \) \( \mu \)s, \( V_{min}=250 \) mV and considering \( \Delta T^{\text{signal}} \) of some \( \mu \)s. Therefore, the background induced by the positrons signal (i.e. Bkg[010] and Bkg[011] datasets) is negligible. A signal region (hereinafter S) can be defined as the time window \( \Delta T^{\text{signal}} \) between \( \sim 5 \) \( \mu \)s and \( \sim 25 \) \( \mu \)s. Correspondingly, a control region C will be defined between -101 and -1 \( \mu \)s and 50 and 550 \( \mu \)s. The control region has a total length of 600 \( \mu \)s, while the length of the signal region can be varied. All the plots in Figure 5.7 show the time distribution of the coincident pulses. Thresholds are set as \( V_{min}=250 \) mV and \( T_{min}=1 \) \( \mu \)s. The time window considered for the three data sets (Prod[111], Prod[110], Bkg[101]) is the whole 650 \( \mu \)s interval. The afterglow contribution from the positron burst was found negligible. The number of counts was assumed to only include the contributions from cosmic rays, \( \bar{p} \) annihilations as well as any \( \bar{H} \) annihilations.

Given all the above considerations, the \( \bar{H} \) signal was searched as a number of events in excess in the signal region with respect to the average value of the events in the control region, in the Prod[111] data set. The comparison between the plots acquired in the Prod[111] and Prod[110] datasets is shown in Figure 5.4 and Figure 5.5. Comparing the plots, the presence of such expected excess in a signal region few tens of \( \mu \)s long is clearly visible.

Figure 5.6 also shows an excess of counts in the signal region with respect to the mean value of counts in the control region in the Bkg[101] data set. Remarkably, data shown in the figure have been acquired for a larger number of trials than for the Prod[111] data set. These counts are induced by laser interaction with antiprotons. Unlike background from cosmic rays and continuous annihilations of antiprotons which have a constant rate, counts in the Bkg[101] data set are time-dependent and represent the only relevant background in the measurement. The signal can be interpreted as annihilations of \( \bar{p} \) following the desorption of gas from the cryogenic walls hit by the laser. Importantly, the laser is repeatedly fired with a 10 Hz frequency into the vacuum chamber in a time window starting several seconds before the \( e^- \) injection on the target.

Considering the sample Bkg[101], in the signal (S) and in the control (C) regions the measured

<table>
<thead>
<tr>
<th>Production data set</th>
<th>Antiprotons</th>
<th>Positrons</th>
<th>Lasers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prod[111]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Prod[110]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Background data set</th>
<th>Antiprotons</th>
<th>Positrons</th>
<th>Lasers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bkg[101]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Bkg[011]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Bkg[100]</td>
<td>✔</td>
<td>✔</td>
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</tr>
<tr>
<td>Bkg[010]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Bkg[001]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Bkg[000]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

Table 5.1: Different data sets acquired and analysed to assess the result presented in this chapter. Antihydrogen production is expected in the Prod[111] dataset. Bkg[000] dataset corresponds to the acquisition of the environmental background.
5.2. ANTIHYDROGEN SIGNAL

Figure 5.4: Time distribution of ESDA distribution of the coincident pulses with mean amplitude above 250 mV, detected after 1 μs from the laser firing time for the Prod[111] data set.

Figure 5.5: Time distribution of ESDA distribution of the coincident pulses with mean amplitude above 250 mV, detected after 1 μs from the laser firing time for the Prod[110] data set.

Figure 5.6: Time distribution of ESDA distribution of the coincident pulses with mean amplitude above 250 mV, detected after 1 μs from the laser firing time for the Bkg[101] data set.
number of counts \( n_{[101]}^S \) and \( n_{[101]}^C \) can be written as

\[
\begin{align*}
  n_{[101]}^S &= (n_\mu + n_{\text{trap}} + n_{\text{gas}})_{[101]}^S \\
  n_{[101]}^C &= (n_\mu + n_{\text{trap}})_{[101]}^C.
\end{align*}
\] (5.1a)

In the relations above, \( n_\mu \) and \( n_{\text{trap}} \) indicate the number of counts from cosmic rays and antiproton annihilations in the trap, not related to the presence of the laser. The quantity \( n_{\text{gas}} \) is the number of counts due to the annihilations of antiprotons with the laser induced desorbed gas. It is worthy to note that the laser induced background \( n_{\text{gas}} \) disappears 50 \( \mu \)s after the laser pulse. For such reason, the contribution is not included in Eq. 5.1b.

Considering that the number of counts due to losses induced by laser is proportional to the number \( N_{[101]} \) of trapped \( \bar{p} \) by a factor \( \epsilon \), i.e. \( n_{\text{gas}} = \epsilon N_{[101]} \), the proportionality factor can be determined starting from the relations in Eq. 5.1, taking into account that \( n_\mu \) and \( n_{\text{trap}} \) are proportional to the duration of the time interval of evaluated as

\[
\epsilon = \frac{1}{N_{[101]}} \left( n_{[101]}^S - n_{[101]}^C \frac{\Delta T_{\text{Signal}}}{\Delta T_{\text{Control}}} \right)
\] (5.2)

To estimate the number of counts \( n_{\text{exp}}^S \) expected in the \( S \) region in absence of \( \bar{H} \) production in the Prod[111] data set, it has to be considered that

\[
\begin{align*}
  n_{[111]}^S &= (n_\mu + n_{\text{trap}} + n_{\text{gas}})_{[111]}^S + n_H \\
  n_{[111]}^C &= (n_\mu + n_{\text{trap}})_{[111]}^C,
\end{align*}
\] (5.3a)

where \( n_H \) is the number of counts due to \( \bar{H} \). The total number of \( \bar{p} \) in the data set Prod[111] is \( N_{[111]} \). Therefore, the number of counts expected in the signal region \( n_{\text{exp}}^S \) can be determined, recalling the proportionality between \( n_{\text{gas}} \) and \( N_{[111]} \), and using the expression of \( \epsilon \) from Eq. 5.2, as

\[
\begin{align*}
  n_{\text{exp}}^S &= \left[ n_{[111]}^C \frac{\Delta T_{\text{Signal}}}{\Delta T_{\text{Control}}} + \left( n_{[101]}^S - n_{[101]}^C \frac{\Delta T_{\text{Signal}}}{\Delta T_{\text{Control}}} \right) \frac{N_{[111]}}{N_{[101]}^S} \right].
\end{align*}
\] (5.4)

The total number of interacting antiprotons in the Bkg[101] data set is greater than that in the Prod[111] data set \( (N_{[111]} = 1.08 \times 10^9, N_{[101]} = 1.58 \times 10^9) \). This is discussed in Sec. 5.2.2.
The absence of $\bar{\text{H}}$ signal ($n_{\bar{\text{H}}} = 0$) in the sample Prod[111] is the null hypothesis considered to quantify the evidence of $\bar{\text{H}}$ formation. If the null hypothesis is true, the number of counts $n_{\text{exp}}^5$ should be expected in the signal region of the Prod[111] data set. The number of counts $n_{\text{exp}}^5$ corresponds to the signal due to the cosmic background, $\bar{p}$ losses measured in the control region (rescaled to the counts in the signal region) and the additional $\bar{p}$ losses due to the laser desorbed gas. Hence, $n_{\text{exp}}^5$ would be statistically compatible with $n_{[111]}^5$. In a 25 $\mu$s long signal region which extends from 1 to 26 $\mu$s after the laser pulse, the measured number of counts is $n_{[111]}^5 = 79.0$ while $n_{\text{exp}}^5 = 33.4 \pm 4.6$. Thus, a $p$-value of $6.6 \cdot 10^{-7}$ is obtained and the hypothesis of the absence of signal is rejected with 4.8 $\sigma$ (local significance). The number of counts above background and the significance of the signal above 4 $\sigma$ are robust against variations in the choice of the width or offset of the S interval. The number of detected antihydrogen atoms in the 25 $\mu$s wide S region is $45.6 \pm 10.0$. Taking into account the detection efficiency, this corresponds to a number of

$$N_{\bar{\text{H}}} = 110 \pm 25$$  \hspace{1cm} (5.5)

produced atoms. This number is in good agreement with the prediction of a dedicated Monte Carlo (described in Section 5.2.3) in which the Ps excitation process is modelled, all geometrical details of the interaction region are included, as well as the number and shape of the antiproton plasmas, the number of Ps and its measured velocity. The cross section used for the simulation is that found in [30].

The temporal evolution in the plots shown in this section is longer than expected if the only relevant parameter was the $\bar{p}$ temperature mentioned in Chapter 3. Antihydrogen formation between $\sim$400 K temperature $\bar{p}$ and a burst of Ps* with range of velocities discussed in Chapter 4 should result in a few $\mu$s wide signal. The experimental range of velocities, instead, extends up to 25 $\mu$s. The investigation of this effect in deeper detail was not possible due to the small size of the sample. The background signal at late times can be the result of several factors. It can be due to the presence of a small fraction of excited positronium slower than $10^4$ m/s, or due to an antiproton temperature lower than expected in the $\bar{p}$ cloud. Both of these effects are reasonable and would result in an enhanced signal at later than expected times. Another possible explanation is related to the possibility that the Rydberg $\bar{\text{H}}$ atoms could be reflected from the electrode metallic surfaces. The trap electrodes in the production trap are gold plated and negative values of the positron work function in case of gold are reported in the literature [86]. The interaction of a Rydberg-excited antihydrogen with a metallic surface is mainly due to the electrostatic interaction with its induced image charge. The dipole of a Rydberg atom is large enough to induce a charge polarization effect in a metallic bulk. The so-formed induced effect results in an attractive net force [87]. At the smaller end of the range of separations the influence of the image charge interactions becomes stronger, and the positron could potentially be able to pass over or tunnel through the potential barrier into the conduction band producing annihilation. A negative value of the positron work function could reflect the positron back from the electrode. In this case, the whole Rydberg atom can be transported with it. This would be the antimatter counterpart of the reflection of Rydberg matter atoms from negative electron affinity surfaces described in [88].

5.2.1 Monte Carlo simulation

A dedicated Monte Carlo (described in [89]) was developed to model the main physical processes in the experiment. Notably, it includes the full 3D geometry of the e$^-$ to Ps converter and of the antiproton trap region. In the simulations, a ortho-Ps cloud was generated from the e$^-$ impinging estimated positron on the target, with appropriate Ps spatial and temporal spread. The amount of formed positronium is taken as input from measurements as well as its cooling in the target. Positronium atoms have a given velocity randomly extracted from the experimental distribution reported in [75]). Each atom is then propagated along a straight line with its standard lifetime in vacuum unless it reaches some mechanical surface.

The interaction with the laser pulses is simulated to reproduce Rydberg excitation. UV laser parameters play a more significant role in Ps excitation than those of the IR laser. UV laser parameters,
the relative timing to the average Ps emission time, are taken into account with the measured (two-
dimensional Gaussian) spatial intensity and temporal profile. As the pulse length is relatively short if
compared to the typical motion of each Ps in that time, the Ps cloud can be considered frozen at the
moment of the laser pulse so that some of the Ps atoms are subsequently excited to the Rydberg level
$n_{\text{Ps}}=17$. Each Rydberg-Ps atom is then propagated along the original trajectory with unchanged velocity
(recoil effects are neglected, as well as the influence of the magnetic and electric fields) until it reaches a
mechanical surface or interacts with the $\bar{p}$ plasma.

In typical experimental conditions, simulations indicate that $\sim 10\%$ of the Ps atoms reach Rydberg
states, in agreement with measurements. A fraction of $\sim 10\%$ of the generated Ps atoms can pass
through the antiproton plasma simulated with the mean values of the expected position, number, size,
density and temperature. The average interaction probability found is $5 \cdot 10^{-5}$ per single Ps* atom
traversing the antiproton cloud. This takes into account the charge exchange probability through the
charge exchange cross section in [30]. Considering $2 \cdot 10^6$ e$^+$/cycle (providing $1.4 \cdot 10^5$
Ps/cycle), the number of Ps* traversing the $\bar{p}$ cloud is $\sim 1.4 \cdot 10^3$ and the number of expected $\bar{H}$ is $\sim
0.07/\bar{H}_{\text{cycle}}$. Therefore, with 2206 production cycles, the expected total number of produced $\bar{H}$ is $\approx 100$,
in agreement with the observation.

5.2.2 Error budget

Assuming a Poisson distribution, the standard deviation on $n_{\text{Ps}}^E$ is its square root. The uncertainty
on $n_{\text{Ps}}^{\text{exp}}$ was estimated by propagating the errors in Eq. 5.3. The standard deviations on $n_{\text{Ps}}^E$ and $n_{\text{Ps}}^C$
are again the square roots of themselves. The most significant error is that on $n_{\text{Ps}}^{\text{exp}}$, with
$n_{\text{Ps}}^{\text{exp}} = 42$. All the other contributions are negligible.

As described in the above sections, $N_{\text{Ps}}^{111}$ and $N_{\text{Ps}}^{101}$ represent the sum over all the $R_{\text{cycle}}$
of the number of antiprotons in the two data datasets. The number of survival antiprotons at the end
of each run, after several production cycles, was measured by emptying the trap and counting the
annihilation pions on the ESDA. The number of antiprotons initially available in the trap is estimated
from the proportionality between the $\bar{p}$ losses detected during the transfer from the P-Trap to the
$\bar{H}_{\text{trap}}$ (discussed in Chapter 3) and the number of $\bar{p}$ left in the $\bar{H}_{\text{trap}}$ that was available for the first
$\bar{H}$ production cycle. Such proportionality was verified in a series of dedicated measurements at the
beginning of the 2018 year run. Thus, the number of antiprotons available at each cycle is determined
by knowing the initial and final number of $\bar{p}$ and assuming an exponential loss with time. Instead,
assuming that losses linear in time, results in a systematic error of 3.5% on the measurement of both
$N_{\text{Ps}}^{111}$ and $N_{\text{Ps}}^{101}$. Statistical uncertainties are negligible. The total uncertainty on $n_{\text{Ps}}^{\text{exp}}$ was estimated
by using a Monte Carlo method which also took into account the correlation between the systematic
uncertainties on $N_{\text{Ps}}^{111}$ and $N_{\text{Ps}}^{101}$.

5.2.3 Antiproton losses induced by laser

As described in Chapter 2, the environment surrounding the $\bar{H}_{\text{trap}}$ is pumped down to pressures
better than $10^{-15}$ mbar and cooled down to 10 K during the preparatory phase of the experiment. Then,
it is kept in such conditions for many months until the end of the year run. All the cold surfaces
act as effective cryo-pumps, resulting covered by several layers of molecules of the residual gas. This
mechanism ensures an extremely high vacuum, as needed for the survival of cold antiprotons for hours.

In each antihydrogen production run, the two lasers are fired at 10 Hz inside the apparatus starting
from fifteen seconds before the $e^+$ implantation in the target. Both UV and IR lasers hit the MACOR
screen covered by a metallic mesh that is mounted in close proximity to the electrodes of the produc-
tion trap for the diagnostics of the position and size of the lasers, as illustrated in Chapter 4. The laser
pulses are known to induce desorption [90] of the molecules adsorbed within the area of the laser spot
($\approx 12 \text{ mm}^2$). Molecules freed in this way fly outwards from their desorption point and hit other cold
surfaces with a high probability to be re-adsorbed. Before being adsorbed again, they produce a local extra density of gas in the region around the point hit by the laser. This extra density of gas $d_g$ can be roughly estimated as the number of extracted molecules divided by a suitable volume $V_g$ of some cm$^3$. The number $\Delta N_\beta$ of $\bar{p}$ annihilating in a time $\Delta t$ due to the interaction with this residual gas is given by

$$\Delta N_\beta = N_\bar{p} \cdot d_g \cdot \sigma \cdot \nu_{rel}^{rel} \cdot \Delta t. \quad (5.6)$$

Here, $\nu_{rel}^{rel}$ indicates the relative velocity between the antiprotons and the desorbed gas and $\sigma$ the annihilation cross-section. Relation 5.6 shows that the laser induced losses are proportional to the number of antiprotons, as mentioned in Sec. 5.2.

Although a precise estimation of the extra density of gas $d_g$ can be complicated, a rough estimation of the range of the relevant quantities gives compatible results with the antiproton losses observed in the Bkg [101] dataset. Considering the total number of cycles, the contribution is of the order of one antiproton per $\mu$s during a time interval of few tens of microseconds. As a reference, it can be assumed that the laser pulses extract almost all the gas from the surface, that the adsorption sites are some $10^{14}$ or $10^{15}$ per cm$^2$, that the adsorption sites are occupied by hydrogen, nitrogen and water [92] and that during the time between successive pulses ($0.1$ s) a fraction of the order of $10^{-5}$ of a mono-layer is formed and extracted, giving $d_g \approx 10^7$ cm$^3$. Considering a volume $V_g$ of few tens cm$^3$, with $\nu_{rel}^{rel} \approx 10^6$ m/s, $\sigma \approx 10^{-16}$ cm$^2$ [92] and $N_\bar{p}=1.58 \cdot 10^8$, a number $\Delta N_\beta \approx 1$ in 1 $\mu$s is obtained.
Chapter 6

The AEgIS Low Energy Antiproton Facility

According to the original AEgIS proposal, the Collaboration plans to measure the gravitational interaction of antimatter using a cold, pulsed beam of antihydrogen. Such beam is expected to be formed using an inhomogeneous electric field. Antihydrogen atoms would be moved via Stark acceleration toward a classical moiré deflectometer [93]. The antiatoms passing through the deflectometer annihilate on a position-sensitive detector, forming a fringe pattern. The gravitational acceleration on antihydrogen can be inferred from the shift of patterns formed from the annihilation of different horizontal velocities $\bar{\text{H}}$ beams. A major upgrade of the original proposal of the experiment is going to be submitted at the time this thesis is being written. The gravity module of the experiment is to be redesigned including the detection system and its electronics. However, detectors to be used for such a measurement have to be able to resolve the vertical displacement in the arrival position of antihydrogen atom. The detector surface serves as annihilation target. The hitting position has to be reconstructed through the detection of the annihilation products.

A dedicated low energy antiproton test stand facility was built with fully electrostatic optics to provide slow antiprotons of known energies while minimizing the background produced by the annihilation of faster antiprotons in order to test various detection technologies. Activities on such test line run symbiotically with the main experiment, favouring the optimisation of the antiproton time in the experiment. The antihydrogen’s temperature will be one of the most critical parameters as it directly puts constraints on the resolution required for the final detection system. The optimization of any detection techniques towards this goal requires detailed tests to be carried out in conditions as close as possible to those expected for the final configuration of the experiment.

I carried out a simulation with realistic parameters has been carried out based on pre-existing work [94] to provide an estimation of the beam parameters required for experiments with detector exposed to low-energy antiprotons, including the continuation of detector tests of antihydrogen detector candidates. A summary of the main detector test carried out over the last years is reported. Particular attention has been given to tests of the Timepix3 pixel detector as a candidate for the position detector in the gravity measurement [95]. Motivations that lead to the building of the test line are briefly explained in Section 6.1 while hardware details are discussed in Section 6.2. A simulation which tracks the particles from the end of the AD line through the branches of the test stand vacuum chamber is described in Section 6.3. Finally, in Section 6.4 an overview of the main detector test activities is reported.

6.1 Motivations

In principle, detector tests in a test chamber directly connected to the AD pipe or inside the AEgIS main apparatus could be possible. The AD delivers bunches of $3 \cdot 10^{6}$ antiprotons at an energy of 5.3 MeV every 110 s. This number could be increased or reduced by using the trap system of the experiment. An ad-hoc degrading system designed to be easily tunable could provide an energy reduction of the
particles and could adjust the intensity of the beam. The number of antiprotons reaching the target could also be selected by changing the thickness and the composition of the degrader foils. However, despite all the possible efforts, it would not be possible to achieve the precision to select particles one by one. In addition, a significant fraction of the antiprotons passing through the degrader would annihilate, with the effect that the products of annihilations would disturb the measurements on the detectors to be tested.

With a dedicated beam-line, instead, it is possible to provide slow antiprotons of known energies while minimizing the background produced by the annihilation of faster antiprotons. In order to slow the antiprotons down to energies of a few keV, thin foil moderators are used, while a more efficient energy selection of the particles is achieved by the shape of the final section of the line, which is split in two branches.

### 6.2 Hardware overview

The AEgIS low energy antiproton facility beam-line is situated in the AEgIS experimental zone at the end of the AD extraction line. It is composed of a system of tunable degraders, a vacuum chamber and a detector test chamber. The AD extraction line is closed with a titanium window which acts as a first degrader. The closing window of the AD extraction line and the vacuum chamber are separated by a 6 cm thick air gap in which a system of tunable-thickness aluminium degrader foils can be placed.

A CAD representation of the test stand facility beam line is given in Figure 6.1. The line consists of two vacuum chambers, one following the direction of the AD injection pipe into the experimental area and the other tilted 40° with respect to the main line of the chamber. At its beginning, the line has a circular titanium window with a thickness of 25 μm and a diameter of 4.0 cm that allows the antiprotons to enter and provides an additional (and final) degrading of the beam. The beam-line is built up of several Einzel lenses [97] that focus the beam without altering its energy. Three lenses focus the beam, two on the straight part of the line and one on the bended section. Two electrostatic bending electrodes are set to deflect the beam towards each of the two end-plates of the beam-line and provide the energy selection. The variable-thickness aluminium degrader can be placed in the air gap between AD and the test beam-line to further reduce the energy of the beam.
As indicated in Figure 6.2, detectors to be tested can be installed on four different positions, each with different exposure to the beam. Positions are:

1. the end of the AD line,
2. the beginning of the detector stand facility beam line,
3. the straight end-plate,
4. the bended end-plate.

The definition of four installation positions allows for the availability of different energy ranges and fluxes of incident antiprotons. Arrival position and energy deposit are distributed differently on every surface. It is possible to place the detectors anywhere on each of the four surfaces labelled in Figure 6.2, depending on the aim of the measurement, on the characteristics of the detector and on the structure of its support. The variable degrader and the voltages on the electrodes can be manually tuned. To this purpose, best settings to maximise the number of antiprotons of energy below ~10 keV on position 4 were 33 µm of degrader thickness, 3 kV of bending voltage and a focusing voltage between 3 and 4 kV on each of the Einzel lenses.

The picture on the left side of Figure 6.3 shows the beam-line at the end of one of the extraction points of the AD before the detector chamber is mounted. The detector chamber is installed on the open flange on the left. Two Einzel lenses for focusing and a pair of deflection electrodes guide the low-energy antiprotons towards the detector. They are installed at the entrance of the straight line and at the beginning of the bent branch of the vacuum chamber and are shown in detail in Figure 6.4. The electrodes of the electrostatic deflector are also visible on the left side of Figure 6.4. The degrader thickness and the electrode voltages can be tuned manually to achieve the optimum conditions for the experiment to be performed.

6.3 Simulation

A full simulation with realistic parameters ans based on pre-existing work [94] as well as on the GEANT4 tool kit and on the Ion Beam Simulation C++ library [98] was carried out in two steps. First, a realistic beam at the entrance of the beam line is simulated in GEANT4 tracking the 5.3 MeV antiprotons released by the AD towards the entrance of the detector stand beam line. The path between the AD window and the entrance of the line is in air and it includes the AD window, followed by an air gap of
6 cm where a 33 μm thick aluminium degrader is placed. Then the beam is tracked up to the 25 μm titanium layer that shields the vacuum of the line. The aluminium degrader can be tuned by varying its thickness and position at each experiment, or it can be removed. The output of this simulation is the position and the momentum of antiprotons right after they passed the titanium window to the detector test stand line. As an example, a visual output of the simulation of 100 antiprotons coming from the AD is shown in Figure 6.5. The three vertical surfaces represent the exit of the AD line, the degrader foil and the entrance of the detector test stand line, respectively. In this example, the sensitive surface of the detector is placed at the entrance of the test stand beam line.

Once the beam entered the line, it is simulated via a 3D simulation written in C++ using the IBSimu library. It takes into account the geometry of the beam line including the Einzel lenses and the electrostatic bending electrodes that are installed inside. The voltages set on the Einzel lenses and bending electrodes are input parameters. Once the geometry of the optics and each of the voltages are set, the resulting electric field driving the particles is calculated by solving the Poisson equation numerically using the finite difference method. The simulation tracks the beam through the optics of the beam-line. The momentum of all the particles is known at any point along its track and, therefore, one can extract the flux and the energy distribution on the detector for all the experiments to be carried out in the line.

The simulation is carried out for all of the four positions indicated above. It reads the output of the Geant4 simulation as a list of the particles of the beam. Each particle is defined by its charge, energy, position and angle. The particles are then tracked considering the geometry of the line and the fields produced by the electrodes. The trajectories through the line and towards the four detection points are thus determined.
6.3. SIMULATION

Figure 6.5: A graphic output of the GEANT4 simulation of the path between the end of the AD line through the entrance of the detector test stand line, in air. The three layers represent the exit of the AD line, the degrader foil and the entrance of the detector test stand line, respectively.

Figure 6.6: Two different views of the output of a realistic simulation with $3 \cdot 10^7$ particles. Electrodes and lenses were set to direct particles towards the end of the bended line. In the picture on the right, the blue line indicates the geometry of the chamber at the intersection of the two lines. Particles are tracked up to the end of the line.

6.3.1 Results

The simulation described above models a run for a realistic antiprotons beam from the AD. Four different experimental conditions were simulated. All the simulations include the 33 μm aluminium degrader to decelerate the beam. Of course, the presence of the degrader does not affect the output of the simulation in Position 1.

The analysis of the output of the simulation is shown in the plots in Figure 6.7 for Position 1 (end of the beam line), Figure 6.8 for Position 2 (at the entrance of the vacuum chamber with 33 μm beam degrader), Figure 6.9 for Position 3 (end of the straight line inside the chamber), Figure 6.10 for Position 4 (end-plate of the bent line).

Energy distribution, arrival position, incident energy per entire AD shot and average energy per single particle are extrapolated. To model the exposure right after the end of the AD line, a sensitive circular area with radius of 2 cm was considered. On the two surfaces inside the detector test stand line, the whole end-plates of the chamber (radius of 10 cm) are taken into account for exposures. However, all the histograms are binned in order to provide the flux of antiprotons per millimetre squared. The histograms of the incident energy and average energy per particle, on figures 6.7 and 6.8 bottom left
and bottom right sides both have a ten times finer grain.

The entries of the histograms indicate the amount of particles that survived along their path towards the designated target, given as an output of the simulation. The histograms showing the average energy per particle are obtained from the histogram of the incident energy and the arrival position and they depend on the binning of the source histograms. The average energy per particle is thus referred to the unit of area. Position 1 is right at the end of the AD line and 95% of the $3 \cdot 10^7$ antiprotons that are delivered survive with about half of the original energy (see Figure 6.7 on the top left and top right sides). If the beam degrader and the 3+3 cm of air gap between the lines are included into the calculations, 40% of the particles are scattered and do not reach Position 2 (see Fig. 6.8, top left). The comparison between the energy distributions of Position 1 and Position 2 shows a dramatic difference in the energy spread between the two exposure positions as a consequence of the degrading layers. However, spacial distribution of the antiprotons and the integral of the energy of all the arriving particles show the same natural shape for both the cases, with the highest number of particles arriving at the middle of the detection region and carrying the highest amount of energy (see Figures 6.7 and 6.8, bottom left). This is consistent with the plots of the average energy carried by the single particles which show a constant distribution in the bottom right sides of both figures.

Figure 6.7: Position 1, end of the AD line.
Results at Positions 3 and 4 are more directly related to experiments aimed to test the behaviour of the detectors with very low-energy antiprotons. In fact, the top left figures 6.9 and 6.10 show the distribution of the arrival position for antiprotons reaching to the end-plate of the straight and on the bent lines of the test chamber, respectively. Such distributions are almost flat, allowing experiments of exposure to antiprotons with very stable parameters. Regarding the results of the simulation at Position 3, this is confirmed by the plots of the incident energy and the average energy per particle (bottom left and right) which show distributions that are fully stable across the area of the entire end-plate. Furthermore, in Position 3, at the end of the straight line, the peak of the antiproton energy distribution is around 300 keV, as it is shown in Figure 6.9, top right. The total energy distribution and the average energy per particle taken from simulation at Position 4 (Fig. 6.10, bottom left and bottom right) also show an excellent stability with the strong advantage that the energies are all below 10 keV with a strong peak at 3 keV which are extremely low values (Fig 1.10 top right).
6.4 Detector tests

Three main activities have been carried out at the line so far: diamond detector tests, in collaboration with CIVIDEC Instrumentation, Wien; antiproton exposures of CR-39 samples from CIIT, Islamabad; and tests of Timepix3 detectors from Medipix Collaboration at CERN for their use as a position detector for antihydrogen annihilation. In the next sections, I will describe the detectors in more detail. Where possible, I will report and discuss the results of measurements.

6.4.1 Diamond detectors

The diamond detector consists of a 500 µm thick diamond Knopf with gold metallization and an active surface of $4 \times 4$ mm$^2$. The device is shown on the top panel of Figure 6.11. The read-out chain also included a broadband (2GHz) current amplifier and a computer read-out system with an oscilloscope application, provided by the visiting institute.

The plot on the bottom left of Figure 6.11 shows the response of the detector to the exposure to a bunch of antiprotons from one AD shot. Data were acquired placing the detector at the centre of
the bended end-plate, in Position 4. It is possible to distinguish an initial multiple pulses region with high signal-rate followed by lower energetic individual signals, in the plot of the waveform. The initial flash can be interpreted as a first burst of pions, followed by individual pulses from single events due to low energy antiprotons. Some huge pulses, however, saturated the amplifier. Since the antiprotons were low energetic, most of them annihilated in the electrode already. In few events, recorded pulses got very high, which appear to be antiprotons annihilating in the diamond. These are probably due to antiprotons annihilating inside the detector, while most of the annihilations were expected on the electrode surface. This suggests that the metallization of the detector was too thick for low energy antiprotons to reach the detector. The plot on the bottom right side of Figure 6.11 shows an isolated pulse waveform of one such event. From the full waveforms, the initial flash was cut and each pulse taken separately from each other. Pulses saturating the amplifier are excluded from this analysis as well as double recorded pulses. For each of the remaining pulses, amplitude and area were measured. The histograms in Figure 6.12 refer to such values, separately for 2017 and 2018 measurement campaigns. Number of counts are shown with respect to maximum pulse amplitude for amplitude histograms and measured area of a pulse for area histogram. 2017 and 2018 data are acquired with electrodes of different thickness and composition. In 2017, a 500 nm Au-Ti electrode was used. In 2018, the electrode

Figure 6.10: Position 4, end-plate of the bent line.
Figure 6.11: On the top: the gold-plated Knopf detector. On the bottom left: diamond detector response to antiproton annihilations. On the bottom right: the antiproton annihilation waveform. Courtesy of Cividec Corp.

Figure 6.12: Amplitude and area histograms of diamond detector responses to antiprotons. Courtesy of Cividec Corp.
was 100 nm thick, made of titanium with a gold ring for bonding. Measurement with the thinner electrode were expected to observe a higher number of annihilations in the diamond material. This was unfortunately not observed, suggesting that the electrode for the second measurement campaign was still too thick.

### 6.4.2 CR-39 as antiproton detector

CR-39 is a plastic polymer commonly used in the manufacture of eyeglass lenses as it is transparent in the visible spectrum and opaque to UV light and it has about half of the weight of glass with a refractive index only slightly lower and a better abrasion resistance.

Scientific interests in this material mainly concern its capability to detect the presence of ionizing radiation. Particles traversing the polymer structure break the chemical bonds of the structure, producing a track that can be reconstructed by immersing the material in an alkali solution to allow an etching process to take place predominantly in the areas with damaged bonds. The resulting etched plastic can give information about direction and energy of the impacting particles and insights about the composition of the source. The interest towards this material in antimatter physics lies in the possibility to track not only the antiprotons hitting the target but also the nuclear fragments produced by the antiproton annihilations resulting in a tagging of the particles.

Samples from CIIT have been exposed in the AE\(\bar{\text{g}}\)IS secondary beam-line in 2017 and 2018 with an extensive use of the simulation described in the above sections. A detailed report of the simulated results was sent to the institution. Results of the exposure activities and analysis of the exposed samples haven’t been provided.

### 6.4.3 Timepix3 as position detector for antiproton annihilations

The work on Timepix3 detectors allowed to explore an alternative method to emulsions for tagging antiprotons and reconstructing their annihilation point in AE\(\bar{\text{g}}\)IS [95].

Timepix3 is a silicon detector consisting of a 675 \(\mu\)m thick silicon sensor covered with a 0.5 \(\mu\)m thin aluminium layer and bump-bonded to an ASIC with a customised read-out. The size of the sensitive surface is 256 \(\times\) 256 pixels with a pixel pitch of 256 \(\mu\)m. Each pixel is self-triggering and able to simultaneously measure both Time of Arrival (ToA) and Time over Threshold (ToT) with a time resolution of 1-2 ns. A picture of the detector is shown in Figure 6.13.

To fit with the AE\(\bar{\text{g}}\)IS requirement for a detector able to resolve the vertical displacement in the gravity measurement of antihydrogen, the position-sensitive detector must be able to tag antiprotons, reconstruct their annihilation point and measure their time of flight through the moiré deflectometer [93]. In particular, a vertical fall of \(\sim\)20 \(\mu\)m is expected. One of the difficulties is represented by the
volcano effect, a disturbance in the read-out of a detector occurring whenever a region of the sensitive surface is hit by an antiproton or a nuclear fragment that releases a large amount of energy. Pixels in the region affected by the passage of such a particle can record a lower energy deposit than expected. Tests with high-energy ions impacting a silicon detector with the same read-out as the Timepix showed that the effect occurs above a deposited energy per pixel of 450 keV. The features of the low energy detector test chamber and its reliability in energy selection ensured that all the antiprotons to be studied have a kinetic energy far below that quantity. In particular, results from the simulation described above and a series of measurements carried out during the AEgIS beam time at the AD show that the kinetic energy per antiproton hitting the final end-cap of the deflected branch of the vacuum chamber stays below 15 keV. The penetration depth in aluminium of antiprotons at this energy is 0.1 μm. Therefore, the annihilations occur on the top of the 0.5 μm thick aluminium layer on the surface of the sensor. In this way, the active region can only record the signals from nuclear fragments. This results in an increased precision of the antiproton tagging given by this detector in the conditions provided by the low energy test stand facility. Figure 6.14 shows the raw hits of antiprotons annihilating on the detector. Images can be recorded with an efficient time selection and can then be analysed.

An algorithm for characterizing and tagging the antiproton cluster and for a precise 3D reconstruction of the annihilation prongs has thus been developed inside the Collaboration, providing a good tagging efficiency and a false tagging rate of 1% [95]. The measurement needed in AEgIS is the determination of the vertical shift of the fringe pattern created by antihydrogen passing through the moiré deflectometer. Therefore, the relevant position resolution is that on the vertical direction. The reconstruction of the annihilation point was implemented via the comparison of a mass-centre method and a vertex fitting method. Using the first one, the annihilation point is estimated by the weighted relative position of the energy depositions in the central region of the annihilation pattern, once the halo is software-removed. The position resolution achieved is 93 μm. The vertex fitting method consists of fitting straight lines to the prongs, taking the annihilation point as the intersection between two of such lines. The lines are fitted by the orthogonal-least-squares method. The vertical position resolution is improved to 48 μm. However, two or more prongs per annihilation are required and 45% only of the clusters match such condition. The comparison of the two methods on a sub-sample of clusters might result on a disagreement on the fits provided by the two methods. Excluding clusters where the two methods show non-compatible results can provide such a sub-sample of clusters that are more accurately reconstructed. Setting conditions on the difference of the estimations, a sub-sample consisting of 22% of the clusters was selected. For such sample, a position resolution of 22 ± 0.5 μm was obtained, compatible with a proof of principle measurement where a shift in the fringe pattern is observed.
Chapter 7

Fast decay low afterglow positronium detection

With geometrical limitations and in the presence of a strong magnetic field, the detection of excited states of positronium in the production region is one of the aspects of antihydrogen production that has required the greatest effort. The imaging technique developed before the beginning of the last year run has critical limitations and stringent design requirements. The technique requires the use of an MCP or a similar detector to be placed right at the end of the AEgIS trap system, in the region where the gravity module should be installed, according to the original proposal of the experiment. In addition, as the Ps flight path from the target to the trap electrodes should be visible to the detector, the target had to be moved few millimetres upwards from its original position, resulting in a reduction of the fraction of excited Ps atom able to reach the antiproton cloud. Furthermore, the detection of the dissociated positrons from positronium atoms requires the latter to be photo-ionised, with some ionisation efficiency, implying that the measurement is indirect.

As a result, a direct technique that does not impose design restriction, like SSPALS, could be desirable. The ortho-positronium having a lifetime of 142 ns and inducing slight distortions of the exponential decay curve, the detector must have a very rapid response, minimal afterglow and a wide angle coverage to identify its laser-excitation. In this respect and for all the motivations introduced in the Chapter, performances of the external paddle scintillators are not fully satisfying and the quest for a new material becomes compelling. With the typical Ps yield of about 7%, the ratio between the area of the delayed and prompt signals is expected to be of the same order. In addition, the delayed signal includes contributions from the delayed fluorescence of the scintillator, from after-pulses of the PMTs and from possible electrical effects related to details of the PMT divider. The time duration of the prompt and delayed signals varying greatly, the ratio of their amplitudes can reach a factor of a 100 or a 1000. Therefore, it is of paramount interest for the Collaboration to search for detection system giving the minimum possible signal following a large prompt pulse in absence of Ps formation.

Diphenylacetylene (DPAC) doped with stilbene is a new scintillating material with good light yield ($\sim 10^5$ $\text{MeV}$), fast rise time ($\sim 10$ ns), fast decay time ($\sim 10$ ns) and almost no delayed light if the concentration of doping material is very low. Among several other possible candidate scintillators [99] suitable for an ultra-low afterglow detector, DPAC-stilbene presents the lowest delayed light component. The detection of the long lived fraction of Ps and H eventually, both in their fundamental state and in Rydberg excited states in the production region, at 1.0 T magnetic field, are a motivated interest of the Collaboration towards the DPAC-stilbene scintillator.

This chapter describes the characterisation of this material and tests for the viability of its implementation in AEgIS for detection of positronium, Rydberg-Ps and eventually excited states of antihydrogen. The work was developed through several data taking campaigns in order to test the performance of the material in different conditions and it allows a characterization for the requirement of the experiment. Besides the response to cosmic-ray muons (Sec. 7.3) and the response to the single photon
(Sec. 7.4), the production of positronium and its excitation to Rydberg states have been detected in Sec. 7.5 and Sec. 7.6, respectively.

### 7.1 The sample

A sample of DPAC-stilbene with dimensions $2 \times 4 \times 8 \text{ cm}^3$ and 2.6% of doping concentration over the total mass was developed at Lawrence Livermore National Laboratory (LLNL) in the U.S. and shipped to CERN as a courtesy of Dr. N. Zaitseva (LLNL).

Diphenylacetylene is sold as solid powder for crystal growth in laboratories. The sample here tested was doped with a small fraction of stilbene giving a scintillator with no significant delayed light component. DPAC molecule, which represents the 97.4% of the material, is composed by 14 carbon and 10 hydrogen atoms. Remarkably, this is the same composition as the anthracene molecule. Stilbene (2.6% of the total mass) has almost the same composition of DPAC, being composed by 12 carbon and 10 hydrogen atoms. The contribution to stopping power from the doping material will thus be neglected.

A calculation on the basis of these data gives a photon mass attenuation length $\lambda = 11.01 \text{ g/cm}^2$ and a mean free path of 11.12 cm. Details about the calculation are reported in Sec. 7.4.3.5.

As the aim of this work was to evaluate new scintillators for possible new detectors for Ps diagnostics in the production region of the AEgIS main experimental apparatus, the sample was tested and characterised in comparison with the two main dedicated detectors for Ps studies, i.e. the one of the scintillator slabs of the ESDA and a small lead tungstate in use in the Ps test chamber. In addition, a piece of EJ-200 commercial scintillator was shaped of the same dimensions of the DPAC-stilbene sample (Fig. 7.1), in order to rule out any effects due to difference in size between the DPAC-stilbene and the EJ-200 paddle scintillator. The DPAC-stilbene samples and the piece of EJ-200 were coupled to photomultiplier tubes of the same model from the same producer and with performances analogue to each other.

### 7.2 Signals and data acquisition

External scintillator slabs used for Ps studies are optically connected to EMI 9954B photomultiplier. PMT2o is one of such photomultiplier, connected to one of the paddles which have the widest solid angle from the production region, i.e. the region where the converter target and the electrodes of the production trap are installed.

The output of the PMTs used for Ps studies are typically connected to a high resolution fast digitizer (12 bits, 4 Gs/s in AEgIS). To further improve the amplitude resolution at the longest decay times, the signal from the PMT is split in two components and digitized with two different vertical ranges, with
high and low gain. The two curves are then software joined and the result is equivalent to increase the effective number of bits of the digitiser.

SSPALS spectra (Sec. 4.1) present a prompt peak and a tail. The prompt strong peak is due both to the cumulative annihilation of the fraction of $e^+$ not converted into Ps and to the decay of the singlet Ps component. The decay of the ortho-Ps, instead, should be searched in the tail of the signal which also suffers the afterglow of the scintillator. In absence of physical obstacles around the target region, the signal in the tail shows an exponential time decay with 142 ns time constant. Rydberg excitation, necessary for antihydrogen formation and Ps studies in AEgis, increases the Ps lifetime causing slight variations in the time shape of the delayed signal. In addition, supplementary time structures can appear in the delayed signal if Ps atoms hit obstacles while flighting in the experimental apparatus.

Photomultiplier tubes initially tested were the EMI 9954B, the same as those already used for scintillator slabs in the main experimental setup. Later (see Sec. 7.3), scintillators were coupled to Hamamatsu R1828-01 were used to improve results in sensitivity.

### 7.3 Studies of detector performance using cosmic-ray muons

Charged particles produced by the interaction of cosmic ray with the atmosphere provide a high-statistics source that can be used to study the performance and calibration of detectors. Motivations for the work presented in this report reside in the need for improvements in the detection of the long lived fraction of Ps, both in its fundamental state and in Rydberg excited states. Long-lived positronium studies are typically performed by analysing the time profiles of the detector response to Ps formation, with ortho-Ps expected to decay with relatively long time scales while in its fundamental state and even longer once undergoing laser excitation.

In this framework, the detector response to cosmic rays is an extremely useful tool for positronium studies. The signal due to the passage of charged particles is expected to abruptly fall to zero, ideally producing a no-tail signal with an amplitude comparable to those of positron bunches annihilation on the target. Under such condition, the tail of a signal due to the passage of a cosmic ray can only be amenable to the fluorescence of the scintillator itself or to effects induced by the photomultiplier or its voltage divider.

In the sections below, detector response functions are obtained by acquiring several cosmic-ray signals. The average time profile is then normalized to 1 Volt peak value to favour a fair performance comparison between the detectors.

#### 7.3.1 Preliminary tests

The performances of DPAC-stilbene were first compared to those of the small EJ-200. The two scintillators were initially coupled to the same model of photomultiplier tubes currently used in the AEgis main apparatus, as introduced. Figure 7.2 shows the detector response functions to the interaction with cosmic-ray particles in linear and logarithmic scale for both the DPAC-stilbene sample (green line) and the small EJ-200 piece (blue line). When the two materials are coupled to the same or analogue photomultiplier, they show comparable yield. This can be seen in the distribution plots of peak amplitudes and integrated charge which span over similar ranges (see Sec. 7.3.2). The amplitude of the tail of the DPAC-stilbene scintillator is lower the one measured with the EJ-200 coupled to the EMI PMTs (blue and green curves). When the DPAC-stilbene is coupled to the Hamamatsu PMT, the tail is even more significantly reduced: 50 ns after the normalised peak value the amplitude of the tail is $10^{-5}$ and from 100 ns on, it is as low as $10^{-4}$. This intrinsic low tail will be useful in enhancing the sensitivity to Ps detection compared to what is achieved with the EJ-200 scintillator.
CHAPTER 7. FAST DECAY LOW AFTERGLOW POSITRONIUM DETECTION

Figure 7.2: Cosmic rays signals with the EJ-200 and DPAC-stilbene scintillator-based detectors. The plots show the sum of several PMT signal digitized at 4 GS/s. The resulting curves are normalized to 1 V peak value and here displayed in linear scale (on the top, detail) and semi-logarithmic scale (on the bottom, full curve).

7.3.2 Detector performance as a reference for positronium studies

This section describes the comparison of the detector response to the exposition to cosmic rays for the DPAC-stilbene and the small EJ-200. As a reference, the same study has been carried for the PbWO₄ routinely used for Ps diagnostics in the AEgIS Ps test chamber. The DPAC-stilbene and EJ-200 samples with the same dimensions have been coupled to photomultiplier tubes of the same models and from the same manufacturer, Hamamatsu R1828-01, while the PbWO₄-based detector was kept to the conditions for its best performance for Ps detection and coupled to the Hamamatsu R11265-100, as usual.

7.3.2.1 Peak amplitudes and integrated charge distributions

Figures from 7.3 to 7.5 show the distributions of peak amplitudes and integrated charge collected by the three detectors.

In each histogram, the height of the bins is first normalised to the number of entries and then rescaled to a nominal time interval equal for all the detectors. The values on the vertical axes are therefore representing the frequency of occurrence. The charge is expressed in pC and is obtained by integration of the area below the single curves for 200 ns after the beginning of the peak. The quantity obtained by this last operation is rescaled according to the sampling frequency. Negative values here do not contribute to the sum and are counted as zeroes. The peak starts at the time in which the signal reaches a safe level of the peak amplitude itself, which had been found previously. This method was chosen as an alternative to a fixed threshold in order to reduce slewing effects between signals of different peak amplitudes and areas leading to more accurate studies on time profiles in Section 7.3.2.2.

DPAC-stilbene and PbWO₄ show distributions with similar shape while the response of the EJ-200 looks less defined. Remarkably, EJ-200 showed a much higher rate than the other detectors, suggesting that this material is more sensitive to signals of lower energy like environmental background. Two main structures can be distinguished in the distribution, separated by a lower region, by looking Figures 7.3, 7.4, 7.5. The peak at lower amplitude is typically due to background noise while the following one is
attributable to the cosmic rays at minimum ionizing energy. This two-structures distinction is less clear for the EJ-200, for which it can be assumed that the peak due to the passage of the MIPs is centred roughly around 4 V, as shown in the left side of Fig. 7.4. The red line indicates a Gaussian fit whose parameters are reported in the figure.

Figure 7.3: DPAC-stilbene based detector. Distribution of peak amplitudes (on the left) and of charge collected (on the right).

Figure 7.4: EJ-200 based detector. Distribution of peak amplitudes (on the left) and of charge collected (on the right).

Figure 7.5: PbWO₄ based detector. Distribution of peak amplitudes (on the left) and of charge collected (on the right).

To more accurately determine the light yield of DPAC-stilbene with respect to the plastic EJ-200, the two scintillators were put in coincidence with a larger slab and acquired with the same photomultiplier (Hamamatsu R-1828-01) at the same voltage. In this configuration the MIP peak is more clearly visible
and the ratio of the two peak positions for DPAC-stilbene and EJ-200 results 2.50 ± 0.05. Taking into account the EJ-200 response of 10000 photons per MeV, as quoted by the manufacturer, the light yield on MIP particles for DPAC-stilbene can be estimates as 25,000 ± 500 γ/MeV. Considering the stilbene concentration of 2.6%, the result is in agreement with the value reported in Ref. [99].

7.3.2.2 Time profiles

A fair comparison between detectors shouldn’t be done barely on the same amplitude intervals since in principle the detectors can perform differently. Peak amplitude and deposited charge spectra reported in Figures from 7.3 to 7.5, in fact, clearly show that the distributions of PbWO₄ span over different ranges of DPAC-stilbene and EJ-200 based detectors. For this reason, a comparison on detector responses was made on the corresponding regions of the peak amplitude distributions. The distributions have been divided in 11 regions, from R₀ to R₁₀. The peak ranges for the different regions of correspondence are reported in Table 7.1.

<table>
<thead>
<tr>
<th></th>
<th>1st peak</th>
<th>Middle</th>
<th>2nd peak</th>
<th>Fall</th>
<th>Higher amplitudes</th>
</tr>
</thead>
<tbody>
<tr>
<td>R₀</td>
<td>R₁</td>
<td>R₂</td>
<td>R₃</td>
<td>R₄</td>
<td>R₅</td>
</tr>
<tr>
<td>DPAC-st.</td>
<td>0 ± 1.5</td>
<td>1.5 ± 3.0</td>
<td>3.0 ± 7.0</td>
<td>7.0 ± 10.0</td>
<td>10.0 ± 13.0</td>
</tr>
<tr>
<td>EJ-200</td>
<td>0 ± 0.5</td>
<td>0.5 ± 2.5</td>
<td>2.5 ± 4.0</td>
<td>4 ± 5.5</td>
<td>5.5 ± 10.0</td>
</tr>
<tr>
<td>PbWO₄</td>
<td>-0.4 ± 1.0</td>
<td>1.0 ± 1.5</td>
<td>1.5 ± 2.0</td>
<td>2.0 ± 2.5</td>
<td>2.5 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>3.0 ± 4.5</td>
<td>4.0 ± 5.0</td>
<td>5.0 ± 6.0</td>
<td>6.0 ± 7.0</td>
<td>7.0 ± 8.0</td>
</tr>
</tbody>
</table>

Table 7.1: The separation in different peak amplitudes regions according to their distributions. Values are expressed in Volts.

The time profiles of the three detectors for all such regions are shown in figures from Fig. 7.6 to 7.15, both in linear and logarithmic scales. Cumulative plots are reported in Figures 7.16 and 7.17 for the entire region between the two peaks and for the high energy cosmic rays region, respectively.

Figure 7.6: Time profile on cosmic rays acquisition of the three detectors in linear (on the top) and logarithmic scale (on the bottom) in the peak amplitude region R₁ (see Table 7.1).
Figure 7.7: Time profile on cosmic rays acquisition of the three detectors in linear (on the top) and logarithmic scale (on the bottom) in the peak amplitude region R2 (see Table 7.1).

Figure 7.8: Time profile on cosmic rays acquisition of the three detectors in linear (on the top) and logarithmic scale (on the bottom) in the peak amplitude region R3 (see Table 7.1).

Figure 7.9: Time profile on cosmic rays acquisition of the three detectors in linear (on the top) and logarithmic scale (on the bottom) in the peak amplitude region R4 (see Table 7.1).
Figure 7.10: Time profile on cosmic rays acquisition of the three detectors in linear (on the top) and logarithmic scale (on the bottom) in the peak amplitude region $R_5$ (see Table 7.1).

Figure 7.11: Time profile on cosmic rays acquisition of the three detectors in linear (on the top) and logarithmic scale (on the bottom) in the peak amplitude region of the MIP peak ($R_6$ according to Table 7.1).

Figure 7.12: Time profile on cosmic rays acquisition of the three detectors in linear (on the top) and logarithmic scale (on the bottom) in the peak amplitude region $R_7$ (see Table 7.1).
Figure 7.13: Time profile on cosmic rays acquisition of the three detectors in linear (on the top) and logarithmic scale (on the bottom) in the peak amplitude region R8 (see Table 7.1).

Figure 7.14: Time profile on cosmic rays acquisition of the three detectors in linear (on the top) and logarithmic scale (on the bottom) in the peak amplitude region R9 (see Table 7.1).

Figure 7.15: Time profile on cosmic rays acquisition of the three detectors in linear (on the top) and logarithmic scale (on the bottom) in the peak amplitude region R10 (see Table 7.1).
Figure 7.16: Time profile on cosmic rays acquisition of the three detectors in linear (on the top) and logarithmic scale (on the bottom) in the peak amplitude whole region between the two peaks, from $R_2$ to $R_5$ (see Table 7.1).

Figure 7.17: Time profile on cosmic rays acquisition of the three detectors in linear (on the top) and logarithmic scale (on the bottom) in the whole high energy peak amplitude region, from $R_8$ to $R_10$ (see Table 7.1).

Figure 7.18: Time profile on cosmic rays acquisition of the three detectors in linear (on the left) and logarithmic scale (on the right) in the peak amplitude region of Ps studies in AEGIS (see following sections).
Figure 7.18 shows the time profiles for the three detectors at the peak amplitudes corresponding to those detected in typical Ps data takings with PbWO$_4$ in the AEgis dedicated test chamber, according to the comparison between the distributions. The plot clearly shows that DPAC-stilbene is the first to reach the baseline and stays below the others for several thousands of seconds. There is a ringing effect in the first dozens of ns after the peak and an after-pulse around 300 ns which becomes more evident at higher energies (from R7 to R10, indicatively). The after-pulse is also visible after the same time as for the EJ-200, which is coupled to the same PMT as the DPAC-stilbene. Both effects are interpreted as instrumental and do not affect the measurements presented here. The time profile of the PbWO$_4$ shows an unexpected shape which is persistent all over the peak amplitude regions. A bump arises about a hundred of ns after the main peak and reaches 0.4% of the full height of the peak. This effect is present in all the peak amplitudes regions and, for all of them, it reaches the same maximum level with respect to the normalised peak, indicating that it is not depending on the peak amplitude. As a possible explanation, one could assume that the signal from PbWO$_4$ based detector lasts 2 μs, i.e. the curve comes back to its baseline and the bump is part of the tail of the signal itself. It is reasonable since both delayed emission of the scintillator and electrical effects of the PMT or its divider can contribute to the intrinsic tail of the detector. As a consequence, this could lead to an interpretation of the bump as the remnants of the intrinsic tail of the detector after a negative electrical reflection, due to an impedance mismatch. Such interpretation is supported by the rise time of the bump (less than 100 ns, from around 100 ns to 200 ns, e.g. in Fig. 7.18) which is compatible with the amplitude of the peak in all the figures for the time profile of the PbWO$_4$ detector. Without such reflection, the decay of the curve from the peak to the baseline would be similar to the one of the EJ-200. In case of photon interaction in the the same experimental setup and acquisition chain, the time profile of the PbWO$_4$ does not show the same structure, as it will be shown later on, suggesting that this effect depends on the interaction of charged particles in the material. This evidence could support the usage of PbWO$_4$ for particle identification via pulse shape discrimination techniques.

Figures from 7.6 to 7.15 show that the signals from the three detectors present the same behaviour all over the peak amplitude regions, with the signal from the DPAC-stilbene reaching the baseline in few dozens of ns after the peak and always in great advance with respect to the other scintillators here considered. The EJ-200 and PbWO$_4$ show component of delayed light higher than DPAC-stilbene in all of the peak amplitude regions. It is worthy to note that the distance between EJ-200 and DPAC-stilbene increases with the peak amplitudes (from region R1 to R10) even at very short times after the peak.

A comparison of the time needed to go back to the baseline is given by Figure 7.19 for DPAC-stilbene (pink) and EJ-200 (blue). Both plots show the decay time to the peak amplitude (plot on the left) and

![Decay time vs Peak amplitude](image1.png)

![Decay time vs Integrated charge](image2.png)

Figure 7.19: Time to reach the baseline from the peak time for the DPAC-stilbene (pink bullets) and EJ-200 (blue bullets) detectors versus the corresponding peak amplitude (plot on the left) and charge collected (plot on the right).
to the charge collected (plot to the right). The time to go back to the baseline is computed as the
difference between the time at which the peak is recorded for each curve and the time of the first point
detected at 0.1% of the peak value, here assumed as the baseline in order to get rid of the electrical
noise. Not surprisingly, the time needed by EJ-200 increases with the peak amplitude while the decay
time of the DPAC-stilbene presents a modest growth only.

The plot in figure 7.20 shows the peak to charge linearity for each of the curves acquired by the three
detectors. The peak amplitude does not look linear with the charge collected over a large interval
for charged particles crossing the material. Analogue studies have different results for photons, as
discussed in the next section.

7.4 Single 511 keV photon

The detector response to single photon from positron annihilation, is the next logical step of this
work. Several preliminary studies have been carried to determine the best setup and try to minimize
electrical artefacts which heavily affect the measurements. However, some effects persisted and had
some impact on the results.

7.4.1 The source

A sodium source has been used for measurements in this section. $^{22}$Na is an artificial isotope with
a 2.6 years half-lifetime which decays into neon ($^{22}$Ne, stable) via three main decay channels:

- **Positron emission**, $\beta^+$, B.R. = 89.8 %:
The $^{22}$Na nucleus emits a positron getting into a $^{22}$Ne excited state. The positron from $\beta$ decay
annihilates with an electron either in the source itself or on the outer band of the material
of the physical support of the source producing two 511 keV photons emitted *back-to-back* for
momentum conservation. The de-excitation of the nucleus (3.7 ps) produces an additional 1.274
MeV photon. A line at $1.275 + 0.511 = 1.786$ MeV could also appear as the time interval between the
de-excitation of the nucleus and the annihilation radiation is unresolvable.

- **Electronic capture**, E.C., B.R. = 10.2 %:
The $^{22}$Na nucleus captures an electron from one of the inner atomic orbitals getting into the same
$^{22}\text{Ne}$ excited state as above. The hole is filled by another atomic electron with the consequent emission of an Auger photon with non-predictable energy.

- **Direct decay, B.R. = 0.06 %:**
  The nuclide can also decay into stable neon directly with an emission at 1.82 MeV. However, only a trace of the sodium nuclide decay directly to the ground.

Due to its relatively short half-life time, the ageing of the source should be taken into account even in case of short lasting measurements. The activity of the sample used for the measurements was reported by the CERN’s Radioactive Source Management Service to be 63.31 kBq on Feb 27th, 2019. Data taken for the results here presented have been acquired in 7 days, during dead time of positron activity, from May 18th to 24th, 2019. The activity of the source has thus been considered stable over this period albeit scaled by a 1/18 factor on its half-life to the value of 59.79 kBq.

### 7.4.2 Detection scheme

The detection scheme is shown in Figure 7.21. The source was placed on the surface of a NE111 scintillator used for timing. The detector housing the scintillator to be tested was placed at a known distance of the sample on the source axes (dashed line). Both the detectors were read out in the way described in Sec. 7.2 i.e. with the signal from the PMT split and acquired in high and low resolution at the same time. The trigger condition for this measurement was set as a way to record tracks with a logic AND condition between the high resolution channels of both detectors and both set at -20 mV level. In this way, it is expected to detect the coincidence of both $\gamma$ rays emitted back-to-back from the source with an efficient background rejection. The time coincidence between the timing detector and the detector to be tested should ensure that the signal detected by both detectors come from interaction with $\gamma$ emitted from the source.

The NE111 scintillator ensures good timing performances due to its fast rise time response. DPAC-stilbene and EJ-200 samples were coupled to a Hamamatsu R1828-01 photomultiplier each and both tested in separate data takings. A 10 s delay in the acquisition chain was set in order to safeguard the data transfer from the scope to the central DAQ. The maximum acquisition rate is thus 0.1 Hz for both the detectors as a drawback of this safety measure. Both the detectors show such rate when exposed to the source as in the detection scheme of the figure. Background measurements, taken without the source, in the same acquisition scheme, show a lower rate: $f_{\text{bkg}}^{\text{EJ200}} = 0.035$ Hz, $f_{\text{bkg}}^{\text{DPAC-ST}} = 0.040$ Hz pointing out that the background can be neglected in such detections scheme.

### 7.4.3 Estimation of the number of interactions

The number of interactions has been estimated by calculation. In this section, the main steps are reported.

#### 7.4.3.1 Geometry

A general description of the samples was already given in the above sections. The sensitive volume is 64 cm$^3$ and the scintillator surface exposed to the source, according the detection scheme (Sec. 7.4.2), is 32 cm$^2$.

In the configuration described for the exposition to the single photon, a solid angle of 1.77 sr can be calculated, corresponding to 4.45% of the sphere surface. In this calculation the exposed detector surface (which is flat) is assumed to be much smaller than the full 4$\pi$ sphere and consequent geometrical effects will be neglected.
7.4.3.2 Material composition

As anticipated, the sample used in this work is composed by diphenylacetylene doped with a small fraction of stilbene. DPAC molecule, which represents the 97.4% of the material, is composed by 14 carbon and 10 hydrogen atoms which is the same composition as the anthracene molecule, although the shapes of both molecules are different as shown in Figure 7.22.

![Molecules of diphenylacetylene and anthracene](image)

Figure 7.22: The molecules of diphenylacetylene (on the left) and anthracene (on the right).

Also densities are different, with

\[ \rho_{\text{DPAC-stilbene}} = 0.99 \text{ g/cm}^3 \]  

(7.1)

Stilbene (2.6% of the total mass) has almost the same composition of DPAC, being composed by 12 carbon and 10 hydrogen atoms. The contribution to stopping power from the doping material will thus be neglected.

DPAC and anthracene also differ in their radiation length. Computing for DPAC the textbook expression \[^7\] one gets

\[ L_{\text{Rad}}^{(\text{DPAC})} = 43.76 \text{ g/cm}^2 \]  

(7.2)

which, dividing by the material density (Eq. (7.1)), gives

\[ X_0^{(\text{DPAC})} = 44.20 \text{ cm} \]  

(7.3)
The same quantities for anthracene are well-known (see e.g. [100]):

\[ L_{\text{rad}}^{(\text{anthr.})} = 43.49 \text{ g/cm}^2 \]  \hspace{1cm} (7.4)

and

\[ \chi_{0}^{(\text{anthr.})} = 33.90 \text{ cm}. \]  \hspace{1cm} (7.5)

Not surprisingly, results from Eqs. (7.2) and (7.4) are in agreement.

### 7.4.3.3 Photon interaction

The number of particles interacting with the material can be determined from the attenuation suffered by a photon beam passing through a material, i.e.

\[ I(x) = I_0 e^{-\mu x}, \]  \hspace{1cm} (7.6)

where

- \( I_0 \) is the incident intensity,
- \( \mu \) is the absorption coefficient,
- \( x \) is the thickness of the material which can be assumes to always be at its minimum, 2 cm.

The absorption coefficient \( \mu \) directly depends on the probability of interaction between incident radiation and the absorber material and it is the inverse of the mean free path of the photon

\[ \mu = N\sigma = \sigma \frac{\rho N_A}{A}, \]  \hspace{1cm} (7.7)

with \( N_A \) being the Avogadro's number, \( \rho \) the density of the material and \( A \) the molecular weight. For material compounds the total absorption coefficient should be computed keeping into account the different weight fraction of the elements with the relative density according to the Bragg's rule

\[ \frac{\mu}{\rho} = \sum_i \omega_i \frac{\mu_i}{\rho_i}. \]  \hspace{1cm} (7.8)

### 7.4.3.4 Cross section for photon interaction

The three processes give a contribution to the total cross section in the case of photon interaction. The cross section per atom will thus be

\[ \sigma = \sigma_{\text{phel}} + Z \cdot \sigma_C + \sigma_{\text{pair}}, \]  \hspace{1cm} (7.9)

with the Compton effect expected to give the higher contribution. Below, the single terms will be considered.

#### Photoelectric effect

Theoretically, this effect is hard to treat due to the complexity of the wave functions for the atomic electrons. For photons at energies above the K-edge (\( \sim \) keV), if one can assume that only one electron of the outer shell is involved and the energy is non-relativistic (\( \hbar \nu \leq m_e c^2 \)), the cross section can be calculated in the Born approximation:

\[ \sigma_{\text{phel}} = 4\alpha^4 \sqrt{Z^2 \phi_0 \left( \frac{m_e c^2}{\hbar \nu} \right)^2}, \]  \hspace{1cm} (7.10)
where $\phi_0 = \frac{8\pi r^2}{3} \alpha$ and $\alpha$ is the fine structure constant. Energy of 511 keV are border line for the requirement, since $\hbar \nu^{(511 \text{ keV})} = 8.19 \cdot 10^{-7}$ and $m_e c^2 = 8.14 \cdot 10^{-7}$. However,

$$\sigma_{\text{phel}}^{\text{DPAC}}(511 \text{ keV}) = 9.66 \cdot 10^{-30} \text{ cm}^2,$$

(7.11)

compatible with no interactions due to photoelectric effect, as expected from literature.

**Compton scattering**

The calculation of Compton cross section is done here, starting from the integration over the solid angle of the Klein-Nishina formula

$$\sigma_c = 2\pi r_e^2 \left\{ \frac{1+\gamma}{\gamma^2} \left[ \frac{2(1+\gamma)}{1+2\gamma} - \frac{1}{\gamma} \ln(1+2\gamma) \right] + \frac{1}{2\gamma} \ln(1+2\gamma) - \frac{1+3\gamma}{(1+2\gamma)^2} \right\},$$

(7.12)

with

$$\gamma = \frac{\hbar \nu}{m_e c^2},$$

(7.13)

which gives as the total probability per electron for a scattering to occur:

$$\sigma_{C}^{\text{DPAC}}(511 \text{ keV}) = 0.2863 \text{ b}. $$

(7.14)

At this point, one could ask for the fraction of the incident photons which are scattered and can eventually produce further interactions over that of the photons which are absorbed by the scattered electrons. The contribution of the scattered photons to the total cross section can be calculated analytically using the following expression

$$\sigma_{C,(s)} = \pi r_e^2 \left\{ \frac{1}{\gamma^2 \ln(1+2\gamma)} + \frac{2(1+\gamma)(2\gamma^2 - 2\gamma - 1)}{\gamma^2(1+2\gamma)^2} + \frac{8\gamma^2}{3(1+2\gamma)^3} \right\},$$

(7.15)

which gives

$$\sigma_{C,(s)}^{\text{DPAC}}(511 \text{ keV}) = 0.1875 \text{ b},$$

(7.16)

suggesting that about half of the photons which undergo Compton interaction can potentially give rise to further interactions. Such further possible interactions will be neglected in this calculation since the estimation for their energy distribution is not straightforward. Left side of Figure 7.23 shows the computed cross section as a contribution of the energy of the incoming photon. The values calculated here are in agreement with the plots.

**Pair production**

To give rise to the production of an electron-positron pair, a photon should have an energy greater than 1.022 MeV. So, even if this contribution can be neglected for our 511 keV problem, it could be taken into account for further refinements due to the emission line at higher energies.

The main contribution to the overall cross section is thus that from Compton interaction. Putting everything together in accordance to Eq. (7.9) and following considerations, it is possible to get

$$\sigma_{tot} = 0.2863 \text{ b}$$

(7.17)

It can be worthy to compare the computed cross section for DPAC with the well-known plot for photon interaction on carbon from the PDG’s Review of Particle Physics, reported in the right side of Figure 7.23. Again, the comparison looks fairly reasonable.
7.4.3.5 Number of interactions

Now it is possible to calculate the absorption coefficient $\mu$ introduced in Eq. (7.7). Computing results obtained above, one gets

$$\mu = 0.90.$$  \hspace{1cm} (7.18)

The photon mass attenuation length, or mean free path, $\lambda$ [cm] will then be

$$\lambda = 11.12 \text{ cm}$$ \hspace{1cm} (7.19)

giving as photon absorption length $\lambda$ [g/cm$^2$]

$$\lambda = 11.01 \frac{\text{g}}{\text{cm}^2}$$ \hspace{1cm} (7.20)

in good agreement with the data available for absorption length of carbon and reported in Figure 7.24.

The number of photons interacting in the material will be estimated in the following steps. Neglecting the contribution from direct decay, one can consider the full amount of emitted photons to be produced by beta decays and electronic capture. While electronic capture produce one single photon, beta decays give rise in the end to three photons, i.e. the two from the positron annihilation and the one due to the nuclear de-excitation, with in principle two possible energies. From considerations in Section 7.4.1, it is possible to estimate 59790 decays per second, which goes into one single photon in 10.2% of cases and in three photons in the remaining 89.8%. The overall amount of photons emitted in one second is thus

$$N_{\text{ph}}^{(1s)} = 167170.$$ \hspace{1cm} (7.21)

However, photons who are emitted back-to-back have a degree of freedom less than those coming from other processes which, in principle, can be considered as emitted in all directions. This consideration should give to the effective number of photons potentially reaching the detector which follows:

$$N_{\text{ph},\text{eff}}^{(1s)} = 113481,$$ \hspace{1cm} (7.22)

divided as

$$N_{\text{ph},\text{eff}}^{(1s)}(511 \text{ keV}) = 53691,$$
$$N_{\text{ph},\text{eff}}^{(1s)}(1.274 \text{ MeV}) = 59790.$$ \hspace{1cm} (7.23)
CHAPTER 7. FAST DECAY LOW AFTERGLOW POSITRONIUM DETECTION

Figure 7.24: Absorption length for several absorbers as a function of the energy of the incident photon. In blue the extrapolation for carbon for 511 keV energy photons. [7]

All this together, from Eq. (7.6) it is finally possible to calculate the number of interactions due to 511 keV gamma rays:

$$N^{DPAC,(1s)}_{i, 511 \text{ keV}} = 312$$ (7.24)

The same considerations as above can be applied to the 1.274 MeV photons. It has to be remarked that such photon energy is far from the conditions of Born’s approximation for the computation of the pair production contribution and photoelectric contribution to the cross section. However, Figure 7.23 indicates that the last two processes may have once again a negligible contribution. Calculating the Compton cross section, one gets $$\sigma_C(1.274 \text{ MeV}) = 1.86 \cdot 10^{-25} \text{ cm}^2$$, obtaining as the overall contribution from such photons

$$N^{DPAC,(1s)}_{i, 1.274 \text{ MeV}} = 243$$ (7.25)

The same calculation can be done with data available from the EJ-200 data sheet [102]

$$N^{EJ200,(1s)}_{i, 511 \text{ keV}} = 329,$$
$$N^{EJ200,(1s)}_{i, 1.274 \text{ MeV}} = 247.$$ (7.26)

Results given for the number of interactions take only into account the first interaction. As the major contribution in the cross section is given by the Compton effect and the probability of a secondary interaction resulted not negligible, the most reliable prediction would result out of a simulation.

7.4.4 Measured distributions

Data have been taken with the detection scheme introduced in Section 7.4.2 (Fig. 7.21) and acquired as described in the above sections.

Pictures in Figs. 7.25 and 7.26 which follow show the distributions of peak amplitudes and integrated charge for DPAC-stilbene and EJ-200 coupled to a Hamamatsu R1828-01 photomultiplier each. However, the energy deposit of a photon from a sodium source in a carbon-based material could be smaller than the energy of the photon itself since the dominant effect in our conditions should be the Compton scattering, as discussed above (Sec. 7.4.3.3). A peak attributable to the maximum energy release due to the conversion of the 511 keV photon is clearly visible in all the distributions. A smaller peak is also
visible at higher energies and could be interpreted as due to the interaction of the 1.274 MeV photon. The best fits give for DPAC-stilbene

\[ V_{\text{DPAC}} = 7.98 \pm 0.28 \text{ V}, \]
\[ Q_{\text{DPAC}} = 1704 \pm 17 \text{ pC}, \]  

and for EJ-200

\[ V_{\text{EJ200}} = 4.80 \pm 0.07 \text{ V}, \]
\[ Q_{\text{EJ200}} = 4880 \pm 56 \text{ pC}, \]

\[ V_{\text{EJ200}} = 12.02 \pm 0.25 \text{ V}, \]
\[ Q_{\text{EJ200}} = 2411 \pm 39 \text{ pC}. \]  

It has to be considered that the supply voltage was lowered from 2300 to 2100 V for the measurements in this section, to reduce the noise in the tails of the signals. For a comparison between the plots in Figs 7.25 and 7.26, described by the above equations, and the analogue results obtained with cosmic rays, the gain characteristics of the photomultiplier has to be taken into account, provided by the manufacturer in [103].
7.4.5 Time profiles

In this section, the time profiles of the two detectors are compared with respect to the corresponding regions of the full distributions, in analogy with the analysis performed for cosmic rays (Sec. 7.3). Figure 7.27 presents the performance comparison of the two detectors in the regions corresponding to the maximum energy release due to the conversion of the 511 keV photon, showing the averaged traces of the two detectors, normalised to 1 V. EJ-200 has a smaller FWHM and looks to decay faster although DPAC-stilbene reaches the 0.1% level of the peak first.

This is more evident on logarithmic scale, as shown in the right side of the figure. The increase of the signal at around 300 ns for the blue curve and a bit farer for the pink one is attributable to after-pulses. The photomultiplier tubes coupled to the two scintillators, in fact, are the same model from the same producer and tend to respond the same way to analogue inputs. Another effect accountable to PMTs and their electronics is the ringing which is dominant in the first hundreds of nanoseconds after the peak and it has a negative impact in every precision measurement in the tail of the signals. According to the producer, the effect is well-known and it can happen for very fast-rise signals. A modification to the voltage divider could have reduced the issue [104]. Despite this, it is visible from pictures that DPAC-stilbene is below the EJ-200 over several hundred of seconds from the end of the peak in the region of interest for our studies.

Plots in Figure 7.28 help to quantify the comparison on decay time to the 0.1% level of the peak. DPAC-stilbene based detector (pink bullets) reaches the baseline within 40 ns from the peak time with this level slightly increasing with the peak amplitude and integrated charge. EJ-200 (in blue) shows instead a worst stability.

The linearity between the integrated charge and the peak amplitude is shown in Figure 7.29. It is possible to identify two regions of linearity with decreasing slopes. In the first one, (linearity region, DPAC: 0÷12 V, EJ-200: 0÷7 V), the detector collects the full energy released by the particle. For bigger signals, the peak amplitude does not reflect the full charge collected and it is possible to talk about part-saturation region. In the figure, blue and pink bullets indicate EJ-200 and DPAC-stilbene, respectively.

7.4.5.1 Cleaning the ringing effect

It is clear from the above section that DPAC-stilbene based detector reaches the baseline in great advance, if compared to the EJ-200. This becomes more clear if one tries to filter the ringing effect from the plots of the time profiles (Figure 7.27). The period of the ringing is comparable with the time interval of the peak i.e between its rise time and decay time preventing us the possibility to use a simple running average between few consecutive points, even trying to dynamically adapt the pace where to apply the damping. The mid points of the oscillation were determined with a three-steps algorithm in order to identify a fiducial curve for the decay from the peak. Top left side of Figure 7.30 summarises the steps for the identification of the fiducial curve and it shows the results for DPAC-stilbene. Local peaks (orange bullets) and valleys (in green) are detected paying attention to discriminate such points from local trends of the curve which are due to inhomogeneity of the signal or eventual additional noise with smaller period. A second function checks if peaks and valleys are alternate in time i.e. if a valley follow to any peak and vice versa. When this is not the case, the centre-of-mass of consecutive extremes is computed and the bullet repositioned. Finally, the blue open circles identify the half way between any peak-valley pair. The result of the application of the cleaning procedure is shown in the right side of the same figure, where the fiducial bullets are superimposed to the original curves. A bare interpolation of fiducial bullets is shown in bottom left and bottom right side of the figure, in detail of a linear scale and in logarithmic full scale, respectively. The application of smoothing functions, available e.g. in Root or Wolfram Mathematica, on these two data series would produce nicer plots. However, all the analyses here presented, included plots in Figures 7.28 and 7.29, are produced using values computed from original data, for the sake of reliability.
Figure 7.27: Averaged traces normalised to 1 V of the two detectors in the peak amplitude region of the maximum conversion of 511 keV photons. The right panel shows the plot in logarithmic scale.

Figure 7.28: Time to reach the baseline from the peak time for the DPAC-stilbene (pink bullets) and EJ-200 (blue bullets) versus the corresponding peak amplitude (plot on the left) and charge collected (plot on the right).

Figure 7.29: Linearity between the integrated charge and the peak amplitude for single photon interaction. DPAC-stilbene and EJ-200 are represented in pink and blue respectively, as usual.
7.5 Detection of positronium emission

Positronium is only produced in AEgIS by sending positron bunches to target converters. Measurements of Ps production are usually obtained by comparing the time profile of the averaged normalised curve for Ps production to data with positrons annihilating on a non-converting surface. To significantly compare such time profiles, the path travelled by photons from $e^-$ annihilations on non-converting surface should be consistent to that of gammas from positrons hitting the target, plus eventually those from Ps decay. Ideally, all of them should travel the same distance in the same chamber with possibly no obstacles inside and at the same environmental conditions.

Measurements discussed in this section are obtained from data taken in the Ps test chamber, described in Sec. 7.5.1. The target converter is placed on a movable target holder. When the target is removed from its position, positrons hit the surface right behind, at about the same distance from detectors as for Ps production. Also the material budget can be considered to be the same for the two data taking conditions. The structure of the Ps test chamber and the overall economy of time management in the experiment allowed to acquire data with the DPAC-stilbene based detector only in comparison with the PbWO$_4$ housed in the test chamber. Due to physical limitations of the AEgIS experimental zone, the DPAC-stilbene based detector is placed at longer distance from the annihilation point than the PbWO$_4$ with several centimetres of steel in between.

Data that were conceded for this measurement have been taken in different periods, with no information available for the number accumulator pulses for each $e^-$ bunch, unknown number of shots and no information at all about the moderator age.
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7.5.1 A dedicated positronium test chamber in AEgIS

Production and spectroscopy positronium experiments can also be done in a dedicated setup at environmental temperature connected to the positron accumulator. Positrons moderated, captured, accumulated and compressed in the positron system can be sent either in the main apparatus or in the Ps test chamber where they are implanted at 3.3 keV into a nano-channelled target analogous to that of the main apparatus. A representation of the chamber is shown on the left side of Figure 7.31. The test chamber has its own dedicated diagnostics for positronium detection. A 20 × 25 × 25 mm³ lead tungstate PbWO₄ scintillator is coupled to a Hamamatsu R11265-100 photomultiplier tube and placed 40 mm above the sample to record γ rays emitted in e⁺-e⁻ annihilations. The geometry of the Ps production region is shown on the right side of Figure 7.31.

Positronium is typically formed in the Ps test chamber by implanting a pulse of positrons (some $10^5$ e⁺/pulse, about tens ns pulse duration) with a kinetic energy of 3.3 keV into a nano-channelled silica target converter. Positronium atoms exit the nano-channels and diffuse into the vacuum losing a fraction of the emission energy by collisions with the walls. Rydberg-Ps atoms are excited to high principal number quantum levels by suitable laser pulses, while diffusing from the target. In the target region, positrons are guided by a 25 mT magnetic field and focused by an electrostatic lens formed by the last electrode of the transfer line set at -3000 V and the target kept at ground potential, inducing an electric field of about 300 V/cm, in front of the converter.

Ps is typically detected using the SSPALS method (Single-Shot Positron Annihilation Lifetime Spectroscopy). The technique, widely introduced in previous chapters, is based on monitoring the lifetime of Ps, which varies depending on its internal quantum state. The idea is to analyse the time profile of the analogue signal of a PMT connected to the scintillator detecting the gamma produced in the annihilation of e⁺ and Ps in different experimental conditions.

The ratio between the area of the delayed and prompt signals is expected to be of the same order. In addition, the delayed signal includes contributions from the delayed fluorescence of the scintillator, from after-pulses of the PMTs and eventually from possible electrical effects related to details of the PMT divider. Being the time duration of the prompt and delayed signals largely different, the ratio

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Figure 7.31: Two depictions of the experimental Ps test chamber. On the left, the working principle of Ps experiments in the chamber is shown [105]. On the right: distances of the target from the walls of the chamber and the detector holders [106].
of their amplitudes could be as large as a factor 100 or 1000. A scintillators with almost no intrinsic delayed light component should be capable of better performances in detecting such a tiny signals.

7.5.2 Checks on acquired data

Figures 7.32 and 7.33 show the distribution of peak amplitudes and charge collected for data taken in presence of positronium and data with no positronium formation, respectively.

Typically, the prompt peak of pulses acquired for positronium formation should show a lower amplitude than in condition of no Ps formation. With positronium formation, in fact, the annihilation of a significant fraction of positron is delayed, resulting in a reduction of the peak amplitude in favour of a considerable lift of the signal tail. The difference in amplitude between the averaged normalised curves of the two series gives a cross-check on the estimation of the amount of Ps produced.

The peak amplitude distributions for the data available for the measurements here presented, instead, show the opposite behaviour, with the distributions for Ps production centred around higher values than those for data with no Ps formation. To compare the two series, an equalisation is needed. Unfortunately, information about moderator age and absolute number of positrons per single run turned out to be unavailable for these runs. Another viable option could be an equalisation in integrated charge. It will be assumed that each detector would have collected the same amount of charge with and without Ps production, if the positron conditions were the same (Section 7.5.2.1). The considerations that follow support this assumption.

Figure 7.34 shows the peak-to-charge linearity for both the detectors and both the data series here considered. Peak amplitudes for DPAC-stilbene are scattered across a very tight range around 30 V, while the charge collected varies across a considerably wide spectrum. This suggests that the photomultiplier could be in a pre-saturation region, with the peak amplitude approaching a limit value (the peak is not sharply flattened at its top) and the amount of charge collected remaining linear with the energy deposited in the material i.e. with the light collected by the photomultiplier. Even though this is quite a typical behaviour in pre-saturation regime, the statement of charge linearity has to be verified. As a first check, it is possible to note that the distributions in Figures 7.32 and 7.33, right side, behave differently, with the charge distribution looking much wider than that for the peaks, hinting that the assumption looks reasonable. The bottom part of Figure 7.34 shows the detail for the two detectors. The fit functions hereinafter in this section are simple first order polynomial with two parameters, $p_0$ indicating the $y$-intercept and $p_1$ the increment of the straight line.

The plots in Figure 7.35 show the signal decay time defined as the time needed by the detector to go back to its baseline (same as in Sec. 7.3.2.2) for PbWO$_4$ and DPAC-stilbene detectors with and without Ps production. PbWO$_4$ reaches the 0.1% level of the signal peak in about 600 ns with $e^+$ annihilations only and it takes longer (up to 1 $\mu$s) when Ps is formed. Also the integrated charge is significantly different between the two data series. In both the plots the two distributions look well separated between each other. Distributions for DPAC-stilbene , instead, appear to be more uniform. While the peak amplitude is known to be saturated by reason of considerations above, the time to reach the baseline is only very little affected by the formation of positronium. The detector, in fact, takes a time between about 500 and 700 ns for both the data series. It can be noted that the bullets corresponding to measurements in presence of Ps reveal considerably more integrated charge collected, while the points from the two series look very well aligned, as also indicated by the two fit lines. This could give us the criteria for an equalisation of the two data series. If the data series with and without Ps formation were taken at the same condition, one would have the two clouds in the right-bottom part of Figure 7.35 overlapped to each other by a simple translation along the straight line composed by the two fit functions.

7.5.2.1 Charge equalisation

At this point, an equalisation procedure could consist in a vertical rescaling of the curves acquired for no Ps production by the numerical factor needed to overlap the charge distributions in Figure 7.33.
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Figure 7.32: Peak amplitudes distributions of PbWO$_4$ and DPAC-stilbene based detectors with positronium and in condition of no positronium formation.

Figure 7.33: Integrated charge distributions of PbWO$_4$ and DPAC-stilbene based detectors with positronium and in condition of no positronium formation.

Figure 7.34: Peak amplitude compared to the integrated charge for PbWO$_4$ and DPAC-stilbene based detectors with and without Ps production. Top: an overall picture. Bottom: the two detectors in closer detail.
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Figure 7.35: Signal decay time compared to peak amplitudes (top) and integrated charge (bottom)

Figure 7.37 shows the charge distributions resulting from such operation. For the sake of completeness, all other plots corresponding to figures from 7.32 to 7.35 are reported in Figures from 7.36 to 7.39. In particular, the charge distribution for DPAC-stilbene result overlapped.

Figure 7.36: Peak amplitudes distributions of PbWO₄ and DPAC-stilbene based detectors with and without Ps formation after equalisation.

7.5.3 Time Profile

The tail of the Ps curve is typically higher than that for no Ps formation in the first few hundreds of ns after the prompt peak. The amount of produced positronium is determined from the comparison of the averaged normalised curves for Ps and no Ps production. Ps production is quantified from the
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Figure 7.37: Integrated charge distributions of PbWO₄ and DPAC-stilbene based detectors with and without Ps formation after equalisation.

Figure 7.38: Peak amplitude compared to the integrated charge for PbWO₄ and DPAC-stilbene based detectors with and without Ps production for equalised data. Top: an overall picture. Bottom: the two detectors in closer detail.

difference in area of the two curves. Figure 7.40 shows the comparison between the time profile of the two detectors acquiring for positronium and no positronium formation. The curves for e⁺ annihilations were only rescaled according to Section 7.5.2.1.

Unfortunately, the response of the DPAC-stilbene detector is severely affected by electrical noise. The small peaks at 400 ns for the PbWO₄ and at about 350 ns for the DPAC-stilbene are due to after-pulses. In this kind of measurements, a reliable determination of the baselines with the consequent
equalisation of the curves is of paramount importance. Figure 7.41 shows the curves in a time interval taken in the pre-signal region. Graphical smoothing procedures fail in reducing the noise in the no positronium curve for the DPAC-stilbene detector. An attempt in which the features of the curves are conserved is made in Figure 7.42.

### 7.5.3.1  Ps decay time measurement

Gammas from ortho-Ps annihilation can be emitted even at longer times than 142 ns. Such photons populate the tail of the signals after the prompt peak in time profile plots. If the difference between the curves from the two data series is really due to the contribution of annihilations from long lived positronium, it should exponentially decrease with a time constant of 142 ns. Figure 7.43 shows an exponential fit \( e^{x}(p0 - x / (tau)) \) on the difference between the two averaged normalised curves for the two detectors. The errors on the single points take into account the deviation of each single curve from the average and the electrical noise. The electrical noise (Figures 7.45 and 7.46) is computed for both the series and in both the channels (low and high resolution) of each detector as the standard deviation from the average in a pre-signal region. The two contributions, assumed uncorrelated, are summed in quadrature. The error on the single point of each curve is thus the sum of the errors on corresponding points of the two curves. The errors displayed in the top right corner in figures are the statistical errors on a single fit. Plots in figures 7.43 and 7.44 show the result on a single fit implemented with Root’s TMinuit class with Migrad and Minos methods respectively for computing errors. Figure 7.44 only shows error bars of the single points. The determination of the systematic error is shown in Figure 7.47. The overall estimation for the lifetime of the Ps triplet component is for PbWO_4

\[
\tau_{PbWO_4} = 148.1 \pm 0.2^{(\text{stat})} \pm 0.10^{(\text{syst})} \text{ ns},
\]  

(7.31)
and for DPAC-stilbene

\[ \tau_{\text{DPAC-stilbene}} = 143.3 \pm 0.89^{\text{(stat)}} \pm 0.33^{\text{(syst)}} \text{ ns}. \] (7.32)

The decay value for PbWO\textsubscript{4} is slightly different than the nominal 142 \text{ ns}. This can be due to several reasons. Among them, there could be a non-exact optimisation of the equalisation procedure, discussed above. It has to be taken into account, in fact, that the equalisation procedure was only optimised for DPAC-stilbene based detector.
Figure 7.42: An attempt in noise removal from the curves. On the top, the time profile of the curves is showed. On the bottom, a pre-signal region after the baseline equalisation. Original data are also displayed in gray.

Figure 7.43: Exponential fit on the difference between averaged normalised curves acquired with and without Ps signal.
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Figure 7.44: Exponential fit on the difference between averaged normalised curves acquired with and without Ps signal. Error bars for each point are also shown.

Figure 7.45: Estimation of the contribution to the error due to electrical noise for Ps data.
Figure 7.46: Estimation of the contribution to the error due to electrical noise for no Ps data.

Figure 7.47: Distribution of the lifetime of the Ps long-lived component over ten thousand fit trials.

Figure 7.48: Distribution of the errors on lifetime of the Ps long-lived component over ten thousand fit trials. As the draft is now, I am not using results from this plot.
7.6 Detection of Rydberg positronium

An attempt to detect Rydberg excitation of positronium was made with the DPAC-stilbene based detector in comparison with the ESDA. The measurement here presented cannot be considered conclusive due to the high level of electrical noise. However, it provides a good indication of the viability of the use of this material as a scintillator for Ps* detection in the AEgIS production region. Rydberg excited positronium atoms have their lifetime considerably extended. On the other hand, they are more sensitive to high magnetic fields, like in the AEgIS production region. Therefore, the fraction of Ps excited to Rydberg states decays at longer times and a reduction in the tail of the time profile plots for Rydberg-Ps with respect to that of Ps at its ground state can be detected at times relatively short from the e− peak. An indicator for such measurement is the $S(\%)$ parameter, described e.g. in [107]. It corresponds to the relative difference between the areas of the averaged normalized SSPALS spectra of two data series, acquired in Ps formation condition with and without laser-excitation.

Figure 7.49 shows the response of one of the photomultiplier tubes of the ESDA and the DPAC-stilbene based detector for Rydberg excitation of positronium at the same conditions as for $\bar{H}$ production. As highlighted in Chapter 4, 300 runs do not suffice to see any difference with the EJ-200 slabs and the two curves corresponding to Ps formation with and without laser perfectly overlap. The structure around 200 ns is a well-known electrical reflection present for this measurement configuration only. The structure shortly after 500 ns is an after-pulse. The measurement with the DPAC-stilbene based detector, is strongly affected by electrical noise, as also noted in the sections above. However, analysing the data in the same time range as in [66] for an analogue measurement, i.e. 200 ns after the prompt peak the S parameter gives a reduction of

$$S(\%) = -4.3 \pm 0.3 (\text{stat})$$

compatible with the values reported in Chapter 4 and measured with a different technique.

As at longer times the measurement is dominated by the electrical noise, it is impossible to measure the corresponding excess in the tail of the signal. However, when the integration range changes, one can still see a signal, albeit with wide variations, ranging from 2 to 5, with consistent statistical errors. This confirms that the measurement is dominated by the systematic error, which can estimated as a 1.5%.

![Figure 7.49: Time profiles of data on Rydberg excitation of positronium at the same conditions as for $\bar{H}$ production.](image)

Therefore, it is necessary to solve the problems related to electrical noise to continue to focus on this material, although this first work showed encouraging results. Then, a more accurate measurement campaign on the Rydberg positronium detection should be carried out with more machine time available.
Conclusions

In this thesis, I described the procedures for the first pulsed production of antihydrogen, the main operations and developments for this achievement in preparation of a direct measurement of the Earth’s gravitational acceleration, $g$, on antimatter. To date, in fact, the question of whether antimatter falls in the Earth’s gravitational field with the same acceleration does not yet have a direct experimental answer.

Antihydrogen is now produced in AE$ar{g}$IS via charge-exchange reaction between antiprotons and clouds of laser-excited positronium. The production of $110 \pm 25$ atoms of antihydrogen has been demonstrated, in agreement with the predictions. The calibration for the detection of antihydrogen, the datasets acquired for this measurements and the determination of the result were described. Remarkably, a paper with the results here presented have been submitted to Nature Physics.

Antiprotons in AE$ar{g}$IS are captured, compressed, ballistically transferred, cooled down and stored in conditions suitable for efficient antihydrogen production. An outstanding antiproton plasma compression was achieved, the best ever reached, which allowed an efficient transport to the production trap. A full implementation of a stacking procedure was also achieved to substantially increase the number of antiprotons available per antihydrogen production trial. The compression of several AD shots of antiprotons resulted in the possibility to store of up to $10^6$ antiprotons for tens of antihydrogen production cycles, corresponding to more than one hour, despite the issues due to the non-standard design of the electrodes. Remarkably, such number of stored antiprotons was about 10 times larger than expected in the original AE$ar{g}$IS proposal, with a single-cycle production procedure.

Several novel detection techniques were implemented in the positronium diagnostics. In particular, the use of a kicker pulser to detect the charge induced by the passage of the positron bunch was developed, tested and used as a main technique to monitor the condition of the positrons entering the main apparatus. On the top of this, the conversion of the MCP into a position sensitive detector for slow positronium allowed to characterise the Rydberg state of this unstable atom in magnetic field.

A dedicated low-energy antiproton test stand facility was built with fully electrostatic optics to provide slow antiprotons of known energies while minimizing the background produced by the annihilation of faster antiprotons in order to test various detection technologies. A summary of the main detector test carried out over the last years has been reported.

A novel fast rise low afterglow scintillating material was tested to be introduced as a possible new detector for better characterisation of positronium in the production region. An extensive characterisation of the material was completed and a detector based on it was assembled with a fast response photomultiplier tube. A careful analysis within the boundary conditions of the available data quality is also presented. Such detector succeeded in detecting the formation of positronium and gave encouraging results for the detection of the elusive Rydberg-Ps states in magnetic field.
Bibliography


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