Manipulation of positron plasma using the AEgis system at CERN

Ola Kenji Forslund

2015-05-28

LITH-IFM-A-EX—15/3051—SE
Manipulation of positron plasma using the AEgIS system at CERN

Ola Kenji Forslund
Thesis work done at CERN
2015-05-28

Supervisors
Michael Doser (CERN)
Martin Magnuson (IFM)
Sebastiano Mariazzi (CERN)

Examiner
Jens Birch (IFM)
Dataabhandling

Division, Department

Chemistry
Department of Physics, Chemistry and Biology
Linköping University

Språk
Language

☐ Svenska/Swedish
☐ Engelska/English

Rapporttyp
Report category

☐ Licentiatavhandling
☐ Examsarbete
☐ C-uppsats
☐ D-uppsats
☐ Övrig rapport

ISBN


URL för elektronisk version

Title
Manipulation of positron plasma using the AEGIS system at CERN

Author
Ola Kenji Forslund

Sammanfattning
Abstract

AEGIS is an experiment at CERN where the goal is to directly measure the gravitational force on antimatter by producing antihydrogen. The antihydrogen will be produced by a charge exchange reaction using laser excited positronium and cold antiprotons. Having a well-characterized positron plasma with at least $10^8$ positrons and knowing how it can be controlled is essential for the positronium production. This thesis is based on the goals of AEGIS experiment and describes the positron plasma manipulations being used in AEGIS in order to achieve the required plasma properties for the experiment. The positron system is made up by a source, a Surko trap and a Penning-Malmberg trap. This system was first optimized to increase the number of positrons. The plasma was then moved to the main traps of the experiment where it was systematically characterized in terms of lifetime, cooling efficiency and compression. Positron plasma compression in time, trapping and cooling was tested for the first time in AEGIS using a buncher and Penning-Malmberg traps respectively. In this thesis, it is shown that a compression of more than 50% in time of the positron cloud using a buncher can be achieved. It is also shown that trapping and cooling with an efficiency of nearly 100% in the main traps using a “V” shaped potential trap was successful. On top of that the lifetime inside this “V” shaped potential trap was observed to be longer than 30 minutes.

Nyckelord
Keyword

Positron plasma, AEGIS, CERN
Abstract
AEGIS is an experiment at CERN where the goal is to directly measure the gravitational force on antimatter by producing antihydrogen. The antihydrogen will be produced by a charge exchange reaction using laser excited positronium and cold antiprotons. Having a well-characterized positron plasma with at least $10^8$ positrons and knowing how it can be controlled is essential for the positronium production. This thesis is based on the goals of AEGIS experiment and describes the positron plasma manipulations being used in AEGIS in order to achieve the required plasma properties for the experiment. The positron system is made up by a source, a Surko trap and a Penning-Malmberg trap. This system was first optimized to increase the number of positrons. The plasma was then moved to the main traps of the experiment where it was systematically characterized in terms of lifetime, cooling efficiency and compression. Positron plasma compression in time, trapping and cooling was tested for the first time in AEGIS using a buncher and Penning-Malmberg traps respectively. In this thesis, it is shown that a compression of more than 50 % in time of the positron cloud using a buncher can be achieved. It is also shown that trapping and cooling with an efficiency of nearly 100 % in the main traps using a “V” shaped potential trap was successful. On top of that, the lifetime inside this “V” shaped potential trap was observed to be longer than 30 minutes.
Abbreviations
AD – Antiproton Decelerator
ALPÎA – Antihydrogen, Laser, Physics, Apparatus
AÆgIS – Antimatter Experiment: Gravity Interferometry Spectroscopy
CERN - European Organization for Nuclear Research
FWHM – Full Width Half Maximum
HV – High Voltage
MCP – Multichannel Plate
Ps – Positronium
Ps* – Rydberg state Positronium
o-Ps – Ortho Positronium
p-Ps – Para Positronium
PMT – Photomultiplier Tube
PALS – Positron Annihilation Lifetime Spectroscopy
PS - Proton Synchrotron
RW – Rotating Wall
SSAPLS – Single Shot Positron Annihilation Lifetime Spectroscopy
SCCM - Standard Cubic Centimeter per Minute
WEP - Weak Equivalence Principle
Table of Contents

1 Introduction .................................................................................................................................................. 1
  1.1 Methodology ........................................................................................................................................ 2
  1.2 Overview of AEgIS ................................................................................................................................. 3
    1.2.1 Antiprotons and positrons sources .................................................................................................. 3
    1.2.2 Recombination schemes for antihydrogen ....................................................................................... 3
    1.2.3 Laser excitation ............................................................................................................................... 4
    1.2.4 Experimental setup of AEgIS .......................................................................................................... 5
    1.2.5 Moiré deflectometer ....................................................................................................................... 7
2 Theory .......................................................................................................................................................... 9
  2.1 Antimatter ............................................................................................................................................. 9
  2.2 Positrons .............................................................................................................................................. 9
    2.2.1 Positron sources ............................................................................................................................ 10
      2.2.1.1 Pair production ....................................................................................................................... 10
      2.2.1.2 Radioactive sources .............................................................................................................. 10
    2.2.2 Positron work function ................................................................................................................. 10
    2.2.3 Positrons in matter ....................................................................................................................... 11
  2.3 Positronium .......................................................................................................................................... 13
    2.3.1 Positronium formation potential and work function ...................................................................... 14
      2.3.1.1 Positronium formation processes ............................................................................................ 15
  2.4 Moderation .......................................................................................................................................... 15
  2.5 Trapping none neutral plasmas ............................................................................................................. 17
    2.5.1 Particles and plasmas in Penning traps ........................................................................................... 17
    2.5.2 Cooling in penning traps ............................................................................................................... 19
      2.5.2.1 Laser cooling .......................................................................................................................... 19
      2.5.2.2 Resistive cooling ..................................................................................................................... 19
      2.5.2.3 Electron cooling ...................................................................................................................... 19
      2.5.2.4 Buffer gas cooling .................................................................................................................. 20
    2.5.3 Rotating wall .................................................................................................................................. 20
  2.6 Detection of positrons and positronium ................................................................................................. 21
    2.6.1 PALS ............................................................................................................................................. 21
    2.6.2 SSPALS ........................................................................................................................................ 22
    2.6.3 Detectors ..................................................................................................................................... 22
3.6.3.1 Scintillators ................................................................. 22
3.6.3.2 Cherenkov radiator ...................................................... 23
3.6.3.3 Imaging detectors ....................................................... 23
2.7 Vacuum pumps ................................................................... 23
2.7.1 Turbo pump ................................................................. 23
2.7.2 Ion pump ....................................................................... 24
2.7.3 Cryopump ...................................................................... 24
3 Experimental setup .................................................................. 25
3.1 Positron source ................................................................... 26
3.1.1 Neon moderator ............................................................. 26
3.1.2 Transport from the source to the trap ............................. 27
3.1.3 Shielding of the source from radiation and magnetic fields ............................................................................. 27
3.1.3.1 Hysteresis ................................................................. 28
3.2 Trap ................................................................................... 28
3.3 Accumulator ....................................................................... 30
3.4 Transfer line to the test chamber ........................................ 31
3.4.1 Buncher ........................................................................ 32
3.4.2 Test Chamber ............................................................... 33
3.5 Transfer line to the main traps ............................................ 33
3.5.1 5 T and 1 T traps ............................................................ 34
3.6 Detectors ........................................................................... 35
3.6.1 Detectors along the positron system ............................... 35
3.6.1.1 Calibration of CsIs ....................................................... 35
3.6.1.2 Confirmation of calibration ........................................ 37
3.6.2 PbF2 .............................................................................. 38
3.6.3 Detectors along the main traps ....................................... 38
3.6.3.1 Calibration of PMT-20 ............................................... 39
4 Results and discussions .......................................................... 40
4.1 Positrons in the accumulator .............................................. 40
4.1.1 RW and ring potential dependence ............................... 40
4.1.2 Positron lifetime inside the accumulator ...................... 42
4.1.3 The beam spot size ....................................................... 43
4.1.4 The presence of fields from the main traps .................... 45
4.2 Bunching ................................................................. 47
4.3 Positrons in the main traps .......................................................... 49
  4.3.1 Pass throughs ............................................................ 50
    4.3.1.1 Steering ......................................................... 50
    4.3.1.2 Energy and time distributions ................................ 51
    4.3.1.3 Spatial 2D ..................................................... 53
  4.3.2 Catching and cooling procedures in the 5 T trap ...................... 55
    4.3.2.1 Potentials in the c-trap ....................................... 56
    4.3.2.2 Lifetime and plasma expansion in the c-trap ................ 57
    4.3.2.3 RW scan in the c-trap ....................................... 60
    4.3.2.4 Stacking of positrons in the c-trap .......................... 63
  4.3.3 Transfers to the big trap ............................................... 64
    4.3.3.1 The FWHM and the lifetime inside the b-trap ............... 64
    4.3.3.2 RW in the b-trap ............................................ 66
5 Conclusion ............................................................................ 67
  5.1 Future prospects ............................................................. 68
6 Acknowledgments ................................................................. 69
7 References ........................................................................... 70
1 Introduction

Already in late 1800, the concept and the idea of antimatter were already in speculation. However, the first theoretical acknowledgment of antimatter came first in 1928 by Paul Dirac. He realized that his relativistic Schrödinger-equation allowed positively charged electrons, which are now called antielectrons or positrons. [1] These antielectrons were later discovered in cosmic rays by Carl D. Anderson in 1932 and were named positrons [2]. Ever since, a deep study of antimatter has been genuinely desired. It is believed that big bang created equal amount of antimatter and matter. However, as it stands today, a large fraction of matter is left over. [3] This problem is called Baryon asymmetry. Thus the question is, what happened to all the antimatter? The standard model, particle physics or general relativity cannot explain this asymmetry. Therefore, it is essential to know more about antimatter in order to understand the processes that were undergone during the first few moments after the big bang. However, as antimatter easily annihilate as it comes in contact with regular matter, the study of antimatter is difficult. Due to this, the development of the field has been slow. Nevertheless, progress has been made especially in the last decades as better equipment has been accessible. In big experimental facilities such as CERN, measurements on antimatter are carried out on a daily basis.

European Organization for Nuclear Research (CERN) is an European organization founded in 1954. It is based in the suburbs of Geneva on the border of France-Switzerland. CERN is probably most famous for operating the world’s largest particle physics laboratory and for its scientific achievements. In 2012, CERN discovered the Higgs boson and this was a very important discovery in the world of particle physics. [4]

![Figure 1. An overview over CERN accelerators. The small arrows indicate the direction of the particles.][5]
CERN consists of several accelerators to conduct different experiments. Figure 1 is an overview of the accelerators at CERN. At the moment, one of the most interesting experiments going on at CERN is the measurement of Earth’s gravitational acceleration on antihydrogen. There are several groups working with antimatter at CERN and one of them is called Antihydrogen, Experiment, Gravity, Interferometry and Spectroscopy (AEgIS). It is going to use antiprotons and positronium (Ps) to create antihydrogen. Antiprotons are the antiparticle analog to protons and positronium is a bound state between a positron and an electron, see chapter 2 for more detailed descriptions. Antihydrogen is the antimatter counterpart to hydrogen where the atom is made up of a positron and an antiproton. The probability of recombining antiprotons and positronium is very dependent on the total number of positrons and antiprotons as well as on their densities. A large amount of positronium is therefore essential for this experiment. It is very important to be able to manipulate and control the positron plasma to be able to produce the positronium with desired properties required for antihydrogen production.

This thesis will focus on manipulation of positrons. In particular, the production of a non-neutral plasma of positrons and its transport, cooling and compression in space and in time is described. All measurements and data have been performed using the AEgIS experimental system.

1.1 Methodology

The study of antimatter is of high interest as it holds the key to solve one of the greatest mysteries of the universe, the Baryon asymmetry. All theories suggest antihydrogen and hydrogen to be exactly the same in all aspects of properties. However, this will never be known until real measurements have been carried out. One way of comparing the atoms is through energy spectroscopy measuring the (internal) electronic states between matter and antimatter. Different groups like Antihydrogen, Laser, Physics, Apparatus (ALPHA) at CERN are trying to measure the hyperfine splitting by probing it with a well-tuned frequency of radiation and flipping the spins. In 2010, the ALPHA experiment at CERN was the first to be successful in trapping antihydrogen. However, so far spectroscopy has resulted in expansions of the antihydrogen cloud, resulting in annihilations with the trap wall. AEgIS on the other hand is trying to directly measure the gravitational interaction on antihydrogen by the method described in this thesis and in the section below. If successful, this will represent the world’s first gravity measurement on an antiatom. However, as AEgIS is a relatively new experiment, antihydrogen has not been able to be produced yet. For the production, cold positrons and ultra-cold antiprotons have to be trapped in a certain ways in order to produce antihydrogen through a charge exchange reaction at AEgIS (see “1.2.4 Experimental setup of AEgIS“ and “1.2.2 Recombination schemes for antihydrogen”).

If successful, AEgIS would be the first experiment to produce antihydrogen through the charge exchange reaction. It is believed that the resulting energy of antihydrogen will be significantly lower by production through the charge exchange reaction compared to simply over imposing a positron plasma with an antiproton plasma. This method requires a large number of cold positrons trapped in a compressed manner in a special trap. There still remains a lot of work to be done before antihydrogen is produced following this road. Nevertheless, the goal of this thesis is to perform measurements and to analyze the positron plasma to get the AEgIS experiment closer to its goal. This is going to be achieved by systematically analyzing the different steps and the different methods required to catch and cool a high number of positrons. It is crucial to understand the total number of positrons the positron system is able to produce, the lifetimes, compression and cooling efficiencies of the plasma in the different traps and also how the trap has to be shaped in order to trap and cool the positron plasma. Different detector
types such as scintillators, imaging detectors and Cherenkov detectors are used to characterize the positron plasma (see “2.6 Detection of positrons and positronium”). An imaging detector setup and a plastic scintillator coupled to a Photomultiplier Tube (PMT) are used to characterize the positron plasma in the main traps. The positron distribution in space and time can be obtained with these detectors. The traps used for catching and cooling are so called Penning-Malmberg traps that are described in the section 2.5 Trapping none neutral plasmas. Different cooling techniques as well as a technique called Rotating wall (RW), that is used to compress the plasma, are also described here.

1.2 Overview of AEgIS

As previously mentioned, the primary scientific goal of the experiment is to directly measure Earth’s gravitational acceleration on antimatter. If successful, this would represent a first direct measurement of a gravitational effect on antimatter. AEgIS is currently in stage 1 of its experimental life where the goal is to produce the simplest antimatter, the antihydrogen. Antihydrogen is going to be produced by superimposing Rydberg state positronium with antiprotons. The final goal is to use the antihydrogen to test the Weak Equivalence Principle (WEP) on antimatter; the principles of free fall. This is going to be carried out with 1% precision by sending ultra-cold antihydrogen through a Moiré deflectometer.

1.2.1 Antiprotons and positrons sources

Antiprotons are created in the Proton Synchrotron (PS) by accelerating protons to the speed of light and colliding them with a block of metal. This acceleration is carried out in several accelerators. See figure 1 for an overview over the accelerators. Regular hydrogen is used as a proton source by ionizing it with an electric field. The protons are transported to the first accelerator Linac 2. Linac 2 accelerates the protons to 50 MeV resulting in 5% more mass for the protons. The proton beam is then transported to the Proton Synchrotron Booster which accelerates the protons to 1.4 GeV. The protons are then accelerated in the PS to an energy of 25 GeV and collide with a block of iridium. The protons have enough energy to create new proton-antiproton pairs and are created once in a million through a process called pair production. Created antiprotons travel nearly in speed of light and have too much energy for any experimental use. The antiprotons are then decelerated in the Antiproton Decelerator (AD) and form a relatively low energy beam to about 10% of the speed of light. This relatively slow beam of antiprotons can then be used and trapped to be recombined with positronium to form antihydrogen in AEgIS. [6]

The positrons are supplied with a Sodium-22, a radioactive source installed together with a series of Surko traps (see chapter 3 for a detailed description of the positron system). AEgIS is using pulses of positrons instead of a beam to achieve a high and a dense positron plasma. The pulse is transported to the main traps to be recombined with antiprotons. So far, a number of >10^7 positrons have been accumulated and trapped in the 1 T trap with the AEgIS positron system.

1.2.2 Recombination schemes for antihydrogen

There are several ways to produce antihydrogen. The simplest way would be to superimpose a positron plasma and an antiproton plasma (this was done in 1995 in the ATHENA project at CERN). This is called spontaneous radiative recombination:

\[ \text{e}^+ + \bar{P} \rightarrow \bar{H} + \text{hv} \]
This method can be improved by stimulation of photons called the stimulated recombination mechanism. The idea is to stimulate positrons in a trapped continuum to a deexcited to bound state. However, lasers are monochromatic so only positrons lying in certain continuum can be stimulated to be pumped down into a lower bound state. Therefore, a high-density power laser as well as a low energy spread of positrons is required. It has also been suggested to use a three-body collision in a dense positron plasma in the following way:

$$e^+ + e^+ + \bar{P} \rightarrow \bar{H} + e^+$$  \hspace{1cm} (2)

In all interactions, energy and momentum are always conserved. The idea here is if a positron and an antiproton have an overload of either energy or momentum, these can be transferred to a third positron. As an antihydrogen is created, the third positron has now a new energy with new momentum and can interact with other particles in the plasma. [7]

However, since the goal for AEgIS is to test WEP by using a Moiré deflectometer, it is important that the antihydrogen atoms are cold. A cold antihydrogen plasma will have a small radial expansion and can therefore be focused onto the interferometer. The antihydrogen will be created by the resonant charge exchange reaction: superimposing Rydberg state positronium (Ps*) and antiprotons (P). A reaction using positronium instead of positrons will result in lower energy of antihydrogen (\(\bar{H}\)). The reaction will happen accordingly

$$Ps^* + \bar{P} \rightarrow \bar{H}^* + e^-$$  \hspace{1cm} (3)

where * indicates that the atom is excited to a Rydberg state. The resulting antihydrogen will be in Rydberg state since the reacting positronium is. The formed antihydrogen is formed with a velocity distribution dependent on the antiproton energy, i.e. if the antiprotons are at rest very cold antihydrogen can be formed. The reason for exciting positronium to Rydberg state is to increase its lifetime since the lifetime scales with the third power of the quantum principal number. In addition, the cross section scales with the fourth power of the principal quantum number of positronium. [8] The amount of antihydrogen that can be produced is proportional to the cross section of the reaction. Therefore, exciting positronium to a Rydberg state increases the antihydrogen production significantly.

1.2.3 Laser excitation

Positronium is going to be excited to a Rydberg state by lasers, see figure 2. The excitation appears in two steps: from the ground state to the n=3 state and from there to a Rydberg state, n>20. The transition energy to Rydberg state from ground state will be greater than 6 eV. The reason for using two lasers instead of one is lasers with the energy greater than 6 eV do not yet exist. Positronium in Rydberg state have previously been reported through a n=2 excitation but excitation through a n=3 has never been performed. One of the reasons to excite them through a n=3 is that the positronium lifetime is three times higher in a n=3 state than in a n=2 state. The lasers of use are two dye lasers with 205 nm and 1640 nm respectively. A 205 nm laser will excite the positronium first to n=3 and a 1640 nm laser will directly after excite them to a Rydberg state. These lasers need to have enough power to excite the positronium cloud in a matter of a few nanoseconds.
Figure 2. The relevant energy levels from the ground state to a Rydberg state of positronium. Two cases are presented, with and without a 1 T magnetic field. [9]

The created positronium in AEGiS will be moving in a velocity in the order of $10^4$ m/s. The movements together with the presence of strong magnetic field and electric fields cause the positronium energy level to shift. The energy levels of positronium will be broadened by the Doppler effect and on top of that, the sublevels will be split according to the Stark and the Zeeman effects. [10]

1.2.4 Experimental setup of AEGiS

The AEGiS experiment can be divided into two parts: the positron system and the main traps. The positron system consists of a Surko trap and a Penning-Malmberg trap where the goal is to provide a dense positron plasma with a number of $\sim 10^8$. The main traps are few meters long multi ring Penning-Malmberg traps and are used to slow down and to trap the positrons and the antiprotons to make them recombine into antihydrogen. Figure 3 is an overview over the main traps. The main traps consist of two Penning-Malmberg traps, although they differ in the number of electrodes as well as the strength of the magnetic fields. The first trap uses a magnetic field of 5 T and the latter one uses a 1 T field. A strong magnetic field is desired to trap and cool antiprotons and positrons in an efficient way. However, it is better to have a low magnetic field where the electric acceleration of the Rydberg state antihydrogen takes place. Together, both magnets provide a uniform magnetic field making trapping more continuous. These fields are generated by two superconducting magnets. These superconducting magnets can only operate in cryogenic temperatures, 4 K, and requires liquid helium refills every day to maintain the temperatures. This sums up to total liquid helium consumption to 12000 liters per month. Liquid nitrogen is used as well to save liquid helium as it is expensive. The whole system is pumped with several pumps to maintain an ultra high vacuum.
Figure 3. An overview over the main traps in the AEgIS experiment. The positrons and the antiprotons are provided from the positron system and from AD. Schematics over the positron system are omitted in this figure. The experimental setup section contains all information about the positron system. [9]

Antiprotons are delivered from the AD every 100 seconds in a pulse with a number of $10^7$. Due to their high energy, they are cooled by transferring them through degraders before they are trapped in the 5 T trap. Here, electron cooling further cools them through coulomb interaction (see “2.5.2.3 Electron cooling”). The cooling takes place until antiprotons are cooled to few eV. Once cooled, the antiprotons are then transported to the 1 T trap where they are further cooled to 100 mK which corresponds to a velocity distribution of few tens m/s. A number of $10^5$ cold antiprotons can be ready for recombination by stacking several shots from AD. This stacking can be carried out in parallel with cooling of the particles.

Positrons accumulated with the positron system are magnetically transported to the main traps for trapping and cooling. The positrons are first trapped in the 5 T trap where they lose most of their energy through cyclotron radiation. The electrodes in the traps are raised in right timing for catching and for cooling the positron plasma. They are then transported to the 1 T trap as cooling is completed. The positronium converter is fixed off axis in 1 T requiring positrons to be trapped off axis as well. The positrons are then accelerated towards the target forming positronium. Formed positronium will have a velocity of a few $10^4$ m/s. These are laser excited to a Rydberg state where the goal is to have $>10^6$ excited positronium atoms.

Antihydrogen formation trap is mounted very close to positronium formation target. Part of the on-axis trap is transparent allowing positronium to reach the antihydrogen formation trap where cold antiprotons (100mK) are stored. The formed antihydrogen will then be accelerated with inhomogeneous electric fields by a so called Stark acceleration through a Moiré deflectometer. The antihydrogen will be accelerated immediately after formation to a velocity of few hundreds m/s in the horizontal direction while the radial velocity is kept to few tens m/s. Neutral atoms are not sensitive to constant electric fields but they do experience a force when the dipole moment is exposed to an electric field gradient.
Luckily, the dipole moment scales with the square of the principle quantum number, i.e. atoms in Rydberg state are very sensitive to electric field gradient and can easily be manipulated. For the same reason, these atoms need to decay into ground state as they travel towards the deflectometer so that electric fields do not interfere with the flight of antihydrogen through the Moiré deflectometer. The decay into ground state can be stimulated by lasers if necessary. From the formed pattern, the value of Earth’s gravity on antihydrogen can be measured with an accuracy of 1 %. See figure 4 for the schematics over the processes.

![Figure 4. A schematic representation of antihydrogen formation in AEgIS experiment. [9]](image)

1.2.5 Moiré deflectometer

AEgIS is going to use a Moiré deflectometer together with a position sensitive detector for the gravity measurement on antihydrogen. The idea is to use two identical transmission gratings and a nuclear emulsion detector 25 mm from each other. The grating period will be in the range of micrometers. An antihydrogen beam will interfere through these gratings and form a pattern. However, the antihydrogen pattern will be slightly shifted due to earth gravitation. Using Newton’s second law, the acceleration that the atoms are subjected to can be calculated if the flight time is known according to

\[ \Delta y = \frac{F}{m} t^2 = a \left(\frac{L}{v}\right)^2 \]  

where \( F \) is the vertical component of the force, \( m \) is the mass, \( t \) is the time of flight, \( L \) is the distance between the grating and the detector and \( v \) is the velocity of the atoms. The velocity of antihydrogen can also be calculated very precisely since the velocity depends on the temperature of the atoms. To determine the magnitude of this shift (\( \Delta y \)), a reference beam is required. A monochromatic light with a known wavelength can be used as a reference since there is a known relation between this distance \( L \) as...
a function of the wavelength and the grating period. The reason for using two instead of one grating is the first two gratings set the propagation direction of a diverging beam, i.e. it works as a filter making the beam more monoenergetic. Moreover, this setup requires a very precise distance in order to make sure that the maxima from the first grating to pass through the second grating. Thus, a very intense and clear interference pattern will be the result. [11] See figure 5 for an overall idea.

Figure 5. a) A simple schematic over the gratings and the detector. The two detectors are only for understanding the shift between matter and light pattern. b) A possible flight path for antihydrogen. c) Normal interference of light through two gratings. [9]
2 Theory
This section will bring up the most relevant antimatter physics that is needed to explain the behaviors of positrons and positronium. It is important to have a basic knowledge of antimatter and the apparatus used in experiment in order to understand the results and the discussion part of this thesis. A description of positrons’ interaction with matter as well as trapping and cooling techniques of positron plasma is included.

2.1 Antimatter
Current theory of particle physics states that particles and antiparticles should have the same properties with opposite charges. This property is called “matter-antimatter symmetry”. An antiparticle has exactly the same mass and spin as a particle but the charge is the opposite. On top of that, just as regular particles bind to other particles, antiparticles bind to other antiparticles in the same way. An encounter of matter and antimatter results in annihilation and give rise to energy (most often gamma rays) in accordance with mass-energy equivalence equation $E = mc^2$. Positrons and antiprotons have been observed in cosmic rays, presumably produced by high-energy collisions between particles and regular matter (see “2.2.1.1 Pair production”). Antiparticles can also artificially be created at accelerators through collisions with highly accelerated particles. However, more complex antimatter than antihelium has not be produced or observed yet. Antimatter is one of the most difficult materials to produce today.

2.2 Positrons
The antimatter counterpart to electrons is called positrons. A positron has the same mass and spin as the electron but the magnetic moment and charge is the opposite while the absolute values are the same. As an antiparticle, positrons are highly reactive with regular matter. The most common way for positrons to annihilate is via electrons called electron-positron annihilation. The annihilation results usually in gamma rays in the following way:

$$e^+ + e^- \rightarrow 2\gamma \quad (5)$$

The process must satisfy conservation laws such as conservation of electric charge, conservation of linear momentum and total energy and conservation of angular momentum. If the particles are at rest, each gamma ray is emitted collinearly in the opposite direction with an energy of 511 keV. [12]

Positrons are identical to electrons in many respects, and their behaviors in solids are often similar as well as the thermalisation processes or implantation profiles. An important feature for positrons is that they are distinguishable from electrons. It is impossible to follow the implantation history of electrons as they get lost in the sea of electrons. For positron however, it is possible to follow each positron before its annihilation. The fact that the charge is opposite makes the positrons useful in several areas where electrons cannot be used. Positrons can be trapped in negatively charged traps or defects. This feature makes positrons an ideal source for defect detection in materials by lifetime spectroscopy and Doppler broadening spectroscopy (see “2.6 Detection of positron and positronium”). These techniques provide information not only about the types of defects and the concentration but also about the electron density and momentum distribution. It is also possible to gain information about the material from the reemitted positron and positronium (see “2.3 Positronium”) by measuring the energy distribution. [13]
2.2.1 Positron sources

Positrons can either be generated from radioactive sources or by a method called pair production. Both methods provide positrons in a good manner. Pair production has the advantage that more positrons can be created over the same time compared to radioactive sources. However, generating positrons from a radioactive decay is more preferable as it is more cost effective and easily maintained.

2.2.1.1 Pair production

Positrons can be generated when high-energy photons interact with a nucleus. The energy of the photon can be converted into a positron and an electron through mass-energy equivalence equation. This is typically realized by colliding high-energy electrons into high dense materials such as Ta, W or Pt. These collisions result in bremsstrahlung radiation that interacts with the nucleus followed by this formula:

\[ \gamma + \gamma \rightarrow e^+ + e^- \]  

This method is called pair production as positrons and electrons are generated in pairs. The conservation laws must be satisfied even here meaning the incoming energy must at least be higher than the rest masses of the positron and the electron. This is also the reason why the magnetic momentum or the electric charge is the opposite for the produced particles. The production efficiency depends on the incident electron energy as well as on the thickness of the target. The optimum thickness and energy depend on the material but they can be in the range of mm and MeV respectively. [14]

2.2.1.2 Radioactive sources

There is a particular radioactive decay called beta decay. In these decays, a proton is transformed to a neutron, or vice versa, to preserve an optimal ratio between protons and neutrons. In these decays, a beta particle is emitted in a form of an electron or a positron to preserve the charge. Positrons are emitted when a proton is transformed into a neutron and electrons are emitted when a neutron is transformed into a proton. The decay resulting in positrons is called $\beta^+$ decay. Materials with this kind of decay can be used as a positron source. There are several isotopes with this kind of decay, such as Sodium-22, Cobalt-58 or Cupper-64. These decays result in positrons in all directions. Therefore, a highly dense backing material can be used to provide backscattering of positrons into the forward direction to increase the intensity in the desired direction. The choice of a source is a compromise between cost per Bq and half-life. Cupper-64 half-life is only 12.8 hours while Sodium-22 has a half-time of 2.6 years which makes it a preferable choice in many long term experiments. Half-life of Cobalt-58 is only 71 days but has a much higher activity compared to Sodium-22. Thus, Cobalt-58 is commonly used in experiments where a high intensity beam is desired over short periods. Positrons, generated by pair production and radioactive sources will have a wide energy spread. As it is usually desired to have a narrow monoenergetic beam of positrons, a method called moderation is used. Moderation is an important part of the AEgis positron system and will be described in great detail later. [15]

2.2.2 Positron work function

For particles to be spontaneously emitted to vacuum from a material, the energy level in the vacuum has to be lower than the energy of the ground state in the material. The positron work function ($\Phi^+$) is defined in the same way as the electron work function ($\Phi^-$); the minimum energy required to remove a bulk positron to just outside the surface. The positron and the electron work functions are given by

\[ \Phi^+ = -D - \mu_+ \]  

\[ \Phi^- = -D + \mu_- \]
\[ \Phi^- = D - \mu_- \] (8)

and they are schematically illustrated in figure 6. The work function includes the chemical potential \( \mu_{\pm} \) (bulk contribution) and the surface dipole barrier \( D \) (surface contribution). For positrons, \( \mu_+ \) is defined as the difference between the lowest positron energy level and the crystal zero level while \( D \) is defined as the distance from vacuum level to the crystal zero. Crystal zero is defined as the zero of the Coulomb potential energy. The surface dipole increases the work function for electron as it tries to bind the electrons more tightly to the material. For positron however, since the charge is opposite, surface dipole has a repulsive interaction. This can result in a negative work function in many materials for positrons. Materials that reemit thermalized positrons are said to have negative work function. Studying work functions can provide information about the material itself. The fact that the work function is dependent on different properties such as temperature or intrinsic stress makes it a good property to study. [16]

![Energy Levels Diagram](image)

*Figure 6. A schematic illustration of energy levels for electrons and positrons in a material. [17]*

### 2.2.3 Positrons in matter

There are several ways positrons can interact with matter. A schematic summary of the processes can be seen in figure 7. When energetic positrons incident towards a surface, a fraction will backscatter. The fraction that backscaaters depends on the incident energy as well as on the angle of incident. Also, the denser the material, the more positrons will backscatter.
The implantation depth in the material depends on the implantation energy and on the material. The fraction that enters the material starts to rapidly lose its kinetic energy from incident energy to the Fermi energy and become thermalized. The energy is lost through different processes. The most important process is scattering with atomic electrons followed by excitation of plasmon as well as electron-hole pair excitation and finally phonon scattering. Thermalisation is very fast and takes only few picoseconds. Thermalized positrons scatter between Bloch state and diffuse through the material. The probability for positrons reaching the surface increases with longer diffusion length and lower implantation energy. If a positron manages to diffuse to the surface, there are three alternatives it can undergo depending on the work function of the material: (i) the positron can be trapped in a surface state and annihilate or eventually be thermally detrapped as positronium, (ii) it can be reflected back from the surface potential due to their wave like nature, (iii) they can be reemitted into vacuum with a defined energy characteristic of the material.

![Diagram](image)

*Figure 7. An illustration over the few processes a positron can undergo when implanted in a material. [18]*

For thermalized positrons however, there are several annihilation possibilities. One possibility is that they diffuse around in a delocalized Bloch state until they annihilate with electrons (0.5 ns). The thermalized positrons can also get trapped in defects or voids as they diffuse around. The wave function now will instead be very localized and the positron will most likely annihilate with an electron inside the void or defect. However, it is also possible for the positrons to leave the defect and become delocalized again if the trap potential is shallow enough. If the defects are big on the other hand, the positrons may instead form positronium. There, positronium will eventually annihilate. However, the positronium may diffuse back to vacuum if these voids are connected to the surface. Many inelastic collisions with the walls occur during the diffusion and lower the total energy of the positronium. The energy distribution of these positronium depends on several factors. It depends on the energy of the positronium entering the void, on number of collision with the walls and on the mean energy loss of each collision. [19]
The lifetime of positrons in a material depends on electron density where increased density reduces the lifetime. Consequently, positrons have a very short lifetime in materials such as metal and semiconductors. The lifetime in these materials can be as short as few hundred picoseconds. However, the thermalisation time is more than one order of magnitude shorter, thus the positrons spend most of the time diffusing during their lifetime in thermal equilibrium through the material.

2.3 Positronium

Positronium is a hydrogen-like atom but is an unstable system formed by electron and positron, see figure 8. Positronium is usually produced by implanting positrons with an energy of hundred to few keV into a solid target. Positrons undergo many mechanisms in solids and thermal or epi-thermal positrons can be emitted as positronium. The efficiency of positronium yield depends on the material as well as implantation depth and on the temperature of the target.

![Figure 8. Illustrates a positronium atom. It consists of a positron and electron orbiting around their center of mass.](image)

Positronium can have two configurations depending on the relative spin orientation of the electron and the positron in their ground state. The singlet state is known as parapositronium (p-Ps). The spin of the electron and the positron is oriented antiparallel resulting in a total spin of 0 and the spin projection quantum number \( m_s \) is 0. The lifetime in vacuum is 125 picoseconds. The triplet state is known as orthopositronium (o-Ps). The spin of the electron and the positron is oriented parallel resulting in a total spin of 1 and \( m_s = -1,0,1 \). The lifetime is 142 nanoseconds in vacuum. Consequently, the formation probability is \( \frac{1}{4} \) and \( \frac{3}{4} \) respectively. Parapositronium decays into two gamma rays with an energy of 511 keV each while orthopositronium decays into three gamma rays. The energy of these gamma rays can vary but the total energy will be around \( 2 \times 511 \) keV.

Positronium excitation is mostly done by photon excitation. In a magnetic field free environment, the energy levels of positronium can easily be calculated assuming that positronium and hydrogen energy level would be similar with the only difference is the effective mass. This results in an energy level of half of what it is for the hydrogen atom since the reduced mass for positronium only differs by a factor two from the mass of electron. The energy level in positronium is then given by...
\[ E_n = \frac{-6.8}{n^2} \text{eV} \]  

(9)

where \( n \) is the principal quantum number. The bond between the electron and the positron will break if the internal positronium energy exceeds 6.8 eV, which corresponds to a temperature of 100 K. The lifetime of positronium can be significantly increased by exciting the positronium to a higher state such as Rydberg state which corresponds to \( n>20 \). Positronium lifetime in vacuum can be expressed as

\[ t \sim n^3 \]  

(10)

where \( n \) is the principal quantum number. [23] Cross section of positronium scales with fourth power of the quantum principal number as well. [10] However, the lifetime of positronium in materials is reduced compared to vacuum due to an effect called pick off annihilation. This occurs when the positron in o-Ps annihilates with an electron with an antiparallel spin in the material. This annihilation results in two gamma rays. In addition, the lifetime of positronium can be reduced in magnetic fields as well. o-Ps with the spin component \( m_s = 0 \) are likely to be quenched to p-Ps. [24] Consequently, the lifetime decreases since p-Ps lifetime is shorter than o-Ps lifetime. The likelihood of quenching increases with magnetic field strength. However, the lifetimes of the states with \( m_s = \pm 1 \) are not affected by magnetic fields. Therefore, the maximum o-Ps yield in a magnetic field is 1/3 of the o-Ps fraction. [25]

2.3.1 Positronium formation potential and work function

Positrons implanted in a material can remain as positrons by either be backscattered or be reemitted as positrons, become gamma rays through annihilation with electrons in the material or form positronium and annihilate or be reemitted as positronium. Positronium formation mechanisms depend on the material, i.e. if it is a metal, semiconductor or an insulator. In metals or semiconductor, positronium is only formed at the surface and nothing in the bulk. This is the case when positrons back diffuse to the surface followed by an electron capture. The formation in the bulk is hindered due to high electron density. Higher numbers of electrons screen the Coulomb interaction between the positron and any other electron preventing positronium formation. Therefore, positronium can only be formed if the diffusion length for positrons in these materials is long enough or by having a low implantation energy. [26] Positronium can be formed on the surface provided that the positronium formation potential \( (E_{ps}) \) is negative. \( E_{ps} \) just outside the surface is given by

\[ E_{ps} = \Phi^+ + \Phi^- - 6.8 \text{eV} \]  

(11)

where \( \Phi^+ \) and \( \Phi^- \) are the work functions for positrons and electrons respectively and 6.8 eV is the binding energy for positronium in vacuum. [27] Interestingly, this means that positrons can be emitted from surfaces even if the work function would be positive. If \( \Phi^+ \) would be positive but \( \Phi^- \) would have a value such that \( E_{ps} \) is negative, then the positron can be emitted from the surface in a bound state with an electron, i.e. as positronium. Note that this is not the work function but the positronium formation potential.

For insulators however, positronium is mostly formed in the bulk by thermalized positrons and not on the surface due to the fact that in general, the binding energy of the positronium is not enough to compensate for the positron’s and the electron’s work function, i.e. \( E_{ps} >0 \). However, the thermalisation time in insulator is longer compared in metals and thus a fraction of positrons with sufficient kinetic energy can reach the surface to form positronium. [26]
The work function for positronium which represents the positronium formation in the bulk can be defined in a similar way like electrons and positrons (see “2.2.2 Positron work function”);

\[ \Phi_{Ps} = -\mu_{Ps} + E_B - 6.8eV \]  

(12)

where \( E_B \) is the binding energy of positronium in the material and \( \mu_{Ps} \) is the positronium chemical potential defined as \(- (\Phi^+ + \Phi^-)\). The equation states that the positronium can only leave the material if; the energy required to extract positrons (\( \Phi^+ \)) and electrons (\( \Phi^- \)) + the energy required to break the binding of Ps in the material (\( E_B \)) – 6.8 eV (Ps binding energy in vacuum) is < 0. [28] Formed positronium is a mobile system and can diffuse around in the bulk and will eventually reach the surface as long as it does not get trapped in voids or defects. The conversion yield for most ionic crystals is 30-40 % and is especially high for SiO\(_2\) with 72 % in the bulk and 12 % on the surface. These numbers suggest SiO\(_2\) may be the best positron-positronium converter. [26]

2.3.1.1 Positronium formation processes

There are two processes called Ore and Spur processes for positronium formation in the bulk. Positronium can be formed during thermalisation process when the positron energy lies in the so called Ore gap. The upper limit \( E_u \) is nearly equal to the required energy to ionize an atom in the material and the lower limit \( E_l \) is the binding energy of the positronium in the material (<6.8 eV). Positrons that fall below the Ore gap will annihilate as free particles, i.e. for energies between zero and \( E_l \). Positrons undergoing last collisions at energies above \( E_u \) are injected to the energy range between zero and \( E_u \) with some probability. [29] The spur process describes the positronium formation after that the positron has been thermalized. At the end of the thermalisation, the positron may lose its last energy by exciting an electron from the valence band to the conduction band. These electrons are called spur electrons. The thermalized positrons may now be combined with a spur electron to form positronium. [30]

2.4 Moderation

A low average energy in the eV range with a narrow energy spread of positrons is required to trap them effectively. The energy of positrons emitted or generated from a radioactive source or through pair production is distributed in a range from 0 eV to MeV while the mean energy is usually high. Moderation is used in order to lower the mean energy and to make the energy of positrons monoenergetic. This is done by implanting positrons into a certain material where they thermalize. This results in positrons being emitted from the surface with a lower energy and with a small energy spread that is usually smaller than the thermal energy of the positron in the material, <0.1 eV. Figure 9 illustrates a comparison of the energy distribution of moderated and not moderated positrons from a radioactive source, Co-58. Even though the positrons will be more monoenergetic, the integral over the moderated positrons is significantly lower. The main reason for big losses of positrons is due to the mechanisms the positrons undergo in materials described in the previous sections. Positrons emitted from moderators are partially normal to the surface. These two properties are very important for measuring the energy loss or cross section where a high resolution is required.
The efficiency of moderation varies depending on the material of use as a moderator. The efficiency is defined as the ratio of moderated positron per unit time divided by the number of positrons from the source. The efficiencies of moderation were first as low as \(10^{-8}\) when moderation technique was new. Today there are different materials with an efficiency in the range of \(10^{-3}\). The increase is mainly due to the choice of material as well as in the growing procedures of the material. The fraction of moderated positrons will increase if the material contains no defects capable of trapping positrons or contaminations. Therefore, it is also important to have a good vacuum. It has been shown that the geometry of the moderator has a big impact on the efficiency.

Materials such as thin metal foils or solid rare gases are often used as moderators. A moderator that was commonly used was tungsten. Tungsten has a highly negative work function and has the property of not losing efficiency drastically when exposed to air or surface contamination. A high efficient tungsten moderator, 0.3 %, was first made in 1983 by reducing the defects in the material through annealing. Another material with a high efficiency was discovered in 1986 and it was neon. At a low pressure, neon solidifies as 10 K. Consequently, using neon requires low temperatures and a good vacuum. However compared to tungsten, neon has a higher efficiency, 0.7 %. This efficiency was reached by using a Sodium-22 source where the moderator was directly grown on a cylindrical formed copper cup. The energy spread of the moderated positrons from rare gas solids is bigger than positrons emitted from metal moderators. Although, the total number of cold positrons emitted is higher in absolute numbers compared to metals even if the energy width is larger using rare gas solids. This is attributed to energy loss mechanism in each material. Positrons lose more energy in metal moderator since possibilities of forming electron hole pairs is higher than forming them in an insulator where the main energy loss mechanism is through phonon scattering. Consequently, more positrons can be emitted as epithermal positrons with neon moderators. However, neon has like all rare gas solids a wider band gap resulting in reduced surface dipole, i.e. a positive work function. One way of overcoming this issue is to set a positive potential on the surface over the moderator. The positrons in the surface will be repelled and can be emitted. [31]
2.5 Trapping none neutral plasmas

A none neutral plasma is a plasma where the total charge is not zero, i.e. a positron plasma is a none neutral plasma. As a result, the electric field created by this charge plays an important role in the plasma’s dynamics. In theory, confining a none neutral plasma can be done for an infinite time. However, since asymmetries between magnetic fields axis with beam path axis are very likely in experiments or the fact the mean free path is not infinite, the plasma will expand radially and axially. As a result, this will reduce the lifetime. Nevertheless, the lifetime can be increased significantly by using Penning traps or a rotating wall (RW). [32]

A Penning trap is a trap commonly used in experiments for confining none neutral plasmas. A Penning trap uses an axial magnetic field for confining the plasma radially and a quadrupole electric field for axial confinement. The static potentials are generated by set of electrodes as seen in figure 10. The endcap electrodes are positive relative to the ring for trapping positive charged particles. The magnetic field generated by a solenoidal is superimposed along the trap axis with the direction charged particles travel in. There is an alternative to the Penning trap called Penning-Malmberg trap. The difference is that a Penning-Malmberg trap uses cylindrical potential traps instead of a parabolic. It is easier to have grids of cylinders making it possible to have segments of potentials in Penning-Malmberg traps. Biasing the electrodes in an axial potential well can then trap the plasma. [33]

![Penning Trap Diagram](image)

Figure 10. This figure illustrates the electric field configuration of a Penning trap. The ring and endcap have to be opposite charged. Endcap is positive for trapping positively charge particles while it is negative for trapping negatively charged particles. [33]

2.5.1 Particles and plasmas in Penning traps

Single particles in a magnetic field experience the Lorenz force and this force deflect particles perpendicular to the magnetic field. Lorenz force together with the electric field in a Penning trap cause the particles to start oscillate and the resultant motion consist of a fast cyclotron motion with small radius together with a slow circular magnetron motion with a big radius. This result in a spiral motion around the magnetic field lines radially and oscillates harmonically in the axial plane. The total motion is illustrated in figure 11. Since it is a circular motion, the radius of cyclotron motion shrinks rapidly and emits radiation. This effect is called cyclotron radiation. Emission of radiation results in cooling of particles as energy is emitted. The cooling is especially effective for particles with low masses such as
positrons or electrons and can be cooled in few seconds if the magnetic field is strong. However, it would take years for particles such as antiprotons where the mass is bigger. The cyclotron frequency depends only on the ratio of the electric charge over the mass and on the magnetic field strength. Since this frequency can be measured, measurements of masses of charged particles can be carried out with great precision in Penning traps. [33]

Figure 11. The total motion in a Penning trap for charged particles. The particles oscilate harmonically in the magnetic field direction as they have a fast a cyclotron motion together with slow magnetron motion. The dashed line is the large and slow magnetron motion’s circular component. [33]

For plasmas however, the motion is a bit different. The cyclotron motion is still there as well as the harmonic oscillation. However, due to collision with other charged particles, the magnetron motion is replaced by a collective angular rotation. This collective collisions act also as a cooling for the plasma. The collisions may result in motion in axial direction to a radial where the energy will be lost through cyclotron radiation. The collective rotation is rotating around the magnetic field line with a frequency that depends on the density as well as on the strength of the field in the following way

\[ f = \frac{nq}{4\pi \varepsilon_0 B} \]  

(13)

where \( n \) is the plasma density, \( q \) is the particle charge, \( B \) is the magnetic field and \( \varepsilon_0 \) is the vacuum permittivity [34]. In plasmas, the core is more compressed compared to the outer part. This generates an electric field gradient resulting in an outgoing force. The ingoing Lorenz force from the magnetic force is balancing the outgoing centrifugal and the electric forces. Mathematically, this is described in the following way

\[ 0 = qE_r + qv_\phi B + \frac{mv_\phi^2}{r} \]  

(14)

where \( r \) is the distance from the trap axis and \( E_r \) is the radial component of the electric field. The rate of the rotation \( \omega = -v_\phi / r \) can be solved from the equation yielding two frequencies, a slow and a fast solution. The rates of these frequencies depend on the electric filed. There is a value of the electric field such that the slow and fast frequency is equal. This limit is reached when the electric field, induced by the plasma space charge, is equal to
where $\Omega = \frac{qB}{m}$ is the cyclotron frequency. This is the maximum radial electric field that still allows plasma confinement. This electric field defines the upper limit of the density of the plasma called the Brillouin limit, $n = \epsilon_0 B^2/2m$. The plasma frequency is half of cyclotron frequency at Brillouin limit. An effective compression as well as cooling is necessary to achieve this density. Different cooling techniques are described below as well as a compression technique called rotating wall. [35]

2.5.2 Cooling in Penning traps
Cooling of plasmas is mainly done through cyclotron radiation in a Penning trap with strong magnetic field (depending on the mass of the particles in the plasma). However, additional cooling techniques have been developed over the years. Laser cooling, resistive cooling, electron cooling and buffer gas cooling are techniques used to remove energy from a plasma in a Penning trap. [36]

2.5.2.1 Laser cooling
Laser cooling can be used for cooling ions with an appropriate electronic structure in a Penning trap. The idea is to use lasers and implant photons. As the ions absorb the photons, the momentum of the atom is changed. If the atoms are traveling against the direction of the laser, the momentum is reduced with the amount of momentum the ions absorb. Although due to the conservation of momentum, the excited atom will reemit a photon again and gain the same amount of momentum as it lost. However, the emission directions have an isotropic distribution, hence the gained momentum tends to cancel out. The laser direction on the other hand is constant and is slowing down the atoms in a certain direction resulting in cooling of ions. [37]

2.5.2.2 Resistive cooling
The idea with resistive cooling is to cool the particles in a Penning trap by couple it to an external circuit. The energy is dissipated in the circuit and thus cooling the particles. The oscillating charged particles induce an image charge. By connecting a resistor between the electrodes, this image charge will induce a current through the resistor, i.e. energy is dissipated. The amount of energy that can be removed depends on the temperature of the resistor since the particles will come to thermal equilibrium with the resistor. Therefore, if the resistor is cooled in a cryogenic environment, the particle can be cooled in the region of 4 K by using liquid helium, or even lower using dilution refrigerators. [38]

2.5.2.3 Electron cooling
Electron cooling is effective against particles with high masses, e.g. antiprotons in a Penning trap. This technique was invented in 1966 but was first tested in 1974. Forming the potentials in the trap to a W-shaped potential, the negative electron can be trapped with positively charged particles in the same region wherein they can interact. In the case of antiprotons, as they also are negative, the potential can be a simple well to trap them. Through Coulomb interaction, the antiprotons transfer some energy to the electrons and the electrons will at the same time lose their energy via cyclotron radiation. Once cooled, the electrons can be transported away via electric field. A weak electric field will only affect the electrons, as they are much lighter. [36]
2.5.2.4Buffer gas cooling

Plasmas confined in Penning traps or Penning-Malmberg traps can in theory have an infinite lifetime. However, due to collisions with neutral gases in the trap, the rotation motion decreases leading to a radial expansion and will eventually lead to annihilation with the trap electrodes. This expansion can be reduced by operating in ultra high vacuum. However, since it is impossible to perfectly align the fields, the confinement time is still limited. These asymmetries of the fields torque the plasma and cause the plasma to expand and annihilate with the electrodes or with the inner walls. This makes it more favorable to use buffer gas rather than to operate in ultra high vacuum to cool charged particles. Buffer gas cooling was introduced by Surko, the inventor of the Surko traps, in 1989. The gases are in thermal equilibrium with the trap container through countless collisions with the walls. The buffer gas undergoes inelastic collisions with the charged particles removing the kinetic energy. In principle, any neutral gases will suffice as a buffer gas as long as the collisions result in shorter positron thermalisation time than positron lifetime due to annihilation with the gas. For trapping with Penning-Malmberg traps, the positrons pass the first electrode in order to be trapped. They will then be reflected back by a gate electrode on the other side of the trap. As they are reflected, if they have not lost enough axial energy, they may escape the trap. Therefore, the buffer gas needs to cool the positron enough so the positron do not have enough energy to cross the first electrode as it is reflected by the gate potential. To solve this, it is possible to utilize two neutral gases as buffer gases: one that has a higher cross section with positrons with higher energy acting as stopping gas and another one with a higher cross section with positrons with lower energy acting as a cooling gas. One common combination of gases is to use nitrogen and carbon dioxide.

2.5.3Rotating wall

There is a technique called rotating wall technique to reduce the radial expansion. This technique is about applying an external rotating electric potential that prevents the radial expansion of the plasma. It is not the frame or the electrode itself that is rotating but the potential. A rotating wall is realized by having an electrode segmented into four parts or more. A rotating field is achieved by applying a sinusoidal voltage to each segment where each voltage is phase shifted from the voltage applied on the segment before. The rotating field results in a torque on the plasma and prevents the radial expansion. The plasma can even be compressed if the external force is exceeding the expansion force resulting in higher lifetimes for the plasma. However, applying a voltage to a plasma is equivalent to adding energy to it. Therefore, efficient cooling is required for using rotating walls and do only work with plasmas and not with single particles as plasmas have a collective cooling mechanism. It is also common to use a Surko trap combined with a rotating wall as the collisions with the buffer gas may compensate for this energy increase. [39]

The rotating wall frequency is not related to the frequency of the plasma in a simple way. Although, the correlation is much simpler in a so called strong drive regime. In this regime, the plasma progresses in such a way that the rotating potential frequency is equal or close to the plasma frequency, see equation (13). This regime allows a better control of the plasma, as the density of the plasma is directly proportional to the frequency. It would also be possible to change the density of the plasma even to Brillouin limit by changing the frequency of the rotating wall. However, a good alignment between the magnetic field and the trap is required as the plasma has to reach thermal equilibrium such that the plasma frequency is close to the rotating wall frequency. [34]
2.6 Detection of positrons and positronium

There are several positron and positronium spectroscopy techniques based on different observables. The observables can be: energy distribution, angular distribution or lifetime of positrons and positronium. The energy of the emitted gamma rays are Doppler shifted depending on the momentum the particles have. This shift can be detected and this spectroscopy is called Doppler broadening spectroscopy. The momentum in each particle can lead to an angular distribution of the emitted gamma rays and this spectroscopy is called angular correlation of annihilation radiation. For lifetime spectroscopy, there are mainly two types of positron or positronium spectroscopy called Positron Annihilation Lifetime Spectroscopy (PALS) and Single Shot Positron Annihilation Lifetime Spectroscopy (SSPALS). Both are nondestructive methods and can be used to study voids and defects in materials. [40]

2.6.1 PALS

PALS has for many years been used as a probe to detect defects and impurities in the range of several ångströms to tens of nanometer as well as characterizing materials. It uses the principle that positrons or positronium annihilates with electrons in a material which result in gamma rays. The time between implantation of positrons and the detection of gamma rays is measured and this time corresponds to the lifetime of positron or positronium. As most of the positrons or positronium annihilate in a matter of picoseconds, this kind of spectrum results in a high peak with a low tale (see figure 12). The nature of this method provides a good and high time resolution.

![Figure 12. A typical signal using PALS or SSPALS. Y-axis is count of positrons and x-axis is time in nanoseconds. [41]](image)

The lifetime depends on the electron density, number of defects and vacancies. If defects or voids are present, the positron lifetime is increased and there is a possibility of forming positronium which increases the lifetime. Lower electron density increases the lifetime as well. In such cases, as the lifetime increases there will be a higher count rate after the peak. Therefore, it is possible to understand if defects are present in the material or if positronium was formed. The signal used in this method is gamma rays which allow investigation on deeper level. On top of that, it is a nondestructive method which makes it a powerful investigation tool. However, each separate annihilation needs to be recognize meaning there is typically just one positron in the material at the time during the time of annihilation.
Several positrons can be implanted at the same time provided that the implantation time of each positron is known. [42]

2.6.2 SSPALS
A large number of positrons are implanted into the target at the same time in SSPALS. The main advantage of SSPALS is that data collection time is only limited to the lifetime of study. The measurement of the annihilation is recorded in real time. This provides more possibilities to study momentary phenomena. SSPALS relies on positron pulses with a short temporal width. This method overcomes problems with PALS, namely high number of annihilation at once. The fact that the time resolution depends strongly on the time spread of the positron plasma makes the resolution a lower compare to PALS. SSPALS is useful for detection of nanosecond scale, e.g. the lifetime of o-Ps. However, it has the strong advantage that more measurements can be carried out in shorter time and that many positrons are in the sample at the same time. This makes it possible for new physical prospective such as dipositronium or Bose-Einstein condensation of positronium. [42] [43]

2.6.3 Detectors
The detection of positrons and positronium is done through the detection of gamma rays. The most common way of detecting is to use a scintillating material attach to a photomultiplier (PMT) or a photodiode. Photodiodes are usually used when time resolution is not important while PMTs are used when time resolution is important. The time resolution of a PMT can be up to few picoseconds while photodiodes have a time resolution of few nanoseconds to milliseconds. Scintillating materials absorb gamma rays and emit photons of lower energy. There are many scintillators available with different timing characteristics varying from nanoseconds to milliseconds. It is common to use a relatively high density and luminosity scintillating material with a short decay time for fast detectors. Denser materials tend to have higher luminescence but longer decay times while lighter materials are usually fast. However, the low stopping power results in low efficiency with a low luminescence. Ideally, the material should produce about 20 photons per 511 keV gamma ray and the radiation penetration should be shorter than 1 cm. Although, it is important that the output is not too high as saturation becomes a problem. [44]

2.6.3.1 Scintillators
Scintillators are material with scintillation property. The material exhibits luminescence when excited by external radiation. Materials like Sodium iodide (NaI), barium fluoride or Cesium iodide (CsI) can be used as scintillating detectors. NaI emits photons (maximum emission is 415 nm) when subjected to ionizing radiation such as gamma rays. NaI is very effective and is usually coupled together with a PMT making it a fast detector. Although, the detector has to be sealed in good vacuum, as NaI is hygroscopic. The advantage of NaI is that it can be fined tuned simply by changing the condition during the crystal growth. [45] CsI detectors have the advantage that it is not hygroscopic and can be coupled with photodiodes as well as PMTs. A coupling with a PMT makes the readout very fast. The CsI photodiodes are very compact and do not require any high voltages. They do also have the ability to work under high magnetic fields. CsI gets excited as they are struck by gamma rays. This excitation results in emission of photons of lower energy. The emitted photons are then collected by the silicon photodiode which converts the photons to electrons. Plastic scintillator is another scintillator that is commonly used. These scintillators are fast with a decay time of nanosecond range resulting in a good time resolution. However, the low density results in low stopping power of gamma rays. This means the efficiency is low since most of the gamma
rays hitting the detector do not result in scintillation. In addition, an afterglow of the signal can be
detected as delayed fluorescence has been observed in plastic scintillators. [46]

2.6.3.2 Cherenkov radiator
It is possible to obtain a fastest possible timing resolution for a given photomultiplier using a Cherenkov
radiator since Cherenkov light is emitted instantaneously. Lead (II) fluoride ($\text{PbF}_2$) is a so called
Cherenkov radiator. The fact that no scintillation is detectable and it has a high atomic number with high
density makes the $\text{PbF}_2$ a good Cherenkov radiator. However, a photomultiplier is often coupled with it
to enhance the low output Cherenkov radiation. The detection of gamma rays is based on pair
production. Gamma rays hitting the detector will ionize atoms and the electrons will have a high kinetic
energy. Cherenkov radiation occurs when the velocity of charged particles is higher than speed of light
in a material, i.e. when $v>c/n$ where $v$ is the velocity of charged particles, $c$ is the speed of light in vacuum and $n$ is the index of refraction of the material. Deceleration of the charge particles results on
radiation called Cherenkov light. The disadvantage of using a Cherenkov based detectors is that this
method requires high-energy gamma rays as input. Therefore, Cherenkov radiation is usually only used
for detection of gamma rays in accelerators or in cosmic rays. However, it is still possible to detect lower
energy gamma rays. Although, the electrons will have lower energy and little light is generated as a
result. Despite this, Cherenkov based detectors are good option for positronium lifetime spectroscopy.
[44]

2.6.3.3 Imaging detectors
An image offers a faster method for analyzing the beam size or intensity, i.e. the density or the number
of particles. The most common way to take an image of a signal is to use a phosphor screen. A phosphor
screen emits photons as accelerated ions hit the material. These photons can then be detected with a
camera. The number of emitted photons depends on the phosphor and on the kinetic energy of the ions.
The signal output is usually very low for the camera to detect so a Micro Channel Plate (MCP) can be
coupled to it. A MCP works in a very similar way to a regular electron multiplier where the difference is
that the MCP has several million independent channels where each channels work as electron multiplier.
MCP can be seen as an assembly of millions of electron multiplier. Incident particle ionizes atoms in the
walls and these secondary electrons are accelerated by an electric field applied over the MCP. These
secondary electrons result in more ionization as it travel through the channel and more secondary
electrons are emitted. This process continues and causes an avalanche of electrons. These electrons are
converted to photons by the phosphor screen that is detected with a camera. A MCP has the advantage
that high temporal resolution, spatial resolution and gain can be achieved. [47]

2.7 Vacuum pumps
There are several pumps that can be used to achieve a good vacuum. However, it is common to use
several pumps in order to reach low pressure as vacuum pumps only work within certain intervals of
pressure. A vacuum pump is categorized depending on the techniques it is using to pump such as
positive displacement pumps, momentum transfer pump or entrapment pumps. This section will briefly
describe the principles of one momentum transfer pump and two entrapments pumps namely turbo
pump, ion pump and cryopump as they are the ones that have been used in the AEgIS positron system.

2.7.1 Turbo pump
Turbo pump is a momentum transfer pump where a pressure of $10^{-8}$ mBar can be achieved. It can be
used from atmospheric pressure so is usually used as an initial pump before using other pumps if ultra
high vacuum is desired. A rapidly spinning fan gives the molecules a momentum in a certain direction, usually towards an exhaust in order to create and maintain a vacuum. Most turbo pumps uses multiple levels of rotors or fans mounted in series. The molecules hit the blades and the mechanical energy transfers the molecules to lower levels. These blades are titled ~45 degrees to increase the flow of molecules in a certain direction. [48]

2.7.2 Ion pump
Ion pump is a so called entrapment pump and can reach pressure of $10^{-11}$ mBar. In an ion pump, an electron cloud is stored with a Penning trap and these electrons ionize atoms and molecules within the vessel. The ionized atom and molecules are then accelerated by applying an electric field of 3-7 kV. The accelerated particles do then hit a chemically active cathode absorbing the atoms. The rate of pumping and capacity varies with the atoms and molecules within the vessel. Ion pumps do not use oils and have no moving parts. As a result, it produces no vibration and requires little maintenance which makes the ion pump a popular choice when requiring ultra high vacuum. [49]

2.7.3 Cryopump
Cryopump is an entrapment pump as the ion pump. As the name may suggest, a cryopump is a cryogenic pump and traps atoms and molecules by condensing them onto a cold surface. The surface is cooled by compressing helium. Cryopumps are only effective on some gases as it rely on the condensation, i.e. the freezing and boiling points of atoms and molecules. Cryopumps can only pump as long as the condensation surface remains cold. Over time, the surface will eventually saturate and as a result, the pumping speed will gradually drop to zero. Saturation happens faster at higher pressures so cryopumps are more suitable for high or ultra high vacuums. When saturation has been reached, the cryopump needs to be cleaned and this can easily be done by heating the pump up to room temperature. At higher temperatures, the condensed gas will evaporate and can be pumped by other pumps. [50]
3 Experimental setup

In this section, the apparatus used for the measurements will be described in details step by step from the source to the test chamber and the main traps, see figure 13. However, detectors and apparatus installed and used only for antiproton or electron measurements will not be described as they were not used for positron measurements. The source and the trap were bought as a set from First Point Scientific. Not only the hardware but also the software controlling the system was provided. The magnets in the accumulator however, were built by people in the AEgIS collaboration. These three apparatus are together referred to as the positron system. Most of the apparatus in the system and the transport can be monitored and controlled from a computer using LabVIEW. To simply put it, the positron system is divided into three parts; source, trap and accumulator and is where the positron plasma pulse is processed. The positrons generated from the source are guided and transported with magnetic fields to the trap. All coils in the positron system are water cooled to prevent overheating. In the trap, the continuous positron stream is divided into small pulses by electrodes where each small pulse contains \(10^4\) positrons. These small pulses are then accumulated in the accumulator. The accumulated positrons can from here be dumped all at once to either go the test chamber or to the main traps. During antihydrogen production, positronium will be created in the main traps. A test chamber was assembled for measurements such as laser excitation and to test different samples in a well-controlled environment with potentially zero magnetic field. Measurements of positronium in the test chamber are carried out through SSPALS.

![Figure 13. Illustrates an overview over the positron system. [9]](image)

Each apparatus is separated by valves in order to easily preserve a good vacuum. Each segment is pumped either by roughing pumps, cryopumps or ion pumps to maintain ultra high vacuum. The source area is pumped with a roughing pump and an ion pump while the trap and the accumulator is pumped by roughing pumps and cryopumps. The test chamber and the transfer line between the accumulator and the test chamber are pumped with a turbo pump each.
3.1 Positron source

The positron source used in AEgIS is Sodium-22. Sodium-22 was bought from a company called iThemba and is situated in South Africa. The order takes 6 months and is the only company in the world providing sodium-22. Sodium-22 decays in the following way:

\[
{^{22}}Na \rightarrow {^{22}}Ne + e^+ + \gamma \tag{16}
\]

Sodium-22 has a branching ratio of 0.89 which means it emits positrons 89% of all the decay events. With current activity of 350 MBq, \(3.11 \times 10^8\) positrons are emitted per second. The decays result in positron as well as a gamma ray with an energy of 1.28 MeV. The source area is pumped with an ion pump generating a pressure of \(10^{-7}\) mBar while running and \(10^{-9}\) mBar during stand by.

3.1.1 Neon moderator

AEgIS uses neon as a moderator which is grown directly onto a cup made of copper on the source. The source is in a pressure of around \(10^{-9}\) mBar. At this pressure, neon solidifies at around 10 K. Therefore, there is a cold head on the source that can go down to 7 K. Neon has a positive work function so a potential of 18 V is set over the moderator to repel the positrons from the surface. There is also a Helmholtz coil situated around the source. The magnetic field is used to guide the repelled moderated positrons to form a beam towards the trap.

As time passes, the moderator efficiency goes down and one of the reason is impurities. Impurities are a problem even in operations in an ultra high vacuum environment. In addition, the trap utilizes buffer gas cooling. The buffer gas contributes to the impurity quantity. These impurities act as potential traps for the positrons on the surface and are preventing the positrons from emitting. Moreover, the gamma rays emitted from the source increases the energy of the moderator and therefore the phonon vibration can cause stress in the moderator reducing the efficiency. The efficiency of a moderator decreases dramatically even if only few potential traps are present. However, the reduction of the efficiency decreases after a certain amount of potential traps. The efficiency of the moderator used in this experiment as a function of time is plotted in figure 14. The graph shows how the positron signal decreases with time after a new moderator was grown. From the logarithmic regression (the blue fit), it was calculated that the efficiency drops with 7 %/h the first few hours, while after 5 hours, the efficiency stabilizes.

![Graph showing the positron signal change over time](image)

*Figure 14. A graph over how the position signal changes with time since a new moderator was grown. From the fit, it was calculated that the first few hours, the efficiency drops with 7%/h while after 5 hours, the efficiency stabilizes.* [9]
It is necessary to regrow the moderator from time to time to keep the efficiency in a good level. This can easily be done with LabVIEW that is controlling the apparatus around the source. The whole process starts by increasing the cold head temperature to 25 K. This ensures the old moderator is evaporated. The ion pump is switched off and the roughing pump pumps the evaporated gas. The roughing pump pumps for 60 seconds before the ion pump is switched on again. The ion pump pumps now for 60 seconds before the cold head is cooled to 8.8 K. When this temperature is stable, the ion pump is switched off as new neon is injected. The neon gas solidifies on the cold surface. There is an annealing process of 15 minutes at 9.3 K to remove defects and voids. The neon atoms are more mobile at higher temperatures allowing the atoms to be situated a lowest possible potential, i.e. free from defects. The cold head is cooled down to 7 K and the ion pump is again switched on. This whole regrowth process takes approximately 40 minutes until a new moderator is grown. Usually, it takes additional 15 minutes before the system is completely ready since the pressure is still a bit high after a moderator was regrown.

3.1.2 Transport from the source to the trap
In order to select only moderated positrons, a tungsten block and two coils with opposite polarities (saddle coil) are installed according to figure 15 in the transfer line between the source and the trap. This setup acts as an energy filter. The saddle coil gives rise to a certain magnetic field and as a result, only positrons with certain energy may pass. This results in more monoenergetic beam of positrons. Positrons successfully passed are then guided with a beam tube coil. There is also a matching coil between the beam tube coil and the trap magnet in order to make the magnetic field more homogeneous and thus a smoother transfer.

![Diagram](image)

*Figure 15. A schematic illustration over how the saddle coil and the tungsten block works. The thick black lines illustrate the magnetic field lines from the saddle coil and the thin blue lines are possible pathways for positrons.*

3.1.3 Shielding of the source from radiation and magnetic fields
It is important to shield the source in a good way from radiation, not only for security reasons but also so that the gamma rays emitted do not interfere with the detectors. If interfered, these gamma rays will act as background noise. Therefore, the source is shielded with 30 cm thick lead blocks which are placed in all possible angles. It has also been proved that shielding from external interference is important for the positron beam stability, especially from external magnetic interference. The source is currently shielded from external magnetic fields with μ-metals. The AD ring as well as other magnets situated
close to the source is very likely produce a magnetic field that steer the beam away. There is a dipole beneath the source that is used to steer the antiprotons to the experiment from the AD and this magnet has shown to contribute a lot in positron losses when it is on. In addition, the saddle coil is heavily shielded with μ-metals as it has shown that a good shielding in this area can increase the number of positrons by 100 %.

3.1.3.1 Hysteresis
Another problem the system is experiencing with external magnetic fields is there is a hysteresis effect due to external fields. If nearby experiments or AEgIS change the magnetic environment by turning on or off strong magnets, there is a direct effect and a dynamic change due to hysteresis. It has been shown that a change of only few Gauss around the positron system can affect the number of positrons in a positive or a negative way. The hysteresis effect was studied using the dipole magnet situated right under the positron source. The magnet is supplied with a current of 77 A. The magnet was turned off (after being on for few days) and the signal amplitude from positrons annihilating outside the accumulator was measured as a function of the magnetic field around the saddle coil. The magnetic field was measured by fixing a Hall-probe around the coil. The result can be seen in figure 16. Note that the Hall-probe can only measure one certain direction meaning other directions might have been more strongly affected. Nevertheless, it is clear that the field is changing over time without any change of coils during the time of the measurement which is suggesting hysteresis. It is also clear that the positron annihilation signal is changing as the field around the saddle coil is changing.

![Figure 16](image)

Figure 16. A graph over how the signal amplitude of positrons annihilating outside the accumulator changes with the magnetic field around the saddle coil. The left axis is positrons annihilation amplitude and the right one is the magnetic field. [9]

3.2 Trap
Trap is the apparatus transforming the continuous positron beam from the source into a pulse. It is located between the accumulator and the source. The trap is connected to a cryopump and a roughing pump which pump it to a pressure of $10^{-10}$ mBar when the system is off and goes up to $10^{-4}$ mBar while running due to the buffer gas injection. The trap is a Surko trap, meaning buffer gas is utilized to capture
and cool positrons in a step vise potential as shown in figure 17. It is using a magnetic field of 7000 Gauss for radial confinement generated with a solenoid and five electrodes for axial confinement. 0.5 Standard Cubic Centimeter per Minute (SCCM) of nitrogen and 0.03 SCCM of carbon dioxide are injected into the trap acting as buffer gas. As positrons scatter with buffer gas, it can lose energy in several ways; ionization, electronic excitation, dissociation, vibrational excitation, rotational excitation and momentum transfer. The rates these processes occur in depend on the energy of collision whereas each process has a threshold except for momentum transfer. For ionization, positrons can either directly ionize the atom, form positronium or directly annihilate. Direct ionization is the analogue to ionization with electrons and has the same threshold. Positronium is formed when positrons ionize the atom but bounds with the ionized electron. The threshold is ionizing energy of the atom minus 6.8 eV, as it is the binding energy of positronium in vacuum. Direct annihilation is a process where the positron annihilates with one of the electrons bound to atom. [51] It has been shown that for scattering with nitrogen molecules, electronic excitation is the main process for energy loss in positron scattering [52]. The average loss rate is 9 eV per collision. The energy threshold for positronium formation and electronic excitation is close for nitrogen molecule. The cooling limit is therefore limited by positronium formation. However, the peak of electronic excitation is around 11 eV whereas positronium formation is 25 eV meaning it is possible to have a good cooling with small losses. Nitrogen has a higher cross section for positron with energy around 18 eV compared to carbon dioxide and can therefore cool them so that they can be trapped (positrons are injected into the traps with 18 eV in AEGIS experiment). Carbon dioxide has a lower cross section and act as a cooling gas to cool the positrons as the RW is applied. [53] Carbon dioxide is also used in the accumulator but not the nitrogen. This is achieved by injecting the carbon dioxide directly into the electrodes whereas the nitrogen is injected outside the electrode and is diffused into them. Some nitrogen will of course be leaked to the accumulator since the accumulator and the trap are connected but this is only in small amount.

Figure 17 illustrates the trapping procedures and it is done in three stages: filling, storing and dumping. In the filling stage, the first electrodes form a step vise potential. The inlet potential is set to around 4 V. This value has to be lower than moderator potential to not to reflect any incoming positrons. Gate potential is set to 30 V. This value has to be higher than moderator potential to trap the incoming positron. The slowed down positrons are contained inside electrode 3. In the storing stage, electrode 2 and 3 are raised so that positrons get trapped. Electrode 3 is also working as a rotating wall. The amplitude and the frequency of the rotating wall can be set to any value but is set to an amplitude of 550 mV with a frequency of 6 MHz. It is in the storing stage where the beam is transformed to a pulse. Finally, in the dumping stage, the gate electrode is lowered so that the positron pulse is dumped and can proceed to the accumulator.
The red cloud represents the positron plasma: the continuous beam in the filling stage and the pulse after the storing stage. The electrodes are numbered to distinguish them from each other. This whole sequence takes 0.15 seconds. [9]

The transport to the accumulator is done in a similar way as transport to the trap from the source. It is done with a coil called accumulator beam tube. In addition, there is an accumulator-matching coil to make the field between the accumulator and the accumulator beam tube more homogenous to establish a smoother transfer. However, the trap and the accumulator are slightly misaligned by few millimeters. There is a permanent magnet situated between the trap and the accumulator with an unknown strength correcting the path.

3.3 Accumulator

As the name may suggest, the accumulator accumulates the positron pulses coming from the trap. It is the final stage before a positron plasma pulse is ready. The vacuum is generated with a cryopump and a roughing pump which pumps it to $<10^{-10}$ mBar when the system is off and goes to $7 \times 10^{-8}$ mBar while running. The accumulator is a Penning-Malmberg trap with a magnetic field of 0.1 T for radial confinement. Apart from the main coil, there are two other coils installed inside the accumulator. These are used to improve the homogeneity of the field inside the accumulator. The main correction is done by coil supplied with 109 A power supply while fine correction is done with a coil supplied with 0.5 A. The trap consists of 23 electrodes for axial confinement. 19 of these electrodes are connected in series with resistors and are referred to as ring electrode. Setting a voltage over one electrode will by default set the other electrodes as well. Together, they form a harmonic potential well where the positrons are accumulated. Figure 18 illustrates the accumulating procedures and it is done in two steps: accumulating and dumping stages. The inlet potential is lowered and raised for every pulse coming from the trap. The positrons are trapped in the harmonic well where they are cooled. The cooling is partially by cyclotron radiation, however the magnetic field is weak. The main cooling is done through collision with buffer gas and with each other. The collective cooling becomes more effective if the number of positrons increases. An increase of storage time increases the number of accumulated positrons. However, the number of pulses that can be accumulated is limited by the positron lifetime inside the accumulator. The lifetime in the accumulator is increased if positrons can remain without annihilation as
long as possible. Annihilations are caused by positron scattering with residual gases and by plasma expansions. Expansions are also the case if the axial position of the injected positron pulses and the magnetic field are not perfectly aligned with the tube. Thus, positrons will start to annihilate with the accumulator walls. In other words, misalignment reduces the lifetime. However, the rotating wall is reducing this effect. The lowest electrode in the ring acts as a rotating wall for prevention of radial expansions where the electrode is split to four segments. The rotating wall here can be set to any value. The optimum value depends on the number of positrons and thus how old the moderator is. There are also horizontal and vertical correction coils installed inside the accumulator. The correction coils generate a field in the order of ~0.1 Gauss perpendicular to the main magnetic field and can partially correct the misalignment. The dumping is done by raising all the potentials in the accumulator to form a linear potential as illustrated in figure 18. The derivative of this line determines the energy of the dumped positrons and can be adjusted between 50 and 300 eV. 100 eV is used for transport to the test chamber while 300 eV is used for transport to the main traps.

![Diagram of accumulating and dumping stages](image)

**Figure 18.** A schematic illustration over the potential levels in the accumulator in accumulating and dumping stages. The inlet is lowered and raised for each pulse incoming from the trap. The positrons are accumulated in the harmonic trap. All electrodes are raised to a linear potential for the dumping. The dashed lines are help lines for the reader. The red cloud represents the positron pulse. [9]

### 3.4 Transfer line to the test chamber

As shown in figure 13, the positrons can be transported either to the test chamber or to the main traps. There is an apparatus called buncher situated before the test chamber and is used to compress the pulse in time (see “3.4.1 Buncher”). The main traps have to be off since the magnetic field steers the beam away making the transport difficult. There are in total seven coils as well as correction coils for small correction controlling the transport of the positron pulse between the accumulator and the test chamber. Figure 19 is a simplified overview over the transfer line. All coils are used for transport to the test chamber except for 5* while coils 1-4 and 5* are used for the transport to the main traps. For
transport to the test chamber, coils 1-6 are connected in series and is supplied with 100 A raising a magnetic field between 800 Gauss and 1400 Gauss each. Coil number 7 is supplied by a separated power supply with a current of 35 A resulting in a field of approximately 600 Gauss. For transport to the main traps, coils 1-5* is connected in series and is supplied with 100 A. Each coil gives a field between 800 Gauss and 1400 Gauss. A vacuum of $10^{-10}$ mBar is maintained in the transfer line by a turbo pump and ion pumps.

![Diagram](image.png)

*Figure 19. It is an overview over the transfer line between the accumulator and the test chamber. The coils are numbered after the position from the accumulator where * indicates that it is only used for transport to the main traps. 5* is titled for better transport to the main traps. The correction coils are omitted.*

### 3.4.1 Buncher

The positrons have so far been transported with magnetic fields. However, the last part of the transport is governed by electrostatic transport. The magnetic environment inside the test chamber can easily be controlled with no external magnetic interference. One of the main tasks of the test chamber is to perform measurements on o-Ps in a magnetic field ranging from 0 to 300 Gauss. This switch between magnetic to electrostatic transports is done where the buncher begins. The shielding of magnetic fields is done by having the first electrode built in μ-metal blocking the field on the border. A large fraction of positrons is lost in this border due to divergence of the magnetic field. The electrostatic transport is carried out by some electrodes according to figure 20; V1, V2, VL and buncher electrodes. V1, V2 and VL work as lenses and focus the beam at the target inside the test chamber. V1 is set to -800 V, V2 to -2500 V and VL to -550V as these values seem to give the best focus. The buncher is equipped with buncher electrodes and is used to reduce the time spread of the pulse. These electrodes give rise to a potential according to figure 20. The idea is to accelerate late positrons more than positrons ahead to reduce the time spread with a potential going up to 10 kV. As a whole, the buncher is 30 cm which means that the velocity of the positrons cannot exceed a certain level. Therefore, the positron pulse has to have a lower energy than 100 eV in order to optimize the compression with the buncher.
3.4.2 Test Chamber
The positron plasma is finally transferred to the test chamber where positronium is produced. The target is situated in the middle of the chamber facing the pulse path. The target holder is connected to an actuator making it possible to move the holder back and forth. The holder itself is designed in a way that several targets can be installed at the same time. Therefore, the target for positronium production can easily be changed without breaking the vacuum. The target holder has several holes of a diameter of 5 mm meaning these holes can be used to let the positrons pass through and have a fast diagnostic of the positron beam. A MCP coupled to a phosphor screen and a CCD camera is installed on the backside of the holder to improve the characterization of the beam (see “3.6.1 Detectors along the positron system). This holder is made of aluminium and can therefore be used as a background of positron annihilation measurement since almost no positronium is produced in metals. It is also possible to install three small pieces of aluminium used to steer the beam. One of these pieces has a small circle in the middle with 5mm in diameter where the other two have a 5mm width and 15mm height rectangular. The difference between the latter two is that one of them is titled 45 degrees. The test chamber is pumped with a turbo pump.

3.5 Transfer line to the main traps
For transporting positrons to the main traps, the energy of the dumped positrons from the accumulator is raised to 300 eV. The reason is to lower the magnetic reflection that occurs when charged particles are injected to a region with high magnetic field from a low region. The transfer to the main traps is governed by several coils. The coils 1-5* in figure 19 are connected in series for this transport. In addition to 1-5*, there are six other coils connected in same series where each coil result in a magnetic field of 800 – 1400 Gauss. Figure 21 is a simplified sketch over the transport. The coils connected in series are illustrated with black and white rectangles. In addition to the coils used for main transport, there are five correction coils illustrated with green color in figure 21. The correction coils are supplied with separate power supplies where the power can easily be varied and tuned to steer the beam. In particular, there is a horizontal corrector correcting the horizontal position and a vertical corrector...
placed under the bent in figure 21 (10*) that can push or pull the positrons vertically. A vacuum of $10^{-10}$ mBar is maintained also in this part of the transfer line.

Figure 21. A scheme over of the transport to the main traps looks like. The five coils connected in series with 5* is represented with one big black rectangle. The green rectangles are correction coils correcting the beam path.

3.5.1 5 T and 1 T traps
The main traps can be divided into two regions, namely 1 T and 5 T region. Both traps are Penning-Malmberg traps where the number of electrodes as well as the magnetic field varies. The 5 T trap is the first trap where the catching and the main cooling of positrons and antiprotons are carried out while the second trap is the 1 T trap. As mentioned earlier, a higher magnetic field is desired since cyclotron cooling becomes more effective for positrons and on antiprotons through electron cooling. On the contrary, a lower one is desired for particle manipulation and for the gravity measurement which is the reason for dividing the traps to 5 T and 1 T regions. The magnetic fields are generated with superconducting magnets cooled with liquid helium and liquid nitrogen.

The 5 T trap can be divided into three parts. The first part is called catching trap or c-trap consisting of 19 electrodes (46 cm long) and the second one is called positron trap or p-trap consisting of 14 electrodes. The third part is called transfer trap or t-trap consisting of six electrodes. The electrodes in the middle of the c-trap (c-10 and c-11) are segmented into four parts to function as a RW. In addition, the electrodes in the middle of the p-trap (p-7 and p-8) are segmented into four as well. There are three high voltage (HV) gates connecting each trap segment. The first one (HV1) is the entrance gate and is situated between the c-trap and the transfer line. The second one (HV2) is between the p-trap and the c-trap and the third one (HV3) is between the t-trap and the p-trap. Each electrode can reach voltages as high as few kV and can together form different shapes of potentials to cool and catch charged particles. Despite the name, only the c-trap is used to catch and cool positrons while the p-trap and the t-trap are used to transfer them to the 1 T trap.

The 1 T trap can be divided into four parts. The first part is called big trap or b-trap consisting of 15 electrodes. The middle electrodes b-10 and b-12 in the big trap are four-segmented RW. The second and third parts are called on-axis trap and off-axis trap and consist of 28 and 20 electrodes respectively. The last one is called ultra cold trap consisting of 15 electrodes. All of these traps are sharing the same axis
as center except for the off-axis trap which is situated directly above the on-axis trap. The Ps formation target is situated above the ultra cold or u-trap and is sharing the same axis as the off-axis trap. The positrons will be dumped from the off-axis trap towards the target to form Ps. The electrodes in ultra cold trap are partially transparent in order to let Ps diffuse to the u-trap from the target. It is believed having partially transparent electrodes may disperse already cooled and trapped particles. Therefore, the idea is to dump antiprotons from the on-axis trap exactly at the same time as Ps reach the ultra cold trap.

3.6 Detectors

The AEgIS positron system utilizes several detectors to gain information about the beam. Calibrated CsI-PMT detectors are used to govern the moderated positron beam strength. The accumulated positron number is determined by the calibrated CsI-photodiode detectors. One Cherenkov radiator, the $PbF_2$, is used for positronium formation detection. Positronium detection is also possible with a plastic scintillator. However, the signal to noise ratio was higher with the $PbF_2$. Although, several plastic scintillators are installed along the main traps and there is a phosphor screen coupled with a MCP at the end of the 1 T trap where the photons are detected with a CCD camera. Same imaging detector setup is installed in the test chamber.

3.6.1 Detectors along the positron system

There are two CsI-PMTs used in the system. One is placed to detect annihilation of positron around the saddle coil. The other one is placed just outside the trap. These detectors are fast making it possible for detection of positron annihilation-count per second. It is possible to optimize the parameter between the source and the trap using these detectors. It is desired to have a low count as possible for the detector around the saddle coil and as high as possible for the detector around the trap. For reference, good numbers are 400 C/s for the saddle coil detector and 250 C/s for the trap detector. In addition to the CsI-PMT, there are two CsI photodiodes detector used for measurements and analysis of the positron beam. The signal is read out on a computer using LabVIEW. These detectors can be placed externally from the apparatus. They are very compact and can easily be moved around and point out annihilation locations of positrons. They can be placed on coils since they are not affected by magnetic fields. These detectors are slower compared to CsI-PMTs. Instead, these detectors have been calibrated so that for a certain distance, the signal amplitude is proportional to the number of positrons annihilating. Finally, there is a MCP coupled to a phosphor screen at the end of the test chamber where the photons are detected with a CCD camera. The focusing of the camera was carried out to an order of few pixels. The potential on the phosphor screen is usually set to 4200 V while the MCP is set to 1080 V. The sample holder has to be set so one of the 5 mm holes are in the beam path in order to let the positrons reach the MCP. The MCP has not been calibrated yet meaning only the spatial 2D can be obtained from the pictures.

3.6.1.1 Calibration of CsIs

Both the CsI-photodiodes and the CsI-PMTs have been calibrated during the construction of the positron system. The calibration is necessary in order to understand the correspondence between the readout signal amplitude and the total number of positrons. First, the CsI-PMT was calibrated with a known sodium-22 source (note that this is not the identical source to the one used in the system). The gamma rays with an energy of 1.28 MeV emitted from the source during the decay have to be cut to not to interfere with the detection of positron annihilations. This was done by setting a threshold of detectable
energy of gamma rays on the detector. Together with branching ratio, the total number of positrons emitted from the source can be estimated. The CsI-PMT was placed with a certain distance from the source with defined solid angle. Through this, the signal on the CsI-PMT correspondence to the number of positron is now known. The calibration was later confirmed using the same method but using a Cesium-133 source instead.

From this point, the positron system at AEgIS was used in order to calibrate the detectors. The source had an activity of 21mCi ($=10^{-10}$ Bq) during the time of calibration. The calibrated CsI-PMT is now placed outside the trap in the system with a known distance from a phosphorus screen acting as a stopper to annihilate positrons. Note that this phosphorus screen is no longer installed in this position system today. The electrodes in the trap as well as the buffer gas injection were set to zero and the positrons were transported only magnetically. From the signal detected, the transport + moderation efficiency can be calculated since the number of positrons emitted from the source is known. The efficiency was calculated to be around $3 \times 10^{-3}$ which is very close to the moderation efficiency implying almost perfect transport. From the fact that the number of positron arriving to the end of the trap is known, the phosphorus screen was calibrated as well. From the calibration, the luminescence intensity correspondence to number of positron is known. The number of positron reaching the end of the trap was calculated to be $2.3 \times 10^6$ /s.

After this, the trapping efficiency was estimated with the calibrated phosphorus screen. Note that phosphorus screens are linear. The same acquisition time is kept while comparing the images from the phosphorus screen when the positron transport is continuous and dumped. The continuous transport refers to when the electrodes and the buffer gas injection in the trap are zero while dumped refers to normal dumping procedure of the trap, i.e. trapping and dumping of the positron plasma such that pulses of positrons are made. The ratio between the integral over the images suggest the efficiency of trapping which is found to be around 14 %. This value is a bit lower than the efficiency declared by First Point Scientific of 17 %. Having $2.3 \times 10^6$ positrons per second in continuous case implies having $0.14 \times 2.3 \times 10^6 = 3.2 \times 10^5$ positron per second in dumping configuration. 6.25 dumps are carried out per seconds which means that there are $3.2 \times 10^5/6.25 = 5 \times 10^4$ positrons per dump.

The CsI-photodiodes were calibrated at this point. A CsI-photodiode was placed at a known distance (and known solid angle) from the phosphorus screen. Since the number of positrons is known, the readout signal corresponding to number of positrons is known for the given solid angle. With a similar way as before, the accumulator efficiency was calculated as well. The efficiency can be extracted by placing the calibrated CsI-photodiode with the same solid angle outside the accumulator and comparing the signals. The signals seemed to be the same suggesting high transport and accumulating efficiencies. It is important to remember that these detectors are linear meaning if the detected number of annihilating positron is doubled, then the signal will be doubled as well. Figure 22 illustrates how the signal, i.e. the number of positrons, changes with the number of accumulated positrons in the accumulator. It is easy to see that the detector is linear since the signal amplitude around 1000 pulses is twice the signal for 500 pulses. The fact that the signal starts to saturate around 2000 pulses suggest that the accumulator is not perfectly aligned meaning positron annihilates at the same rate as new positrons are transported into the accumulator.
3.6.1.2 Confirmation of calibration

The calibration above is partially confirmed since the efficiency given by First Point Scientific is not that different from the value obtained. However, another confirmation was also carried. An already calibrated NaI-PMT was put from a certain distance from positron annihilation point. Since the signal readout from a single 511 keV annihilation is known, the number of gamma rays reaching the detector can be measured. A Poissonian distribution can be obtained by doing the same measurement several times. If the distribution is known, then the total number of positrons annihilating can be calculated provided that the solid angle is known. Poissonian distribution is given as

\[ P(n) = \frac{\lambda^n}{e^{\lambda} \cdot n!} \]  

(17)

where \( n \) is the number of occurrences and \( \lambda \) is the random variable given as \( \lambda = \frac{N \cdot d\Omega}{\Omega} \) where \( N \) is the total number of events and \( d\Omega \) is the differential solid angle. The result from the test can be seen in figure 23. From figure 23, it can be concluded that \( \lambda \) has a value between 3 and 4. Since \( \lambda \) is dependent on the total number of events, the total number of positrons can be calculated. The calculated number of positrons in this way was in coherence with the numbers given by the CsI-photodiodes. This suggests that both methods are correct and the detectors are calibrated with great accuracy.
3.6.2 \textit{PbF}_2

A \textit{PbF}_2 crystal coupled to a PMT is used to perform SSPALS measurement detection of positronium formed in the test chamber with a great time resolution. The detector is installed 3 cm from the target holder in a cylindrical hollow in a way to maximize the solid angle. The signal is read on an oscilloscope which is connected to the same LabVIEW program. The resulting amplitude of a signal acquired with the \textit{PbF}_2 is significantly lower comparing to if a plastic scintillator would have been used. However, the important aspect is not the signal amplitude but the signal to noise ratio. For instance, a signal of 8 V acquired with a plastic scintillator corresponded to a signal of 300 mV on the \textit{PbF}_2. However, the signal to noise ratio was higher on the \textit{PbF}_2 due to a higher time resolution. Nevertheless, a small noise is always desired and the reduction is mainly done through shielding of cables and apparatus with aluminium foils.

3.6.3 Detectors along the main traps

There are several plastic scintillator detectors coupled to PMTs installed along the main traps. These are numbered in the order they are installed in starting from the direction of the positrons system. The detectors are shaped as an arc covering the upper and down part of the main traps to maximize the solid angle, see figure 24. Scintillator 20, which will be referred to as PMT-20, was the most used scintillator for the measurements since it is installed closest to the ultra cold trap. This detector was calibrated in a way described in the section below, “3.6.5 Calibration of PMT-20”. PMT-20 was used in order to determine the number of positrons reaching the end of the trap. The minimum number of positrons detectable is limited by the electronic noise. In addition, there is also a MCP coupled to a phosphor screen at the end of the trap where the photons are captured with a CCD camera. The focusing of the camera was done so an order of few pixels can be resolved. It is possible to adjust the gain of the MCP and to set a potential on the phosphor screen. Together, the number of positrons and the dimension of the plasma can be measured. The MCP-phosphorus screen + CCD camera setup can alone determine the number of positrons but it has not been calibrated yet.

![Figure 23. Poissonian distribution where the squares are the obtained data and the solid lines represent the distribution where \(\lambda=2, 3\) and 4. [9]](image-url)
3.6.3.1 Calibration of PMT-20

Only a brief description will be included for the calibration of this detector. The calibration of PMT-20 was done in a very similar way to the CsI-PMT where the difference is that instead of a sodium source, a strontium-90 was used. Using strontium, a certain level of output from the detector corresponding to a certain number of particles can be known. However, the PMT-20 will be installed on the main traps and the gamma rays will attenuate as it travels through the surrounding material before reaching the detector. Therefore, a Monte-Carlo simulation was performed in order to understand how the signal changes so that the total number of particles can be estimated. At the end, the integral over the signal will give a total number of positron annihilated and detected.

Figure 24. An overview over the main traps. Only the scintillators are illustrated in this figure with black rectangles. The scintillators have an arc shape if looking along Z direction to maximize the solid angle. [9]
4 Results and discussions

There is no clear boundary for when a positron cloud can be treated as a positron plasma. It is very important to understand which one of these that are being dealt with during the measurements since the dynamics and behaviors differ. To simplify, a plasma is assumed if the number of positrons is $>10^7$. Note that if nothing else is mentioned, all measurements were carried out with a moderator in its stable state, i.e. with a moderator that is older than 5 hours. Measurements with a new moderator were carried out when a high number of positrons was desired. However, the number of positrons in a shot with e.g. 2000 pulses from the trap can vary depending on the age of the moderator. Therefore, the number of positrons was first checked before any measurements. In addition, the stability of the positron system was checked by acquiring several signals and measuring the fluctuation of the signals. This test was performed when the moderator was in its stable state for which the signal fluctuated within 7%.

This section will be divided into three parts. Firstly, the result concerning the accumulator is presented. In particular, how the accumulator was optimized to increase the total number of positrons and the plasma behaviors inside the accumulator. These diagnoses were mainly performed with the CsI-photodiode detectors. Secondly, the time spread of the positrons inside the test chamber is characterized with a $PbF_2$ crystal coupled to a PMT. The MCP-phosphor screen + CCD camera setup was also used to analyze the spatial 2D of the beam inside the test chamber. It is of interest to see how the buncher manages to compress the positron plasma in time to obtain a better probe for Ps formation. Thirdly and maybe the most interesting results, the positron plasma behaviors inside the 5 T and the 1 T traps. The number of positrons was estimated with the PMT-20 while the spatial 2D was with the MCP-phosphor screen + CCD camera setup.

4.1 Positrons in the accumulator

The accumulator can be seen as the heart of the positron system. The parameters and alignments of the fields inside the accumulator are determining the number of positrons that can be accumulated. It is important to understand how many positrons can be accumulated since this sets the initial conditions to all measurements carried out. Maximizing this number if of a great interest for the experiment since a number of $10^8$ positrons are required for the antihydrogen production. It is also important that the time spread of the positrons is not too large since this will result in some losses during the catching procedures in the main traps. Some of the positrons will have to be cut in order to trap them if the time spread is too large. There are several parameters inside the accumulator that can be varied and affect the lifetime inside. The most probable parameters are the correction coils inside the accumulator, the ring potential depth inside the accumulator, the RW frequency and external fields such as 5 T and 1 T from the main traps. Making a multidimensional analysis with all these parameters is too complex that cannot be performed unless the procedures are completely automated. Instead, these parameters were analyzed by setting all the parameters to initial optimum value that was attained during the assembly of the system and from that point vary one parameter of interest.

4.1.1 RW and ring potential dependence

It is believed there is a strong correlation between the RW configuration and the depth of the harmonic well since the RW is applied at the bottom of the well. This correlation was investigated by varying the ring potential in the accumulator while keeping the RW frequency at 6 MHz. A CsI-photodiode was placed just outside the accumulator to detect the annihilated positrons. The transfer line was off
meaning the accumulated positrons annihilated somewhere outside the accumulator. The ring potential was varied between 0 and 6.5 V where a lower value meant a deeper potential well. 300 pulses were accumulated and two measurements were carried out for each potential to acquire a mean value. The error bar is set to the standard deviation. The result is shown in figure 25. The signal amplitude or number of accumulated positron varies heavily with the ring potential where the optimum value seems to be around 3.6 V. It is not clear why there are several spikes and local minimums.

![Graph showing signal amplitude vs. ring potential](image)

*Figure 25. Shows how the signal amplitude outside the accumulator varies with the ring potential in the accumulator where the optimum is at 3.6 V. The solid line is a guideline.*

Similar method was used for measurements with the RW frequency. The ring potential was kept at 3.6 V while the frequency was varied between 2 MHz and 7 MHz. 300 pulses were accumulated and the detector was placed outside the accumulator. Two measurements were carried out for each frequency. The result of the positron annihilation signal as a function of the RW frequency can be seen in figure 26. A clear optimum value does not seem to exist as in previous case but the highest value is obtained at 5.3 MHz. Observe the sharp drop around 3 MHz and the smaller ones at 4.8 MHz, 5.5 MHz and 6.6 MHz. These are probably due to some resonance effects. The fluctuation in the plateau between 4 MHz and 6.5 MHz is probably due to the instability in the system since it fluctuates within 10 %.
4.1.2 Positron lifetime inside the accumulator

The lifetime of positrons inside the accumulator will determine the total number of positrons that can be accumulated. It is therefore crucial to know and to improve the lifetime for AEGIS experiment and it is believed that aligning the beam or correcting the magnetic field inside the accumulator will. One way of aligning the beam is to use the correction coils which are installed inside the accumulator. The procedure of the lifetime measurement is very similar to the case with the RW and ring potential tests. A CsI-photodiode was placed outside the accumulator and the transfer line was off. Measuring the acquired signal as a function of the accumulated pulses from the accumulator will indicate the lifetime in the accumulator. The vertical correction coil inside the accumulator was supplied with 0 A, 20 A and 40 A while the RW frequency was set to 5.3 MHz and the ring potential to 3.6 V. Three measurements were carried out for each number of pulses and the error bar is set to the standard deviation. The result is shown in figure 27.

![Figure 26. The signal amplitude outside the accumulator as a function of the RW frequency in the accumulator. The solid line is a guideline.](image)
The lifetime is significantly improved using a vertical correction coil supplied with 40 A. For 40 A applied through the correction coil, the signal increases linearly until ~2000 pulses while the linear part for 0 A seems to end around 600 pulses. This means the lifetime is around 2000 pulses (~6 minutes) when 40 A is applied which is three times higher than 600 pulses (less than 2 minutes) which is the lifetime when no correction is applied. The coil was also applied with 20 A to investigate if there was a maximum for currents between 0 A and 40 A. Since there is none, applying a higher current than 40 A through the coil suggest it would increase the lifetime even further. The total number of positrons was calculated to be around $8 \times 10^7$ for 3000 pulses when 40 A was applied. It is interesting to note that a magnetic field of 0.36 Gauss in a field of 0.1 T can affect the alignment this much. This is equivalent to a correction of less than 1%. Also, so far only the total number of positrons have been investigate and does not indicate how well compressed the positron plasma is.

4.1.3 The beam spot size

The total number of positrons can be significantly increased through vertical correction in the accumulator. Although, it is of interest to know also how the spatial 2D is affected by this. It is ideal to have a small beam since a bigger beam one may more easily be destroyed during its transport through the transfer line and the cooling of it in the main traps might be harder. The spatial 2D was measured using a screen placed in the transfer line outside the accumulator. This screen was moved horizontally across the transfer line acting as a stopper forcing the positrons to annihilate. This annihilation signal was measured with a CsI-photodiode as a function of the screen movement which was moved with 1 mm in increment. The result can be seen in figure 28 a). The correction coils in the accumulator were not used. Note that this only gives information about the beam in the horizontal direction. However, it is probably safe to assume symmetry of the beam considering how the accumulator and the RW work.
The acquired data points are the black squares while the red curve is a logistic regression. The signal in figure 28 a) is first very stable. A higher signal means more positrons annihilate meaning none of them is able to cross the screen. As the screen was moved, part of the beam will annihilate and part of them will cross. Finally, all of the positrons were able to cross when the screen had been moved all the way resulting in low signals. The horizontal beam characteristics can be obtained from the curve in figure 28 a) which is equal to the differential of the red curve. This is plotted as black squares in figure 28 b). The derivative has been normalized and the red curve is a Gaussian fit. It is clear from the fit that the horizontal beam characteristic is a Gaussian. From the figure, the Full Width Half Maximum (FWHM) can be obtained to be 4 mm.

The beam was also characterized as the vertical correction coil in the accumulator was supplied with 40 A with the same method to see if aligning the beam inside the accumulator also compresses the positrons better. The screen was moved with an increment of 1 mm and the signal was detected with a CsI-photodiode. The result can be seen in figure 29 a). The acquired data points are the black squares while the red curve is a logistic regression. The horizontal beam characteristic was then acquired by differentiating the red curve from figure 29 a). This is plotted as black squares and normalized in figure 29 b). This is also fitted with Gaussian and is plotted in b) with a red curve. The FWHM is around 2.8 mm. To summarize, the number of positrons and the beam size can be changed by correcting the beam alignment inside the accumulator.
4.1.4 The presence of fields from the main traps

The data presented so far have been acquired while the main traps were off. Similar tests with the correction coil in the accumulator were performed with the main traps on and off to see if the alignment inside the accumulator had changed. In addition, a new power supply was installed so the horizontal corrector in the accumulator was also tested. A CsI-photodiode was placed just outside the accumulator with the transfer line off. The RW frequency and ring potentials were kept constant at 5.3 MHz and 3.6 V. Four different configurations were tested: a none corrected state, 40 A vertical correction, 15 A horizontal correction and 40 A and 15 A on vertical and horizontal correction. The horizontal coil was only supplied with 15 A as it was the limit of the power supply. The result is plotted in figure 30. The error bar is set at 10 % to overestimate the fluctuations of the system.
Note that the position of the detector was not in the same spot as previously for the data presented earlier. A comparison in absolute numbers cannot be carried out but it has to be done relatively since the solid angle is different. However, the lifetime can be compared since it does not depend on the solid angle. It seems like the lifetime is higher when the main traps are on, ~4000 pulses (12 minutes). In addition, it seems a none corrected state is better than having a vertical correction which was not the case when the main traps were off. Instead, a horizontal correction appears to increase the total number of accumulated positrons. This means that the configurations inside the accumulator have changed completely by external fields and is affecting the alignment in the accumulator. A more clear indication of this effect can be seen in figure 31. Figure 31 shows the difference in the number of positrons while the main traps were on and off. The solid angle for the detectors had to be calculated for obtaining the total number of positrons in absolute sense. Both curves were obtained for each optimum configuration, i.e. a vertical correction with 40 A when the main traps were off and horizontal correction with 15 A when the main traps were on. It is clear from the graph that more positrons can be accumulated if the main traps are off.

![Graph showing number of accumulated positrons as a function of the number of pulses. The solid lines are guidelines and the error bar is set to 10% for the fluctuation of the positron system.](image)

In conclusion, the correction coils inside the accumulator can correct the misalignment to some degrees resulting in a better compression and better cooling of positrons, i.e. a higher number of positrons. However, the optimum use of corrections depends strongly on external magnetic interference. In other words, the characteristics of the positrons in the accumulator could in principle change very quickly by having other experiments, in the AD, turning on or off a strong magnet or by having the AD on or off etc. Therefore, it is important to note that the data presented so far may not be valid today in an absolute sense since the configuration inside the accumulator is changing continuously due to external magnetic interference. Nevertheless, the presence of horizontal and vertical corrections allows optimization of total number of positrons for different external field conditions.
4.2 Bunching

The purpose of the buncher is to reduce the time spread of the positron pulse. First, the timing between a dump from the accumulator and switching on the buncher had to be set. If the buncher is turned on too early, then the positrons will be reflected back. If it is turned on too late, then the buncher will not do much since most of the positrons only feel the lower part of the potential. The synchronization was done by measuring the signal amplitude in the test chamber as a function of the time of switching on the buncher. 1000 pulses were accumulated and dumped towards the test chamber and the buncher was switched on with a voltage of 5 kV, which corresponds to a final positron implantation energy in the target of around 3.5 kV. The $PbF_2$ crystal coupled to a PMT was used as a detector recorded on an oscilloscope. The result can be seen in figure 32. The solid line is a guideline and error bar is set to 10% of the signal to compensate for the fluctuations of the positron system.

As it can be seen, there is no signal if the buncher is turned on too early. The amplitude has a peak for a certain timing suggesting compression in time. The amplitude gradually decreases after the peak while the number of positrons is kept constant meaning that the signal is more broadened for timings after the peak. This effect is also confirmed by measuring the FHWM directly as a function of the delay. The signal from the $PbF_2$ was recorded on an oscilloscope meaning a FWHM can be estimated from this signal. The total time spread was estimated by cutting the graph so that 90% of the signal still remained. The time spread as a function of the same time delay is illustrated in figure 33. Two measurements were performed for each delay and the error bar is set to the standard deviation.
Figure 33 is a plot over how the time spread is changing as a function of the delay time on the buncher. The error is standard deviation.

Figure 33 confirms the result illustrated in figure 32. The pulse is more compressed around a delay of 20 ns. The pulse can be compressed to around 8 ns compared to around 22 ns when no buncher is applied. An example of a picture from the oscilloscope is illustrated in figure 34. There are two normalized graphs: one with the buncher on with the optimum timing and one with the buncher off. As it can be seen, the signal is compressed in time when the buncher is on compared to when it is off. The time spread is around 6 ns with the buncher on and 15 ns when it is off. This is a clear indication on that it is possible to compress the positron plasma in time by using a buncher.

Figure 34. Signals detected with the PbF$_2$ recorded on an oscilloscope. The blue curve is the signal acquired when the buncher was utilized. The yellow curve is without the buncher. The signals have been normalized to 1.
It is also of interest to study the spatial distribution of the positron beam inside the test chamber. The focusing of the beam, related to the spatial distribution can be controlled with the lenses along the buncher. A highly focused beam is more favorable considering Ps production. An example of a picture taken with the MCP assembly is shown in figure 35 a) where the background has been subtracted. Figure 35 b) is the corresponding 3D plot of a) where the intensity is given by the color scale. The voltages were set to 4.2 kV and 1.08 kV on the phosphor and on the MCP respectively and the buncher was utilized. The yellow ring in figure 35 a) represents the phosphor screen of a diameter of 2 cm. The FWHM in figure 35 b) was estimated to be around 4 mm and the number of positrons in this shot was estimated to be around $1.5 \times 10^7$. The FWHM was around 3 mm outside the accumulator (see “4.1.3 The beam spot size”) meaning the plasma is expanding during its transport to the test chamber. Probably, most of the expansion is caused around where the transport is changed from magnetically to electrostatic, i.e. where the buncher starts. The magnetic field is diverging around that area which is causing the plasma to expand. Nevertheless, a FWHM of 4 mm is still good and many studies of o-Ps with this beam are possible.

![Figure 35](image)

*Figure 35. Shows a picture taken with the MCP assembly inside the test chamber. a) is the picture taken while b) is a 3D plot of a). The background has been subtracted on the pictures. The yellow ring in a) is representing the phosphor screen.*

### 4.3 Positrons in the main traps

One of the most important and essential objective for AEgIS experiment is to be able to produce positronium inside the main traps. For this, the positrons have to be cooled and trapped in the off-axis trap. The absolute number of positrons and how good the positron plasma is compressed will determine the efficiency and the total of number of Ps that can be produced. The idea is to systematically trap and cool the positrons in the main traps and eventually trap and cool the positrons in the off-axis trap. The results from these measurements are presented in this section. There are mainly three different types of measurements carried out in the main traps. The simplest one is called a pass through meaning that the positrons from the accumulator are simply passing through the main traps and detected. The second one is called cooling meaning positrons are caught in the $5 T_c$-trap and cooled and dumped towards the detectors. The third type is called transfer meaning the positrons are first trapped and cooled in the $5 T_c$-trap but are also transferred to the $1 T_b$-trap. As mentioned, these are detected with the MCP-phosphor screen + CCD camera setup and with PMT-20.

49
4.3.1 Pass through measurements

A pass through configuration is where all the potentials in the traps are set to zero and the positrons are transported in an environment free from electric fields to reach the MCP. A lot of information about the beam can be gained from these measurements such as the position (making it possible to steer the beam), the energy distribution, the time distribution, the spatial 2D distribution and the number of injected positrons. These parameters are very important to understand to achieve cooling of positrons. It is important to steer the beam to the center of the trap to have an effective cooling. The energy and time distributions will determine how big of a fraction that can be trapped. The spatial 2D distribution will give an estimation of the density where a higher density is related to the efficiency of the eventual cooling. The total number of positrons will not only determine the number of Ps that can be produced but is also crucial for good cooling (collective cooling) and will therefore in a way determine the FWHM.

4.3.1.1 Steering

The goal of steering is to steer the beam so that the beam is entering the center of the trap. However, a reference point is needed in order to steer the beam. Several points were obtained by dumping a well-compressed electron plasma from the different traps in the main apparatus. The electrons are dumped from the center of a trap and the center of the spot on the MCP can therefore be used as a reference point and will indicate the center of the trap. Four reference points were obtained and are presented in figure 36. gProd in the figure was obtained by dumping electrons from the u-trap. The second point, pCTrap, was obtained by dumping electrons from the p-trap and the c-trap. The third point, gOnAxis, was obtained by dumping electrons from the on-axis trap. The final point was acquired with positrons in a pass through configuration where the coil in the bent was set to 17 A referred to as pinj-17A in the figure.

![Figure 36](image)

*Figure 36. It is a picture acquired with the MCP without positrons and with background subtracted. The color gradient on the right is pointing out the intensity of the signal. The small 'X' in the figure are acting as reference points. These points have been acquired with electrons except for pinj-17A.*
It can be noted that the fact that pCTrap, gOnAxis and gProd are not overlapping in the figure suggests misalignments of the traps by few millimeters. It is unclear how much this misalignment will affect the cooling efficiency of positrons. Nevertheless, the steering of positron beam was done by having pCTrap as a point of reference since positrons must before anything be trapped and cooled in the c-trap and the p-trap. The steering of the beam was done by changing the supply through the correction coils along the transfer line, in particular the horizontal coil and the coil placed under the bent. This allowed a steering in a horizontal and in a vertical direction. The accumulator parameters were kept constant and 2000 pulses were used. The steering was carried out systematically in two steps. First, the horizontal one was kept at zero and the beam was vertically steered by changing the current through the coil systematically until the vertical positron was aligned. Then, the beam was steered horizontally by changing the current through the horizontal corrector. The result can be seen in figure 37. Even if the signal in figure 37 is well compressed, a dense beam was only obtained some time after that the steering was completed. A figure with a well-squeezed beam was chosen to show the steering was completed in a good way. The signal acquired with PMT-20 for the shot presented in figure 37 measured a number of positrons equal to $1.2 \times 10^7$ which is in a good agreement with the number of positrons estimated with 2000 pulses with the calibrated CsI-photodiodes.

![Figure 37. Positron annihilation on the MCP detected with a CCD camera. The positrons are in this case well-compressed which was not obtained after few weeks after that the steering was completed. A figure with a good compression was chosen to illustrate the steering.](image)

**4.3.1.2 Energy and time distributions**

It is important to understand how big the energy and time distributions are of the positron plasma dumped from the accumulator since it will limit the total fraction that can be caught and trapped in the main traps. The energy and time distributions can be obtained in a pass through configuration. The
energy distribution was measured by measuring, with PMT-20, the number of positrons able to cross as a function of the voltage on the 5 T entrance (HV1). Positrons will be reflected if the voltage set on HV1 is higher than the positron energy and will not be detected. The energy distribution should have an average energy of around 300 eV since the positrons from the accumulator are dumped with an energy of 300 eV. Since the measurements with PMT-20 are dynamic, it is also possible to study the time distribution of the plasma. This was obtained in parallel to the energy distribution measurement. The parameters in the accumulator were kept constant and 2000 pulses were used for each shot. The number of positrons as a function of the HV1 potential can be seen in figure 38 a) where the black circle are the data points. The error bars in a) are set to 10 % of the signal to compensate for the fluctuations from the system and the red line is a Boltzmann fit. The energy distribution can be gained by taking the derivative of the red curve in a) which is plotted and normalized in b) as black circles. The red curve in b) is a Gaussian fit of the circles. It is clear from the fit that the energy distribution had a Gaussian distribution. From the fit, the average energy was obtained to be 292 eV which is relatively close to 300 eV. The FHWM and the standard deviation were obtained to be 69 eV and 29 eV respectively. The standard deviation is <10 % of the average energy meaning the dump from the accumulator is done in a very good and precise way.

The energy distribution will determine the time distribution in the end. The positrons with higher energies will travel faster while the lower ones travel slower. Therefore, it is important that the energy distribution is small enough so that the time distribution does not get too big. If it is too big, then not all of the positrons will be able to be trapped in the c-trap. If the time distribution is too long, then the faster positrons may leave the trap before the slower ones have arrived. The time distribution of the positrons was measured by taking an average of several shots with 2000 pulses. The total time spread was estimated by cutting the graph so that 90 \% of the signal still remained, which was read out to be 50 ± 12.5 ns. Figure 39 is an example of a signal acquired with the PMT-20. The question is though, is the time spread small enough to trap the whole plasma? The trap is in total 46 cm meaning the first arriving positron can travel 92 cm before HV1 has to be raised (see “4.3.2 Catching and cooling procedures in the 5 T trap”). The average energy of the positrons is 292 eV with a FWHM of 69 eV. This means that the
fastest positrons have an energy of 361 eV \((292 + 69 \times 2/2 = 361)\). In a non-relativistic case, 361 eV corresponds to velocity of \(11268843 \text{ m/s} \) \(((361 \times q \times 2/m)^{0.5} = 11268842.95\) where \(m\) is the mass of a positron\) which means it takes 81.6 ns \((0.92/11268842.95 = 81.64103488 \text{ ns})\) to travel back and forth. In other words, at least 90% of the positrons can in theory be trapped if the timing is perfect since the time spread of the plasma is smaller than 82 ns.

![Graph](image)

*Figure 39. A signal from PMT-20. The integral over this graph corresponds to the total number of positrons.*

### 4.3.1.3 Spatial 2D

It is important to have a high dense beam to have an effective cooling of the plasma. Efficiency of the collective cooling depends on the total number of positrons as well as on the density. The spatial spot of the beam was measured with the MCP-phosphor screen + CCD camera setup. It is believed the conditions in the accumulator are determining the final FWHM of the plasma. Therefore, many parameters were analyzed as a function of the spot size in order to understand the effects the parameters had. Increasing the number of positrons from the accumulator increased the FWHM. This is quite evident since a larger number of positrons have to expand radially due to space charge effects unless it is compressed with the RW. This was tested by keeping the parameters constant but doing the same measurements for different number of pulses. In the end, it was discovered that the frequency in the accumulator had a big impact. All parameters were kept constant except for the RW frequency. A picture when using a frequency of 3.9 MHz and 5.3 MHz can be seen in figure 40 a) and b). The background has been subtracted. The total number of positrons detected was \(1.2 \times 10^7\) for 3.9 MHz and \(3.6 \times 10^7\) for 5.3 MHz. It seems that a higher frequency in the accumulator results in a higher number of positrons but with a bad compression while having a lower frequency will result in a much better squeezing but with a lower number. Since the goal is to catch and cool a high number of positrons with a good compression, it is still unknown which configurations that are more suitable for this experiment at this point of discussion (see next section).
4.3.1.3.1 The optimum RW frequency in the accumulator for cooling in the c-trap

It is important to be able to cool as high number of positrons as possible in the c-trap. However, if the initial conditions from the accumulator are too bad as in if the FWHM is too big or if the number of positrons is too low, cooling might be difficult. It was seen in figure 40 that the RW frequency in the accumulator had a big impact on the FWHM as well as on the number. The cooling efficiency as a function of the RW frequency in the accumulator was investigated by measuring the FWHM as well as the number of positrons as a function of the RW frequency. The number of positrons and the dimension were first measured with PMT-20 and the MCP-phosphor screen + CCD camera setup in a pass through configuration before cooling was tested (see “4.3.2 Catching and cooling procedures in the 5 T trap” for the exact procedures in the 5 T region). As seen in figure 40 b), using 5.3 MHz in the accumulator resulted in a high number of positrons ($3.6 \times 10^7$) with a FWHM ~6mm in a pass through configuration. Once the FWHM and the number were obtained, the positrons were transported to the c-trap, stored for 60 seconds and dumped towards the MCP. This resulted in no signal of positrons on the MCP or on PMT-20 meaning no cooling was achieved. Same procedure was tried with 3.9 MHz and as it can be seen in figure 40 a), the pulse has a lower number of positrons ($1.2 \times 10^7$) but with a much lower FWHM, ~0.5mm. Using 3.9 MHz should be more favorable if the cooling is only depended on the density since the number only decreased with three times while the FWHM decreased six times. However, even this resulted in no signal from the MCP when the positrons were stored for 60 seconds in the c-trap and dumped. It was discovered cooling could be achieved using 4.8 MHz. The number of positrons was $1.9 \times 10^7$ with a FWHM of 1 mm in a pass through configuration using 4.8 MHz. The storing of positrons in the c-trap for 60 seconds while using 4.8 MHz in the accumulator resulted in a FWHM of around 1.1 mm with no losses. What is interesting is that the cooling does not entirely depend only on the density. Highest density was achieved using 3.9 MHz but without successful cooling. Probably, the number of positrons was too low resulting in poor collective cooling. There seems to be a threshold for minimum number of positrons required and a maximum FWHM allowed for effective cooling in the c-trap. The
minimum number of positrons required for cooling in the c-trap can be estimated from the frequency scan performed. It was discovered cooling was only successful for frequencies when the compression was decent and the number was around $10^7$ in a pass through configuration. To summarize, there is a minimum density for which cooling can occur as long as the number of positrons is higher than $10^7$ to cool positrons in the c-trap in an effective way. Using 4.8 MHz in the accumulator results in a positron plasma where the threshold for both the number of positrons and the FWHM was overcome. From this point on, a frequency of 4.8 MHz is used for the data presented if nothing else is mentioned.

4.3.2 Catching and cooling procedures in the 5 T trap
The procedure to catch the positron in the c-trap is similar to how the accumulator works, at least potential wise. HV2 is used as a gate and is set to 1 kV to catch the positrons. The injected positrons travel through the trap and are reflected by HV2. HV1 is set to 1 kV before the first reflected positrons escape the trap. It is due to this logic that the time spread cannot be too big. The main difference from the accumulator is that it is necessary to use buffer gas cooling in the accumulator in order to lower the positrons’ energy to trap them. In the c-trap however, the magnetic field is strong enough to reduce the positron energy via cyclotron radiation. Although, the loss is not fast enough to be able to keep HV1 open. Therefore, first an optimum timing for raising HV1 has to be obtained. HV1 synchronization was carried out in a similar way to how the buncher was synchronized. It was synchronized by measuring the number of positrons able to cross as a function of the delay time of HV1 activation while HV2 is set to zero. The delay is set relative to dump from the accumulator and the number was measured with PMT-20. The result can be seen in figure 41 a) and the red line is a linear extrapolation of the data. The number of accumulated positrons was kept constant. The error bar is set to 10 % for the fluctuations of the positrons system.

![Graph](image)

Figure 41. a) Number of crossing positrons detected with PMT-20 as a function of the delay time of HV1 indicated with black squares. The red line is a linear extrapolation of the data points. The error bar is set to 10 % of the signal to compensate for the fluctuation from the accumulator. b) A derivative of the linear extrapolation is normalized and given as the black circles. The red curve is a Gaussian fit of the curve and the FWHM is extracted to 69 ns.

It is clear from the graph that the number of crossing positrons is zero if HV1 is switched on too early. Some positrons are able to cross and others are reflected when it is switched on around the time of arrival (around 500 ns in figure 41 a)). Note that the time in the x-axis in the figure is a reference time
for the electronics and is not the time spent by the positrons crossing the trap. Of course, all positrons are able to cross when it is switched in too late as it is also illustrated in the figure 41 a). It is of desire to switch on HV1 as soon as all positrons have crossed HV1 suggesting an optimum delay time of around 600 ns. In addition, the time spread of the positrons can be calculated by taking the derivative of the red curve in figure 41 a) which is shown in b). The derivative is shown as black circle and the red curve is a Gaussian fit. The FWHM of the Gaussian fit was 69 ns suggesting it is bigger than it was predicted with the PMT-20. Considering the position of the measurements, the time spread of positrons should be smaller at the entrance of the 5 T trap compared to at the end of the 1 T trap. However, the number of data points taken in figure 41 a) makes the time spread calculation not very suitable since the time resolution is lower. On top of that, the fit in a) is just a linear extrapolation making the derivative less continuous. However, the interesting part is the rising part in a) so a linear extrapolation is not too bad of an approximation. Nevertheless, it is safe to assume that time spread is around 50 ns estimated with the PMT-20 and this was just a confirmation.

4.3.2.1 Potentials in the c-trap
The whole c-trap is used to cool the positrons and the potential is already set before the injection of positrons. Several shapes were tested such as a harmonic one or a simple Malmberg potential. However, it was empirically discovered that the best cooling was achieved when the potential had a “V” shaped, see figure 42.

![Cooling potential well](image)

**Figure 42. A principle skis of how the “V” potential looks like. The arrows represent potentials from HV1 and HV2.**

The resulting trap is a very simple trap defined only by a slope and an offset. The positrons can be kept in the trap for a desired time as long as the lifetime is long enough. Upon dumping, the positrons are detected with both PMT-20 and the MCP-phosphor screen + CCD camera setup. There are two types of dumps carried out. There is first a hot dump that is realized when HV2 is lowered to 200 eV. This results in a dump of hot or uncooled positrons. The next dump is called cold where the potentials are reshaped and the whole trap is emptied resulting in a dump of cold positrons. During the storing of positrons, the positrons lose energy through cyclotron radiation. This cooling depends on the time the positrons are
stored. However, the lifetime is strongly depended on the slope of the “V” shaped potential. The optimum slope of the trap was investigated by measuring the number of detected positrons after a storing time of 60 seconds in the c-trap as a function of the potential drop along the electrodes. 2000 pulses were used for each shot which corresponded to 1.2 \times 10^7 positrons in a pass through configuration. The result can be seen in figure 43. The error bar is set to 10 \% of the amplitude for the fluctuations of the positron system.

![Figure 43. Number of positrons dumped from the c-trap after 60 seconds of storing as a function of the voltage drop per electrode. 1.25 \times 10^7 positrons were used for this measurement. The error bar is set to 10 \% of the signal to compensate the fluctuations of the system. The number of positrons seems constant until 8 V of voltage drop.](image)

A higher voltage drop along the electrodes means a steeper “V”. The number of positrons seems constant to a point of 8 V of drop per electrode until the number starts to decrease. Colder positrons can be obtained if the well is lower since that is determining the lowest possible energy. However, it seems that if it is too deep, the positrons are not able to cool in an effective way. Therefore, step size of 8 V seems to be the best configuration for cooling the positrons in the c-trap.

### 4.3.2.2 Lifetime and plasma expansion in the c-trap

It is of interest to know how long of a cooling/storing that is required to have compressed and cooled positrons in the c-trap with current configuration of the trap. Having a shorter storing time would result in a smaller number of positrons in the cold dump since some of them will be in the hot dump. Therefore, it is also of an interest to measure the spatial 2D of the positrons to understand if they are really cooled. If they are, the radial expansion should stop after a certain time of cooling. This was investigated by measuring the number of positrons in a dump from the c-trap as a function of the cooling/storing time in the c-trap and at the same time measuring the spatial 2D. PMT-20 was used to measure the number of positrons and the spatial 2D was measured with the MCP-phosphor screen + CCD camera setup. The number of positrons from the accumulator was kept constant to 0.8 \times 10^7 positrons during the measurement and the result can be seen in figure 44 a) and b).
Figure 44. a) The change in the number of positrons in dump from the c-trap as a function of the storing time in the c-trap. The number is increasing until 40 seconds before it starts to saturate meaning that they are cooled. The error bar is set for the fluctuations from the positron system. b) Changes in the FWHM of the positron plasma as a function of the storing time in the c-trap. The increase stops after 40 seconds and stays at around 1.1 mm.

When the storing time is short, the number of positrons is lower meaning that the positrons are not cooled yet, a fraction of the positrons are still in the hot dump. It seems that the positrons are fully cooled after 40 seconds of storing as it is from that time on when \(0.8 \times 10^7\) positrons can be seen from the dump. On top of that, it is also when the FWHM of the spot stops to increase which suggests that the positrons are cooled. Both a) and b) in figure 44 have the same shape suggesting that the reason for an increase in the FWHM at the start is due to the increase of the number of positrons trapped in the shallow trap. In addition, the fact that the FWHM starts to saturate means the “V” shape potential is actually cooling the positrons. In other words, a long lifetime can be expected. The lifetime was studied by measuring the number of positrons from a dump from the c-trap as a function of the storing time in the c-trap. It was also investigated if the number of positrons from the accumulator could affect the lifetime, i.e. to see if the collective cooling was of any significance. Different numbers of positrons were obtained by having different number of pulses accumulated which was first confirmed with PMT-20 in pass through configuration before the measurements. The number of positrons from the accumulator was chosen according to; \(1.7 \times 10^7\), \(2.7 \times 10^7\) and \(3.1 \times 10^7\) positrons. The result can be seen in figure 45.
The number of positrons is fluctuating. However, a straight line can be drawn within the error bars meaning the number is not decreasing as a function of the storage time, i.e. the lifetime is at least 30 minutes and does not depend on the number of positrons, at least for numbers higher than $1.7 \times 10^7$. However, an infinite lifetime would imply perfect alignment between the electric fields with the magnetic field which is not very likely. Probably, the FWHM is increasing as a function of the storage time. However, the FWHM has to be smaller than the electrodes since the number of positrons is not decreasing.

Measurements with the MCP-phosphor screen + CCD camera setup were carried out in parallel with the measurements in figure 45. The FWHM was estimated from the pictures and the results are shown in figure 46. The FWHM is constantly increasing but there is a sudden expansion for higher number of positrons after 15 to 20 minutes of storing. For lower number of positrons however, the expansion ceases after 15 minutes. This suggests that there is an equilibrium state for a certain number of positrons for certain traps. The goal of AEgIS is to have $10^8$ positrons for antihydrogen production. The positrons would have to be stacked in the c-trap just as the antiprotons if the positron system cannot generate this amount. A further improvement of the lifetime can be introduced by utilizing RW in the c-trap.
Figure 46. Showing the FWHM as a function of the storing time for three different number of positrons where they are distinguished by color. The error bar is set to compensate for fluctuations in the positron system and the solid lines are guidelines.

4.3.2.3 RW scan in the c-trap

The idea with the RW is to prevent radial expansions of the plasma and also to compress it. The optimum RW frequency is expected to be one order of magnitude smaller compared to the one in the accumulator since the magnetic field is one order of magnitude higher in the c-trap. In this case, the hope is to prevent the expansion seen in figure 46. The FWHM of the positron distribution detected with the MCP-phosphor screen + CCD camera setup was investigated as a function of the RW frequency in the c-trap. The positrons were stored for 60 seconds and the RW was on from the moment of injection of positrons until the dump. The amplitude was chosen to be 0.25 and 2000 pulses were dumped from the accumulator for each measurement. The 2000 pulses corresponded to $2.6 \times 10^7$ positrons in a pass through configuration. During the whole measurement, the signal on PMT-20 was checked in order to be sure that the number of positrons was constant. The result is shown in figure 47. It is clear that a better compression can be achieved with certain RW frequencies, especially for frequencies below 1 MHz. Best compression is achieved with 0.75 MHz and there seems to be a rapid expansion around 1 MHz, probably due to some resonance effects. The behavior seen in the first part of the graph resembles a lot of a plasma in strong drive regime since a higher frequency is resulting in a higher density, i.e. a smaller FWHM. This is further investigated in the next section.
Figure 47. Illustrates the FWHM as a function of the RW frequency in the c-trap. The amplitude of the RW was set to 0.25 and 2.6 × 10^7 positrons were dumped from the accumulator for each shot. The error bar is set to compensate for the fluctuation of the positron system and the solid lines are guidelines.

4.3.2.3.1 Strong drive regime
The trend shown in figure 47, where an increase of frequency results in an increase of density is behaving very like plasmas in strong drive regime. In strong drive regime, there is a linear relation between the frequency and the density (see equation 13) which in other words means that a higher frequency should result in a higher density. Unfortunately, there is a rapid expansion of the plasma around 1 MHz. However, there is a way to reach higher frequencies which was attempted by using a “two step” RW technique. The idea is to use one frequency for the first 60 seconds then change to another value of frequency for another 60 seconds. Using this technique, the FWHM was investigated as a function of the second frequency while keeping the first one constant. 0.5 MHz was chosen to be the first frequency since it gave the best compression according to figure 47 (0.75 MHz is actually better but was not chosen since it is very close to the steep slope). 2000 pulses were used from the accumulator for each measurement which corresponded to 2.1 × 10^7 positrons in a pass through configuration. PMT-20 was checked for each shot to see if the number of positrons was constant. An amplitude of 0.25 was used for the measurements and the result can be seen in figure 48. The error bar is set to 10% of the amplitude and the solid line is a guideline.
Figure 48. Is illustrating the FWHM of the positron plasma as a function of the second step frequency of the RW in the c-trap. The first step frequency was at 0.5MHz and the amplitude was constant at 0.25. The plasma was stored for 60 seconds for each frequency. The error bars are set for the compensation of the fluctuation and the solid line is a guideline.

According to figure 48, even further compression seems to be able to be possible using “two step” RW technique compared to having only one step or none at all. On top of that, the FWHM keeps decreasing as higher frequencies are set until the FWHM is as low as 350 µm at 3.5 MHz. Just as in figure 47, there is a sudden expansion for certain value of frequency. A better demonstration of strong drive regime is to plot the density as a function of the RW frequency and see if it is linear. This is plotted in figure 49 where the solid line is a guideline. The first part of the graph has a roughly linear behavior which suggests that the plasma is in strong drive regime. This is a very big advantage since this will make it much easier to characterize the plasma in the trap since the rotational frequency of the plasma is in principle known. This makes it possible to e.g. set desired densities by changing the frequency since the magnetic field is known.
The density or $1/r^2$ is plotted as a function of the second step RW frequency in the c-trap. 2.7 $\times$ $10^7$ positrons were accumulated for each shot. A linear increase suggests that the plasma is in strong rive regime. The error bars are set for the fluctuation of the positron system and the solid line is a guideline.

### 4.3.2.4 Stacking of positrons in the c-trap

It is of interest to know if a number of $10^8$ positrons can be achieved in the c-trap as it is the number AEGIS needs to produce enough excited Ps for antihydrogen formation. However, even with a fully characterize the c-trap, a positron number of $10^8$ cannot be reached as the total number is limited by the positron system. Therefore, an idea was proposed to use the 5 T c-trap as an accumulator. The idea is to accumulate shots of positrons from the accumulator in the c-trap. Just as in the accumulator, by the time a new bunch of positron arrives, the already trapped positrons cannot escape the trap since they have lost most of their energy through cyclotron radiation and are trapped at the bottom of the trap. This procedure is very similar to the accumulator. One shot with 2000 pulses from the accumulator contains around $10^7$ positrons meaning at least ten shots are required to accumulate $10^8$ positrons, which is in total over 1 hour long accumulation meaning the lifetime of positrons inside the c-trap has to be at least 1 hour long. This method is therefore not ideal but it is still interesting to know if AEGIS is able to produce $10^8$ positrons or not with the current radioactive source. This was studied by measuring the number of positrons accumulated in the c-trap as a function of the number of stacks in the c-trap. One stack is achieved with one shot from the accumulator and two stacks with two shots from the accumulator. A RW frequency of 0.5 MHz with an amplitude of 0.25 was used in the c-trap. The RW was first switched on after 20 seconds relative to the first shot from the accumulator for each sequence. 2000 pulses were used for each shot which was in a pass through configuration $1.8 \times 10^7$ positrons. The result is plotted in figure 50. The solid line is a guideline and the error bar is set for the fluctuations of the positron system. It is shown in the graph that a number of $10^8$ positrons are achieved for the sequence with 10 stacks, i.e. ten shots from the accumulator. It is not completely linear since ten shots did not result in $18 \times 10^7$ positrons meaning there were some losses during the storing. Although, it should be noted that the linearity has to be considered for two stacks and higher. The RW is turned on after 20 seconds of storing of the first shot for each sequence meaning the condition is not entirely the
same for when only one stack is investigated and when multiple stacks are. Positrons arriving to an environment where a RW is already on could result in some losses which might be the reason for why 10 stacks did not result in $18 \times 10^7$ positrons. In addition, it seems to be linear for the multiple stacks, i.e. for 2 or more stacks. This suggests more positrons can be stored which is also supported by the fact that there are no signs of saturation after 10 stacks. Although, there seems to be a slight incline between 10 and 15 stacks but then again it could be due to the fluctuation of the positrons system.

![Figure 50. The number of positrons as a function of the number of shots from the accumulator. A number of $10^8$ is achieved after 10 stacks. The error bars are set for the fluctuations of the positron system and the solid line is a guideline.](image)

4.3.3 Transfers to the big trap
The transfer of positrons from the c-trap to the 1 T b-trap has to be carried out adiabatically. Otherwise, the compression achieved in the c-trap would be a worthless effort since a none adiabatic transport results in heating and therefore a radial expansion. The “V” potential is reshaped to a simple well with the same offset for the transport. This well is shifted in space through the p-trap and the t-trap towards the b-trap and the potential is maintained by shifting the electrodes of use. The positrons are trapped in the well as it is shifted. The transport takes few seconds.

4.3.3.1 The FWHM and the lifetime inside the b-trap
Same kinds of tests that were carried out in the c-trap were carried out to characterize the plasma behavior inside the b-trap. Both the FWHM and the number of positrons were measured as a function of the storing time in the b-trap. This test provides information about the compression and the lifetime of the plasma inside the b-trap. On top of that, this gives also an idea of if the transport is completely adiabatic or not. A none adiabatic transport may result in some expansions and some losses. If this is the case, an immediate dump as the transport is complete and measuring the FWHM and the total number of positrons should provide this information. This was studied with two different numbers of positrons: one with 2500 pulses which resulted in $2.1 \times 10^7$ positrons in a pass through configuration and one with 2000 pulses which resulted in $1.7 \times 10^7$ positrons in a pass through configuration. The positrons were
first stored in the c-trap without the RW for 60 seconds which should result in a diameter of <1mm (see figure 46). They were then transported to the b-trap with the procedure described above and kept in the b-trap for certain times. The number of positrons and the FWHM of the plasma were measured as a function of this storing time. The number was measured with the PMT-20 and the spatial 2D was measured with the MCP-phosphor screen + CCD camera setup. These two measurements were carried out in parallel. The results can be seen in figure 51. The red colored circles represent a configuration with \(1.7 \times 10^7\) positrons and the blues circles represent a configuration with \(2.1 \times 10^7\) positrons.

![Figure 51](image_url)

**Figure 51.** a) The number of positrons in a dump from the b-trap as a function of the storing time in the b-trap. The blue circles are with \(2.1 \times 10^7\) positrons and the red circles are with \(1.7 \times 10^7\) positrons. The error bars are set to compensate for the fluctuations from the positron system. There are no data points for storing times longer than 15 minutes with \(2.1 \times 10^7\) positrons due to some problems with PMT-20 during measurements. b) The FWHM of the positron plasma dumped from the b-trap as a function of the storing time in the b-trap. The blue circles are with \(2.1 \times 10^7\) positrons and the red circles are with \(1.7 \times 10^7\) positrons. The error bars are set to compensate for the fluctuations from the positron system. The FWHM seems to be constant up to 15 minutes and starts slowly expanding.

A compression does not seem to be achieved simply by just storing the positrons in the b-trap as it is suggested in figure 51 b). Instead, the FWHM behaves very similar to the positrons as they were stored in the c-trap, see figure 46. It is slowly increasing for the first 15-22.5 minutes of storing and starts rapidly to expand and in this case up to 7 mm of a FWHM. The number of positrons on the other hand, seems to be constant according to figure 51 a). A very long lifetime can be expected judging from the results shown in figure 51 a) and b). The FWHM is smaller than the electrodes’ diameter meaning lifetimes longer than 30 minutes can be expected for both configurations. The number of positrons in the dumps from the b-trap are roughly the same as in pass through configuration suggesting that the transport are carried out without any losses. The FWHM on the other hand has expanded to around 2.5 mm which is at least 1.5 mm bigger compared to a dump from the c-trap meaning the plasma is expanding during the transport. Any manipulations of plasmas with electrodes will of course result in some heating. Although, the fact that the c-trap and the p-trap are not perfectly aligned with the b-trap may be causing the expansion. This misalignment was observed in figure 36. An imperfect alignment of electrodes does not only cause an inhomogeneous electric filed but also an inhomogeneous magnetic field which govern the radial confinement of the plasma. Since the transport only resulted in an
expansion of few millimeters, it seems that it is the misalignment of the traps that is the main reason why the plasma is expanding during the transport. Either way, the RW has to be utilized in order to achieve high compression in the b-trap.

4.3.3.2 RW in the b-trap
The hope is to achieve compression by utilizing the RW in the b-trap. If this is the case, then the result should be similar to figure 47. However, the initial FWHM of the plasma is very different from what it was in the c-trap which could make compression difficult. The initial FWHM was around 1 mm in the c-trap while it is around 3 mm in the b-trap. Since the cooling of positrons was not successful in the c-trap when the initial FWHM was too large (see “4.3.1.3.1 The optimum RW frequency in the accumulator for cooling in the c-trap”), there is a risk it will not work as long as there is an expansion of the plasma during the transport of the positrons from the c-trap to the b-trap. If this is the case, the only way to fix it would be to open up the traps and realign everything.

A systematic scan of the RW frequency has not been performed but is planned for the near future. However, tests have been carried out and a compression has been observed in some cases. Figure 52 are pictures taken with the MCP assembly after 60 seconds of storing in the b-trap. The positrons were stored in the b-trap for 60 seconds without the RW in a) while the RW was utilized with and frequency of 10.2 MHz in b). The background has been subtracted in both pictures. Each shot was with 2000 pulses from the accumulator corresponding to $2.3 \times 10^7$ positrons in a pass through configuration. The FWHM in a) is around 2.5 mm while it is 0.5 mm in b). The strange spiral form in a) is not due to some physical effect but is caused by some defects on the MCP which was damaged last year. It is clear from the pictures that a compression is possible using RW. However, it is important to note the result was not always reproducible, even with the same configuration. Results similar to figure 52 b) were obtained several times but not in a controlled manner. This could be due to the fluctuations of the positron system or age of the moderator. Nevertheless, the initial FWHM in the b-trap is not ideal, which is caused by the misalignments of the traps. Hopefully, results similar to figure 52 can be systematically achieved after that the main traps have been realigned. The main traps have to be opened up and realigned to fix this issue which is a procedure likely to take several weeks or months.

![Figure 52](image-url)

*Figure 52. Pictures taken with the MCP assembly using $2.3 \times 10^7$ positrons. The background has been subtracted in both a) and b). a) was without the RW and has a FWHM of 2.5mm while b) was with the RW with a frequency of 10.2 MHz resulting in a FWHM of 0.5 mm.*
5 Conclusion

The work performed in this thesis was in line with the goals of AEgIS. The positrons have to be trapped in the off-axis trap in a well-compressed manner in order to measure the gravitational force on antihydrogen with the AEgIS system. A large amount of positrons is required in order to have a high yield of Ps to produce antihydrogen. Characterizing the positron plasma in the main traps is necessary in order to achieve the goal. This master thesis focused on the experimental settings that are required to have a desired positron plasma for measurements in the test chamber and trapping in the main traps. Before anything though, the total number of positrons had to be improved which was mainly done by optimizing the positron system. It was possible to increase the total number of positrons significantly by optimizing the accumulator. The total number of positrons accumulated depends on several factors. Especially, changing the correction coils inside the accumulator had a significant effect which was due to a better alignment of the plasma inside the accumulator. A number close to $10^8$ positrons was achieved with AEgIS positrons system by using the right corrections. However, the optimum configuration of the accumulator depends strongly on the external magnetic field interference which is changing on a daily basis in AD. It is therefore not possible to always work with an optimum accumulator. In the meanwhile, the problem was avoided by measuring the total number of positrons before performing any kinds of measurements. Measuring the number before the measurements also solves the problem of having different efficiencies in moderation.

Positron plasma compression in time was possible by utilizing a buncher. The timing of the buncher is of importance as it is determining the maximal compression. A compression in time of more than 50 % is a significant result for future positron work within AEgIS since a bunched plasma results in a more defined probe for Ps spectroscopy. Characterizing different Ps converters is of importance to AEgIS to understand which kind of target that is most suitable for the experiment for antihydrogen production. The total number of Ps as well as the energy distribution of these atoms are of a particular interest for the production. Therefore, it is a great advantage for AEgIS having a functional buncher.

Good steering is a requirement for trapping positrons in the main traps. The positrons have to be injected to the center of the trap to have an efficient trapping and cooling. The steering was performed in pass through configurations which also gave information about the beam. The energy distribution was calculated and the result was very similar to the energy that is set in the accumulator. The time distribution could also be extracted and the data was used to understand the trapping capabilities. Analyzing the spatial 2D provided a great deal of information about the plasma. It is easily understood if compression is achieved or not simply by analyzing the spatial 2D. It was also understood that the RW in the accumulator affected the FWHM significantly. This proved to be an important parameter for achieving cooling and compression in the c-trap. The best way to trap and to cool positrons was empirically discovered to be a “V” shaped potential where the efficiency was close to 100 %. The trapping and cooling procedures in the c-trap were proved to be very similar to the accumulator. First however, the timing for switching on the high voltage gates had to be determined since it is determining the total fraction of positrons that can be trapped. Although, if cooling and compression was achieved or not was strongly dependent on the initial conditions of the plasma. Previously, it has been shown that simply having a high dense plasma or a high number of positrons were not enough to achieve cooling. Instead, cooling was only possible when the number was $>10^7$ and at the same time having a FWHM smaller than ~1 mm. In addition, further compression could be achieved by utilizing the RW in the c-trap. There are important implications that the plasma is in strong drive since the density increased linearly...
with the RW frequency. Having a plasma in strong drive regime is a great advantage for AEgIS meaning easier manipulation of the positron plasma inside the main traps. However, a compression in the b-trap was not systematically realized mainly due to the expansion of the plasma during its transport. The expansion was likely induced by the trap misalignments and by the transport itself. Having an expansion of the plasma during the transport increases the FWHM which will cause the plasma to not to satisfy the initial condition anymore, assuming the initial condition is the same in the b-trap as in the c-trap. Probably, the initial condition in the b-trap is even stricter compared to in the c-trap since the magnetic field is lower.

5.1 Future prospects

In the future, having a stable positron system is crucial, especially if high numbers of positrons are desired. It seems the only way to make the positron system independent from external interference is to shield the whole system with μ-metal. If successful, it would be possible to always have an optimum accumulator and system which will increase the number of positrons used during the measurements. Replacing the sodium-22 source with a new one may also be a good idea to reach $10^8$ positrons. Finally, the main traps have to be realigned with a high precision to remove the misalignments. Removing the misalignments will probably cease the expansion of positrons during the transport from the c-trap to the b-trap. This will make trapping of positrons in the off-axis trap possible in the future. However, realigning the electrodes means also that the superconducting magnets have to be realigned since the electric field will be moved with respect to the magnetic field. A high precision alignment between these fields is very hard to achieve. One way to overcome this may be to install correction coils similar to the ones installed inside the accumulator to correct for the misalignments. Note that the shielding of the positron system, obtaining a new source and the realignment of the main traps are currently in progress as this thesis is being written.
6 Acknowledgments

I would like to take this opportunity to thank all the people at CERN who helped me throughout my year as technical student at AEgIS. I would especially like to express my gratitude to Dr. Michael Doser, who gave me the opportunity to work with the AEgIS experiment, Dr. Sebastiano Mariazzi, who has been very patient with me and his support has been valuable. Finally, I would also like to thank my supervisor at the Department of Physics, Chemistry and Biology (IFM) at Linköping University, Dr. Martin Magnusson, and my examiner Dr. Jens Birch for their helpful input and advice.
7 References


[9] Courtesy of AEgIS experiment.


