CERN Summer Student Project Report

Emilie Hindbo Clausen
Department of Physics and Astronomy, Aarhus University, Denmark and
Supervisor: Daniel Maxwell, Swansea University, Wales
(Dated: 26/8-2016)

I. THE ALPHA EXPERIMENT

The pursuit of the ALPHA experiment at CERN is to trap positron and antiproton plasmas and mix them to form antihydrogen. Once created and trapped the antiatoms are subjected to spectroscopic and gravitational measurements in order to compare them to ordinary hydrogen atoms. Confirmed equivalence, or rather the lack of it, will be a new step towards understanding the absence of antimatter in the universe.

The procedure sounds simple in principle, but there are many complicated technical steps on the way to actually perform these measurements. First of all there is the antiproton decelerator (AD) that lowers the energy of the antiprotons produced from protons (from the Proton Synchrotron) enough for them to be trappable. The positrons come from a Na-22 radioactive source.
Charged particles can be caught in a so called Penning-Malmberg trap consisting of a series of ring electrodes surrounded by a solenoid creating a co-axial homogeneous magnetic field. The electrodes ensures axial confinement while the magnet makes the plasma rotate around the axis and thereby confines it radially.
Just trapping antiprotons and positrons is far from enough. The particles have to be cooled by different techniques such as evaporative cooling (EVC) and interaction with cold electrons that are later discarded (E-kick).
At the same time the plasmas of trapped particles have to be dense when they finally overlap in order to increase the chances of interaction between two constituent antiparticles leading to creation of an antiatom. A technique called "rotating wall" (RW) is used where a rotating electric field is applied to the plasma to control the rotation frequency and thereby the radius by momentum conservation.
Since the individual plasmas contain particles with the same charge, increasing their density leads to repulsion and heat increase, making the formation of cold *and* dense plasmas very challenging.
The technique used for mixing the trapped plasmas without increasing their energy is called autoresonance which aims to excite the antiprotons collectively until they escape from their potential well with the minimum amount of energy and mix with the trapped positrons in a neighboring well. An illustration of the axial electric potential and the location of the two plasmas before and after mixing is shown in figure 1b.

Once created the neutral atoms can only be trapped in

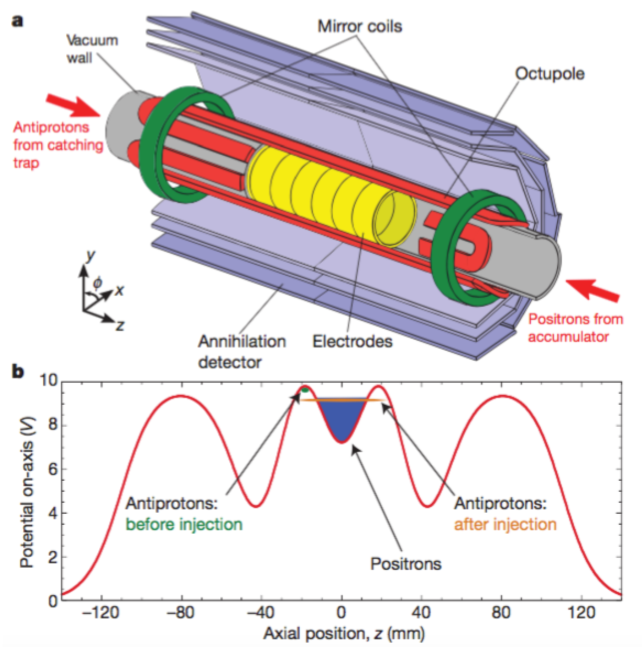

Figure 1: *a) Drawing of the atom trap. Between the two mirror coils (green) there has been added three smaller coils in order two flatten the potential well. b) Graf of the axial electrix potential in the atom trap and where the particles are located. Figure borrowed from the article Trapped antihydrogen, G. B. Andresen, Nature 468, 673 (2010).*

a three-dimensional magnetic field minimum realized by an Ioffe-Pritchard trap as seen in figure 1a. The trap consists of two co-axial coils, called mirror coils, that produce a minimum along the axis (plus three in between to flatten the well) and an octopole that produces a minimum transversally to the axis. The flattening makes sure that the atoms see a more homogeneous field. This makes their Zeeman shifts more constant which is a great advantage when doing spectroscopy. Only trapping of antiatoms with magnetic moments antiparallel to the magnetic field, so called "low field seekers", is possible. [1]

II. DETECTION OF MAGNET QUENCHES

In total the ALPHA setup contains the six magnets for the atom trap plus a solenoid at 2 T around each catching trap, one for positrons and one for antiprotons.

Around the entire setup is a 1 T solenoid. All these magnets are superconducting and require cooling with liquid helium as well as detailed monitoring.
Superconducting magnets are in danger of quenching, that is loosing their zero resistivity in a located area. Because of heat creation in this area the quench will quickly spread to the entire magnet and cause an enormous amount of heat that can destroy it completely. Therefore it is strictly necessary to have a quench detection system so that the current quickly can be dumped to components designed to stand up to that kind of energy release.
This detection system consists of a number of voltage monitors placed in short intervals along the magnet coil dividing the coil into small sections. If a quench happens in one section there will be a sudden voltage increase and the current can be shut off before it spreads to the entire magnet.
When the magnets are ramping there will be a huge voltage increase that drops off when the current becomes stable. Since quenches 9 out of ten times happen during the ramping this huge voltage will drown out the smaller quench signal. Therefore some extra electronic tricks are needed to detect it.

In fact the different sections can be seen as different coils affecting each other. For two coils, 1 and 2, their voltages can be written as

$$V_1 = L_1\frac{dI}{dt} + IR_1 - M\frac{dI}{dt} \quad (1)$$
$$V_2 = L_2\frac{dI}{dt} + IR_2 - M\frac{dI}{dt}, \quad (2)$$

where L is an inductance, I is the current, R is a resistivity and M is the mutual inductance. When the magnets are in their superconducting state the middle terms will be zero. And when the magnets are not ramping the other terms will be zero as well.

Under the assumption that a quench only happens in one of the sections the signals are multiplied by a constant

$$\alpha V_1 = \alpha\left((L_1 - M)\frac{dI}{dt} + IR_1\right) \quad (3)$$
$$\beta V_2 = \beta(L_2 - M)\frac{dI}{dt}. \quad (4)$$

The constants are chosen so that $\alpha(L_1-M) = \beta(L_2-M)$ and it follows that

$$\alpha V_1 - \beta V_2 = \alpha I R_1. \quad (5)$$

In this way the ramping signals cancel out and the quench signal can be detected. Except from the circuit boards all the electronics to perform this task is handmade by the ALPHA team.

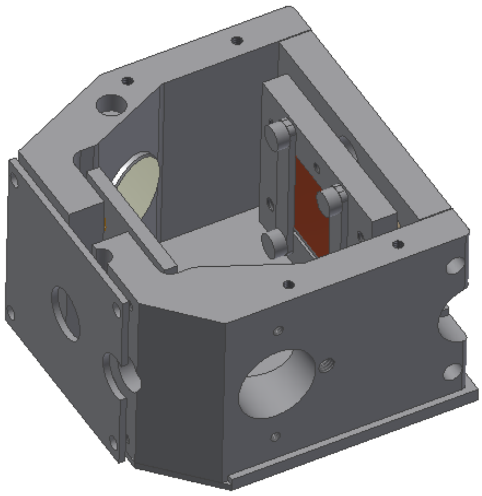

Figure 2: *Figure of the right end of the vacuum chamber where the laser enters through the front hole, reflects off the mirror on the back wall and hits the brown Beryllium plate. The ablated ions are send through the opposite hole and into the Penning-Malmberg trap by a negatively charged acceleration plate.*

III. COOLING OF POSITRONS WITH LASER COOLED BERYLLIUM IONS

The newly created antihydrogen atoms can only be trapped if their temperature is lower than the well depth of ~ 0.5 K k_B. Therefore the traps are kept at cryogenic temperatures of 2-7 K. The antihydrogen temperature seems to be dominated by the positron plasma temperature since the antiprotons reach thermal equilibrium with the positron plasma before antihydrogen creation. In order to perform high precession measurements more than a few simultaneously trapped antiatoms are needed.

A new attempt to cool the positrons further is by sympathetic cooling by laser cooled $^9Be^+$ ions. It is very hard to laser cool the antihydrogen atoms directly since no easily accessible transition is available (lasers as low as 100 nm are still very rare). Once trapped and laser cooled the ions are mixed with the positrons and the two plasmas thermalize resulting in positron cooling.
The $^9Be^+$ ion is chosen because of its readily accessible 313 nm transition and its lightness relative to other candidates such as $^{24}Mg^+$. Lightness is an advantage since lighter species have lower radii in penning traps, hence overlap more with the light positrons, and thereby cools them more than heavier ions.

In ALPHA's test setup the Be^+ ions are created by shooting a 355 nm laser onto a piece of solid Beryllium causing the ions to ablate from the surface. This is done in a 10^{-8} mbar vacuum chamber as shown in figure 2. The laser comes in from the front hole, reflects off the mirror on the back wall, and hits the brown beryllium

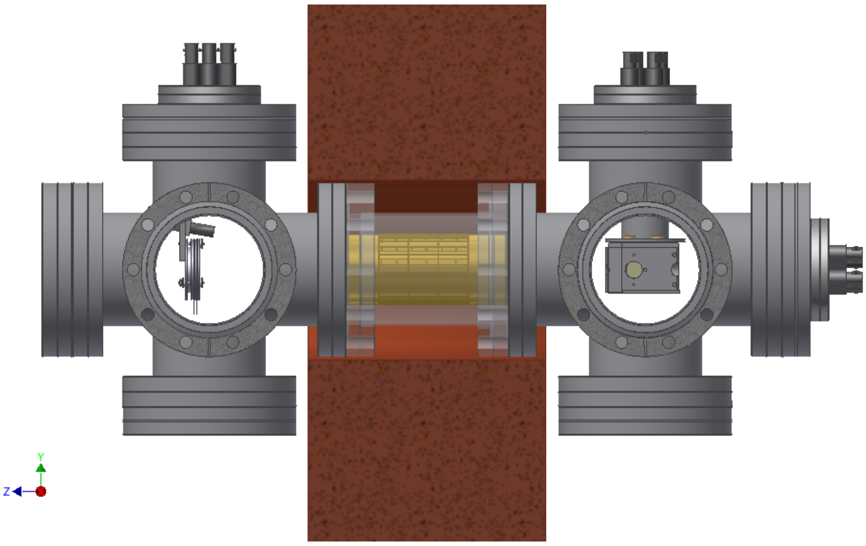

Figure 3: *Figure of the entire vacuum chamber whit ion source on the left, Penning-Malmberg trap in the middle and MCP detector on the right. The incoming laser ray is pointing in the negative x-direction.*

plate which is at a positive potential. The laser power and focus decide the number of ablated ions.
Proper alignment of the laser is a difficult task since the light is in the UV region. Safety glasses are mandatory and touching the beam can be painful when it is focused. Moreover the beam can only be seen when hitting a piece of paper. A green alignment laser can be used to adjust the mirrors and lenses but the mirrors that reflect UV light well only reflects about 1% of the green light making it dimmer for every mirror. Because of the dangerous laser light the entire setup is contained in a black metal box behind a black plexiglas wall.

After ablation the ions are accelerated towards a Penning-Malmberg trap by a negatively charged acceleration plate. The entire chamber can be seen in figure 3. The plasma of ablated ions can be monitored by dumping them to the MCP at the left end of the chamber. Here an actual picture of the plasma is obtained as seen in figure 4. When ions hit the two plates of the MCP electrons are accumulated. These are accelerated towards a phosphorus screen at a postitive potential where they create photons that can be imaged. The picture is used to monitor the size of the plasma, which should be minimized.

Initial tests of the setup were made to find out how different variables affects the number of ablated ions. These tests were done with aluminium as ablation material since more studies have been made on aluminium ablation and because beryllium is poisonous.
Figure 5 shows a graph of the number of singly ionized aluminium atoms as a function of the cathode bias voltage. The acceleration plate was held constant at 40 V and the laser pulse energy at 65 μJ. During these measurements the trapping electrodes was turned off

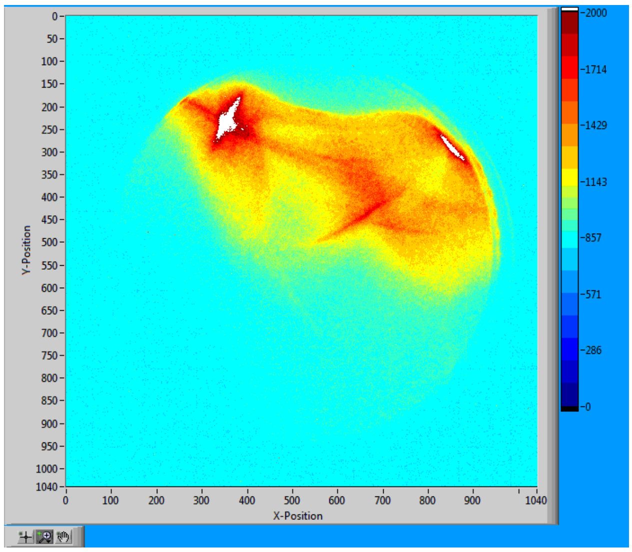

Figure 4: *Picture of an aluminium ions created with a cathode voltage of 40 V, an acceleration plate voltage of -40 V, solenoid current at 40A, laser pulse energy of 65 μJ and grounded electrodes. The front plate of the MCP was at -600 V (to attract the ions), the back plate was at 800 V (to attract the created electrons) and the phosphorus screen creating the photons for imaging was at 4400 V (to attract the electrons further).*

and the solenoid current was constant at 40 A. So, the ions were dumped directly to the MCP only guided by the magnetic field lines.
The graph shows the clear tendency that increasing the cathode bias voltage lowers the number of ions that hit the MCP. This is a wrong interpretation since a more positive cathode would only make it easier for the positive ions to escape from the surface. At very low

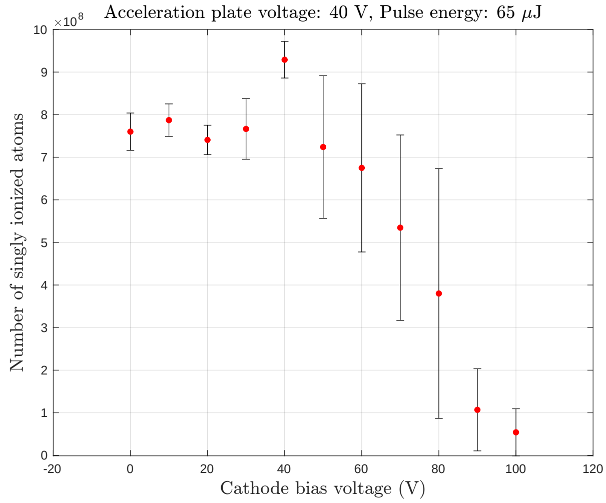

Figure 5: *Graf of the number of ablated ions as a function of the cathode bias voltage. It is physically impossible for the numbers to go down when the voltage is increased since this just makes it easier for the positive ions to escape from the surface. The reason for the decrease is a gradual lowering of the laser energy due to drifting.*

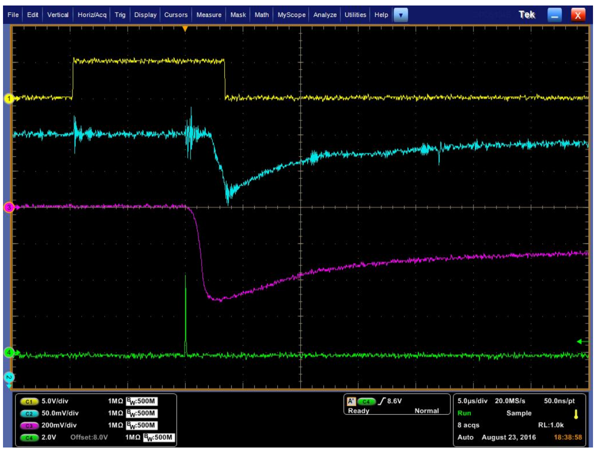

Figure 6: *A picture of the scope taken simultaneously with the MCP image in figure 4. The yellow curve is a trigger signal that makes the laser (green curve) go off a short while after. The purple curve is the cathode low voltage pick-off that naturally turns negative when the positive ions leave the surface. The blue curve is the voltage signal from the phosphorus screen that also turnes negative when it is hit by the electrons created in the MCP.*

positive voltages the less energetic ions would be drawn back towards the surface because of the temporary negative potential. Over a certain threshold energy all the ions will escape and the number should stabilize. The decrease in the number of ions seen on the graph is due to he laser energy falling off with time. The laser is drifting and needs to be re-tuned to regain its original energy.

Each point is an average of ten measurements and the errorbar shows the standard deviation. The cathode (aluminium plate) low voltage pick-off signal, V, shortly turns negative when the positive ions leave it as seen from the purple graph in figure 6. This signal minimum can be read from an oscilloscope and is proportional to the amount of charge leaving by $Q = CV$.

Measuring the capacitance of the circuit, $C = 528$ pF, the charge could be calculated. Dividing with the elementary charge gives the number of ions, assuming everything that hits is singly charged aluminium ions.

When the trapping and laser cooling of aluminium is working, the experiment will be done with beryllium. The final goal is to implement the ion source in the ALPHA experiment which hopefully will increase the amount of caught antihydrogen significantly. [2].

[1] Physics with antihydrogen, W. A. Bertsche, Journal of Physics B: Atomic, Molecular and Optical Physics, 48, 2015

[2] Antihydrogen trapping assisted by sympathetically cooled positrons, N. Madsen, New Journal of Physics, 16, 2014