AD-7/GBAR status report for the 2015 CERN SPSC

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CERN-SPSC-2015-001 / SPSC-SR-151
06/01/2015

The GBAR experiment will use one of the low energy antiproton beam lines from the ELENA ring that is being prepared and scheduled to start operating in 2017. The apparatus is broadly divided into four sections: antiproton deceleration and focussing, positron production and accumulation, antihydrogen cooling and preparation, and detection. In the following, we give updates on the different parts and the status of preparation for installation in the AD hall, referring to the previous report that was submitted in April of 2014 [SPSC14].

1- Electron Linac for Positron Production

In the last report, the NCBJ group had envisaged a standing wave setup composed of two "9 MeV type" accelerating structures driven by two klystrons in order to reach an energy of 20 MeV. However, a subsequent radioprotection analysis showed that the operating conditions would be drastically constraining, especially in the setting up phase. This is due to the fact that the neutron activation threshold is passed at around 10 MeV. Such constraints are not compatible with an apparatus that is part of the experiment and needs extensive tuning. We have thus decided to use a single accelerating structure. This should result in a slow positron flux of $\sim 10^8$ e^+s^{-1}. Procurement will start in January 2015. It is expected that the linac will be installed and commissioned at CERN in February 2016. The shielding for this linac is being optimised in order to minimise the cost and the weight of this structure. This is done in collaboration with the AD/ELENA team at CERN.

2- Antihydrogen Synthesis

The production of $\overline{\mathrm{H}}^+$ ions will proceed via two charge exchange reactions with positronium.

$$\bar{p} + Ps(n_{Ps}, l_{Ps}) \longrightarrow \bar{H}(n_H, l_H) + e^- \qquad (1)$$

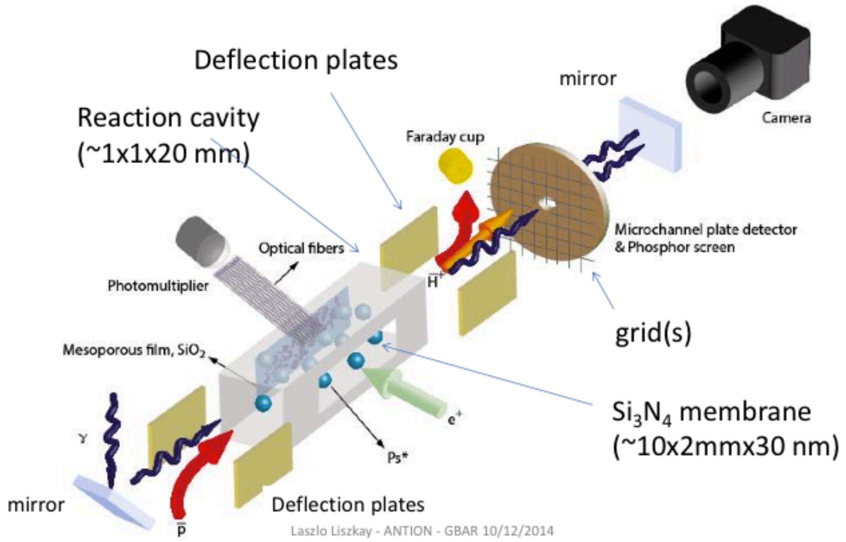
$$\bar{H}(n_H, l_H) + Ps(n_{Ps}, l_{Ps}) \longrightarrow \bar{H}^+ \; + \; e^- \qquad (2)$$

2.a Reaction region

The interaction of antiprotons with the target positronium cloud will take place inside a tube of 1 mm^2 cross section (see Figure 1). The walls of this tube are made of silicon coated with nanoporous SiO_2 on the inside. The positron bunch extracted from the Penning-Malmberg trap enters the cavity (tube) from the side, through a thin (30 nm) silicon nitride membrane. Positronium is formed in the mesopores and emitted into the cavity, where it is confined by the fully reflecting silica-covered walls. In order to increase the antihydrogen (ion) formation cross-section, positronium will be excited by laser beams crossing the cavity. Members of our collaboration recently demonstrated that Ps in an excited state (2S) do not de-excite during the collisions with the silica walls [CRIVELLI14].

Recently, the CSNSM, IPCMS, IRFU and LKB teams obtained a grant from the French National Research Agency (ANTION project, 2014-2017) to prepare this interaction region and to measure the formation cross-sections relevant to the GBAR project.

Our plan is to first perform the measurement of the charge exchange reaction with protons instead of antiprotons, producing hydrogen atoms. This will be done at Saclay where we have a slow positron source based on an electron linac and a Penning-Malmberg trap. Measurement of the cross section using positronium excited to 3D and 2P states will be done in Saclay as well, where a laser hut has been installed. On the basis of theoretical calculations, we expect larger cross section for positronium in excited state, but no experimental data are available yet. When the more powerful linac will be available at CERN in 2016, the trap, reaction chamber, lasers and detection setup will be moved to CERN to measure the second charge exchange reaction producing H^- ions. When the antiprotons from ELENA will then be available in 2017, the same apparatus should allow observing the counterpart antimatter reactions.



Laszlo Liszkay - ANTION - GBAR 10/12/2014

***Figure 1** – Sketch of reaction region with the detection setup to measure the hydrogen ions and atoms formed.*

2.b Ps excitation

The laser system used to excite the two-photon 1S-3D transition of positronium is an ensemble of continuous wave and pulsed Titanium Sapphire lasers at 820 nm frequency, doubled at 410 nm. It has been built and characterized [COMINI14], except for the frequency doubling stage.

At Saclay, we want to determine the number of excited Positronium atoms in 3D level by monitoring the 3D-2P (at 1.3µm) or 2P-1S (at 243 nm) fluorescence. Because of the constraints inside the reaction chamber we plan to use a fiber optic bundle to monitor the fluorescence. To test this detection scheme at LKB Paris, we have built a special glass cell to mimic the Ps cloud geometry (a 40 mm long cylinder of 2.5 mm diameter). This cell contains Cs atoms that have a 6S-8S two-photon transition at 822 nm, which is therefore easily accessible with our laser system. The excitation of the transition is observed by monitoring the 7P-6S decay fluorescence at 456 nm. A first test has been done with a homemade fiber optic bundle (see Figure 2). The figure also shows the first signal observed when a 4mJ/10ns/10Hz pulsed light is focused into the Cs cell at room temperature. The central frequency of the line is as expected. We are currently investigating the reasons of the large broadening and preparing the cooling of the cold finger of the cell in order to mimic the number of Ps atoms expected at Saclay.

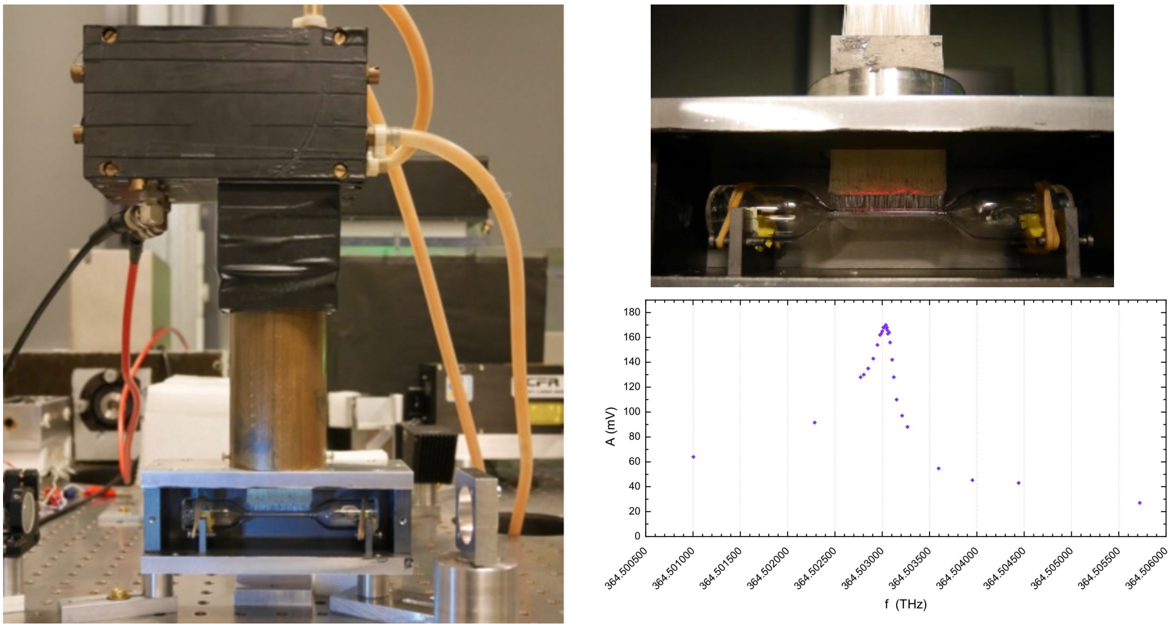


Figure 2 – Cesium cell with fiber optic bundle and photomultiplier assembly *(left),* close-up view of fiber bundle *(top-right)* and 6S-8S transition in Cs, signal monitored on an oscilloscope versus laser frequency measured with a wave-meter *(bottom-right).*

3- Sympathetic Cooling of $\overline{\mathrm{H}}^+$ with Ion Crystals

The precision trap consists of four gold coated, micro-fabricated alumina chips that are arranged in an x-shaped configuration and two end caps made from Titanium (see Figure 3).

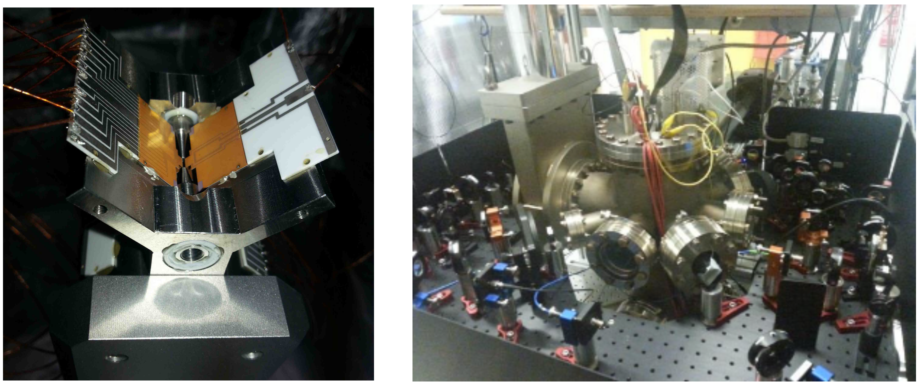


Figure 3 – Mainz precision trap *(left)* and laser table *(right)*.

Firsts tests with $^{40}\mathrm{Ca}^+$ ions have been performed at Mainz. A two-step photo ionisation process forms the ions. Figure 4 (left) shows the level scheme of $^{40}\mathrm{Ca}^+$: the dipole transitions $4^2S_{1/2} \rightarrow 4^2P_{1/2}$ at 397 nm allow Doppler cooling of the ions; the $3^2D_{3/2} \rightarrow 4^2P_{1/2}$ near 866 nm and the transition $3^2D_{5/2} \rightarrow 4^2P_{3/2}$ near 854 nm allow depletion of the metastable D-levels. The quadrupole transition near 729 nm from the $4^2S_{1/2}$ ground state to the metastable $3^2D_{5/2}$ level is employed for sideband spectroscopy and sideband cooling. With a lifetime of 1.2 s, the spectroscopic resolution is limited by the laser pulse duration, the Rabi frequency during the excitation and the frequency stability of the laser source. The harmonic motion of the ion in the trap can be investigated spectroscopically at the level of single vibrational quanta [SCHULZ14].

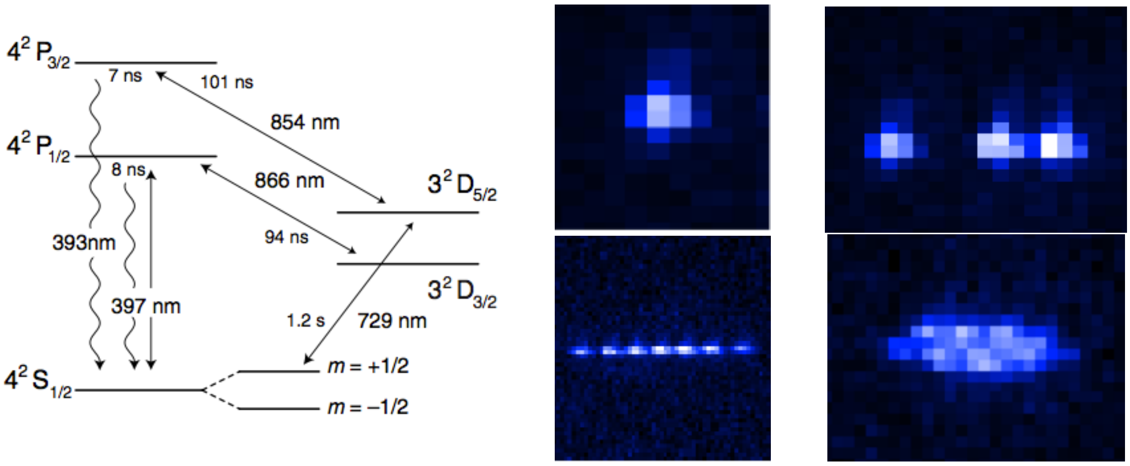


Figure 4 – Relevant levels, transition wavelengths and lifetimes in $^{40}\mathrm{Ca}^+$ *(left)* and images of Ca^+ ions in the precision trap: Single ion (*up left*), mixed crystal (*up right),* linear crystal (*bottom left)* and a zigzag crystal (*bottom right*).

Several configurations of ion crystals have been detected by fluorescence, including single ions (see Figure 4 right).

The observation of Rabi oscillations as shown in Figure 5 allowed determining mean phonon numbers. From this, phonon numbers can be determined with better than 5% uncertainty. Currently, we are optimizing the Doppler cooling parameters that should lead to phonon numbers below 10. In order to reach the lowest temperatures, the harmonic shape of the axial potential well will be adiabatically ramped down, preserving its shape. Similar manipulations of the axial potential have been successfully experimented at Mainz [RUSTER14].

The next steps are to trap mixed Ca^+ and Be^+ crystals and to perform sideband sympathetic ground state cooling using the 313 nm laser source being prepared at Paris LKB laboratory.

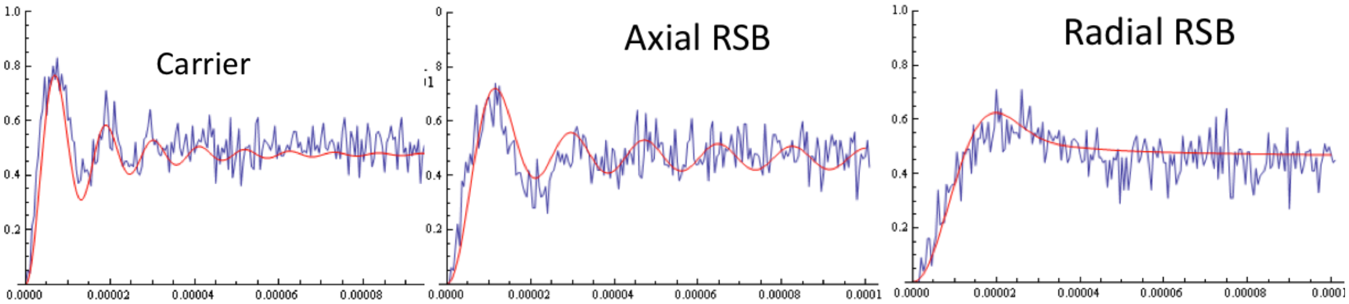


Figure 5 – Determination of mean phonon numbers by comparison with theoretical expectations: $D_{5/2}$ state population as a function of pulse duration.

4- Antihydrogen Free-fall Detection

Tracking will consist of a set of planar chambers allowing for the measurement of both X and Y coordinates with an accuracy of a few hundred microns. The newly developed resistive XY MicroMegas detectors of dimensions 50 × 50 cm^2 with a pitch of the order of 500 microns provide such precision with good efficiency, for a chamber total depth of 1 cm. In order to ensure an overall good tracking efficiency, each of the 5 faces surrounding the vacuum vessel (bottom and 4 sides) will be equipped with 3 layers of chambers, for a total lever arm of 10 cm for tracks normal to the chambers. This configuration will result in a spatial resolution of the order of 1 mm at the vertex extrapolated to the annihilation plate.

A first set of three double planes will be delivered at CERN in April 2015 for tests with cosmic rays. The final tracker should be installed by the end of 2016.

5- Conclusion

The collaboration groups are actively investigating the elements that will form the major parts of the GBAR experiment. These efforts will be continued as formalised in the memorandum of understanding that was signed by all the GBAR funding agencies. The first Finance Review Committee meeting took place in October 2014, with a financial agreement allowing to start construction as planned, in particular for the electron linac. Installation in the AD hall is being prepared in fruitful collaboration with the CERN ELENA team.

References

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