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Report

Development of the Cryogenic System of AEgIS at CERN

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Abstract

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Abstract. The AEgIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) experiment is located at the antiproton decelerator complex of CERN. The main goal of the experiment is to perform the first direct measurement of the Earth's gravitational acceleration on antihydrogen atoms within 1% precision. The antihydrogen is produced in a cylindrical Penning trap by combining antiprotons with positrons. To reach the precision of 1%, the antihydrogen has to be cooled to 100 mK to reduce its random velocity. A dilution refrigerator is selected to deliver the necessary cooling capacity of 100 μW at 50 mK. The AEgIS cryogenic system basically consists of cryostats for a 1-T and for a 5-T superconducting magnet, a central region cryostat, a dilution refrigerator cryostat and a measurement cryostat with a Moiré deflectometer to measure the gravitational acceleration. In autumn 2012, the 1-T cryostat, 5-T cryostat and central region cryostat were assembled and commissioned. The apparatus is cooled down in eight days using 2500 L of liquid helium and liquid nitrogen. During operation, the average consumption of liquid helium is 150 $L \cdot day^{-1}$ and of liquid nitrogen 5 $L \cdot day^{-1}$. The temperature sensors at the Penning traps measured 12 K to 18 K, which is higher than expected. Simulations show that this is caused by a bad thermalization of the trap wiring. The implementation of the sub-kelvin region is foreseen for mid-2015. The antihydrogen will be cooled down to 100 mK in an ultra-cold trap consisting of multiple high-voltage electrodes made of sapphire with gold plated electrode sectors.

INTRODUCTION

The AEgIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) experiment is located at the Antiproton Decelerator (AD) complex of CERN [1-3]. The main goal of the experiment is to perform the first direct measurement of the Earth's gravitational acceleration on antihydrogen atoms within 1% precision. The formation of antihydrogen and the measurement of the gravitational acceleration are performed as follows. Low energy antiprotons from the AD are captured and accumulated in a cylindrical Penning trap. Here, they are cooled by an electron gas to about 4.3 K. The antiprotons are transferred to the recombination region where they are cooled to sub-kelvin temperatures within an ultra-cold Penning trap. At the same time, positrons are produced from a Surko-type source and accumulator, and formed in a positron pulse. Positronium is produced by bombarding a cryogenic nanoporous material with the intense positron pulse and the positronium is excited by laser pulses to a Rydberg state. By resonant charge exchange between the Rydberg positronium and the cold positrons, antihydrogen is produced, which is formed into a beam by Stark acceleration with inhomogeneous electrical fields. Finally, the antihydrogen beam is horizontally accelerated towards a classical two-gratings Moiré deflectometer coupled to a position-sensitive detector and its vertical deflection caused by the Earth's gravitational field is measured. A cross-sectional overview of the AEgIS experiment is given in Fig. 1.

For proper catching the charged particles in the two Penning traps, solenoidal magnetic fields with a special configuration are required. Due to the high energy of the antiproton beam from the AD, the first stage of trapping has to be realized in a 5-T homogeneous magnetic field. The recombination of antiprotons and positrons takes place in a 1-T magnetic field. The magnetic fields are produced by superconducting magnets designed and built at CERN. The superconducting magnet system is discussed in detail in [4, 5]. Although the antihydrogen is horizontally accelerated, it will always have a random velocity in all directions according to the Maxwell-Boltzmann distribution [2]. This random velocity decreases at lower temperatures. To reach a relative precision of 1%, it is calculated that the antihydrogen has to be cooled to 100 mK [1, 2]. A dilution refrigerator is selected, because this is the only cooling technique that is capable in delivering the required continuous cooling capacity at 100 mK.

The experimental set-up of AEgIS is developed, built and tested in different stages. In autumn 2012, the 1-T cryostat, 5-T cryostat and the central region cryostat were assembled and commissioned. The dilution refrigerator and the measurement section containing the Moiré deflectometer are currently under development. The measurement section is planned to be installed in 2014, while the installation of the dilution refrigerator is foreseen for mid-2015. In this paper, the cryogenic system of AEgIS is described and its actual performance during commissioning is discussed. Furthermore, the development progress of the ultra-cold trap is given.

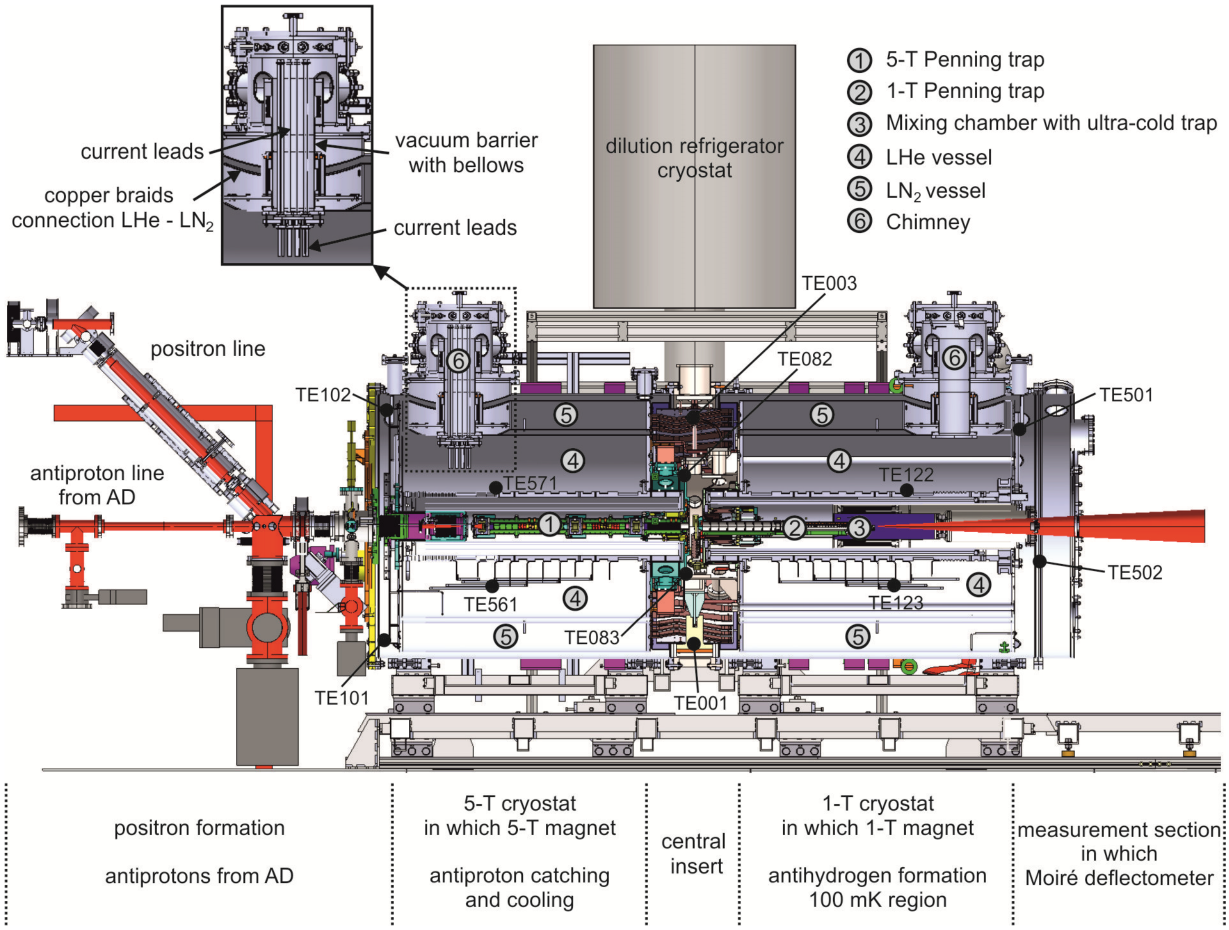

FIGURE 1. Cross-sectional overview of the AEgIS experiment.

THE AEGIS CRYOGENIC SYSTEM

The AEgIS cryogenic system basically consists of cryostats for the 1-T and for the 5-T superconducting magnets, a central region cryostat, a dilution refrigerator cryostat and a measurement cryostat containing the Moiré deflectometer. The cryostats for the superconducting magnets are designed in a classical way and have a similar structure. The superconducting magnets are located inside a cylindrically shaped liquid helium (LHe) vessel with a volume of about 800 L covered by a blanket of 10 layers of multi-layer insulation (MLI). A cylindrically shaped liquid nitrogen (LN_2) vessel of 600 L is surrounding the LHe vessel with a small space in between. The LN_2 vessels are covered with 30 layers of MLI. Both magnet cryostats and the central region cryostat share the same insulation vacuum of about 10^{-6} mbar. The beam line containing the Penning traps is located in the bore of the magnets under ultra-high vacuum conditions below 10^{-12} mbar. The beam line crosses both cryostats and the central region. At one side, it is connected to the beam line of the AD via a bellow assembly making direct thermal contact to room temperature. At the other side, it is connected to the measurement cryostat. During standard operation, the LHe vessels are connected to a helium recovery system while the LN_2 vessels are vented to air. The LHe vessels are equipped with safety relief valves to protect the vessels against excessive pressures in case of, for example, a vacuum failure or a quench of one of the superconducting magnets.

The 1-T and 5-T superconducting magnets are wound with niobium titanium wire and have nominal currents of 85 A and 170 A, resulting in stored energies in the magnets of 29 kJ and 419 kJ, respectively. The superconducting bus bars are routed from the magnet downwards to the bottom of the LHe vessel and then upwards to a chimney equipped with brass current leads. In this way, the operation of the magnets is almost independent of the LHe level. To reduce the LHe consumption, the evaporated helium gas passes along the current leads in that way precooling them. The current leads are enclosed by a stainless steel vacuum barrier that is thermalized to the LN_2 vessel with copper braids (Fig. 1). Bellow assemblies are placed in between the temperature stages of the vacuum barrier to reduce the conductive heat load.

The ultra-cold Penning trap in the bore of the 1-T magnet will be mounted on the mixing chamber of the dilution refrigerator. The other components of the dilution refrigerator are placed on top of the central region in their own cryostat. The last tube-in-tube heat exchanger and sintered heat exchanger is spanning the distance between the still and the mixing chamber. Due to space restrictions, this heat exchanger will only be surrounded by a 1.5 K heat shield connected to the 1 K pot of the dilution refrigerator. A 4.3 K heat shield will work as a vacuum barrier between the insulation vacuum and the ultra-high vacuum. This means that the cold head (below 4.3 K) of the dilution refrigerator shares the ultra-high vacuum with the beam line.

The central region is the area where most of the wiring for the Penning traps enters the cryostat. It contains an internal 4.3 K vacuum barrier that must be mechanically detachable from the LHe vessel of the 1-T cryostat for opening the apparatus. The 80 K heat shields and the 4.3 K vacuum barrier are thermally connected to the 5-T cryostat and cooled by conduction through their bodies. The trap cabling is thermalized at 80 K and 4.3 K stages, which are currently connected to the LHe and LN_2 vessels of the 5-T cryostat. In the future, the central region will be cooled by active cooling lines coming from the dilution refrigerator cryostat.

COMMISSIONING OF THE CRYOGENIC SYSTEM

In autumn 2012, the AEgIS apparatus excluding the measurement section and the dilution refrigerator was assembled and commissioned. To monitor the cryogenic system during cool down, operation and warm up, the system is equipped with various temperature and pressure sensors. The locations of the temperature sensors at the AEgIS cryogenic system are indicated in Fig. 1. Pt1000 temperature sensors were placed at the outside of the LN_2 vessels, at the top and the bottom of the 1-T cryostat and at the top and the middle of the 5-T cryostat. Inside the LHe vessels, home-made calibrated temperature sensors consisting of two carbon resistors and two Pt500s in a bridge circuit are placed at the top and the bottom of the superconducting magnets and at the bottom of the superconducting bus bars. The central region is equipped with Pt1000s at the bottom and the top of the 80 K heat shields, and with bridge sensors at the top and at the bottom of the 4.3 K vacuum barrier. Furthermore, various Cernox™ sensors are placed at the Penning traps. The level of LHe and LN_2 in the cryogen vessels is determined by measuring the pressure difference between the bottom and the top of the cryogen bath with differential pressure transducers. The pressure inside the LHe and LN_2 vessels is monitored with pressure gauges.

Figure 2 gives, respectively, the temperatures of the 1-T cryostat, 5-T cryostat and the central region versus time during operation. The cool down of the apparatus is performed in two stages. First, the LN_2 vessels and superconducting magnets are cooled down slowly to about 80 K with LN_2 to prevent damage of the magnets due to thermal contractions. Then, the LN_2 is removed from the LHe vessels and the superconducting magnets are cooled down further to 4.3 K with LHe. As shown in Fig. 2, the cool down of the apparatus is performed in eight days. In total an amount of 2500 L of LHe and 2500 L of LN_2 is used. It is shown in Fig. 2c that the central region, which is only cooled from the 5-T cryostat by conduction through its body, reaches its final temperature quickly after the magnets are cooled down.

At day 107, the warm up of the apparatus is started by removing the remaining LN_2 from the vessels. At this time, most of the LHe was already evaporated indicated by the increase in temperature of the magnets. Then, the LN_2 vessels were evacuated, filled with helium gas and connected in series with the LHe vessels. The apparatus was further warmed up in about 12 days by a gaseous helium flow from the LN_2 vessels to the LHe vessels. During day 108 till 115, there were problems with a frozen inlet of the 1-T cryostat making the circulation of helium gas impossible. During this period, the cryostat was only warmed-up by the radiative and conductive heat load. The small bumps in the temperature curves are caused by attempts to identify the problem of the frozen inlet. At day 115, the circulation of helium gas in the 1-T cryostat is started, which is indicated by the steeper slope of the temperature curve. In the same period, the steeper parts in Fig. 2b indicate that helium gas is circulated in the 5-T cryostat, while the less steep parts indicate that the cryostat is warmed up by the radiative and conductive heat load.

During operation, the central region 80 K heat shields had a temperature in the range of 80 K - 85 K. The temperatures measured at the 4.3 K vacuum barrier of the central region are in the range of 24 K - 30 K, which are higher than expected. This barrier is only cooled by conduction through stainless steel, which is a very bad thermal conductor at these low temperatures. Therefore, the measured temperatures can easily be explained by a small heat load, for example due to radiation or conduction through wiring. In the future, the active cooling lines will cool

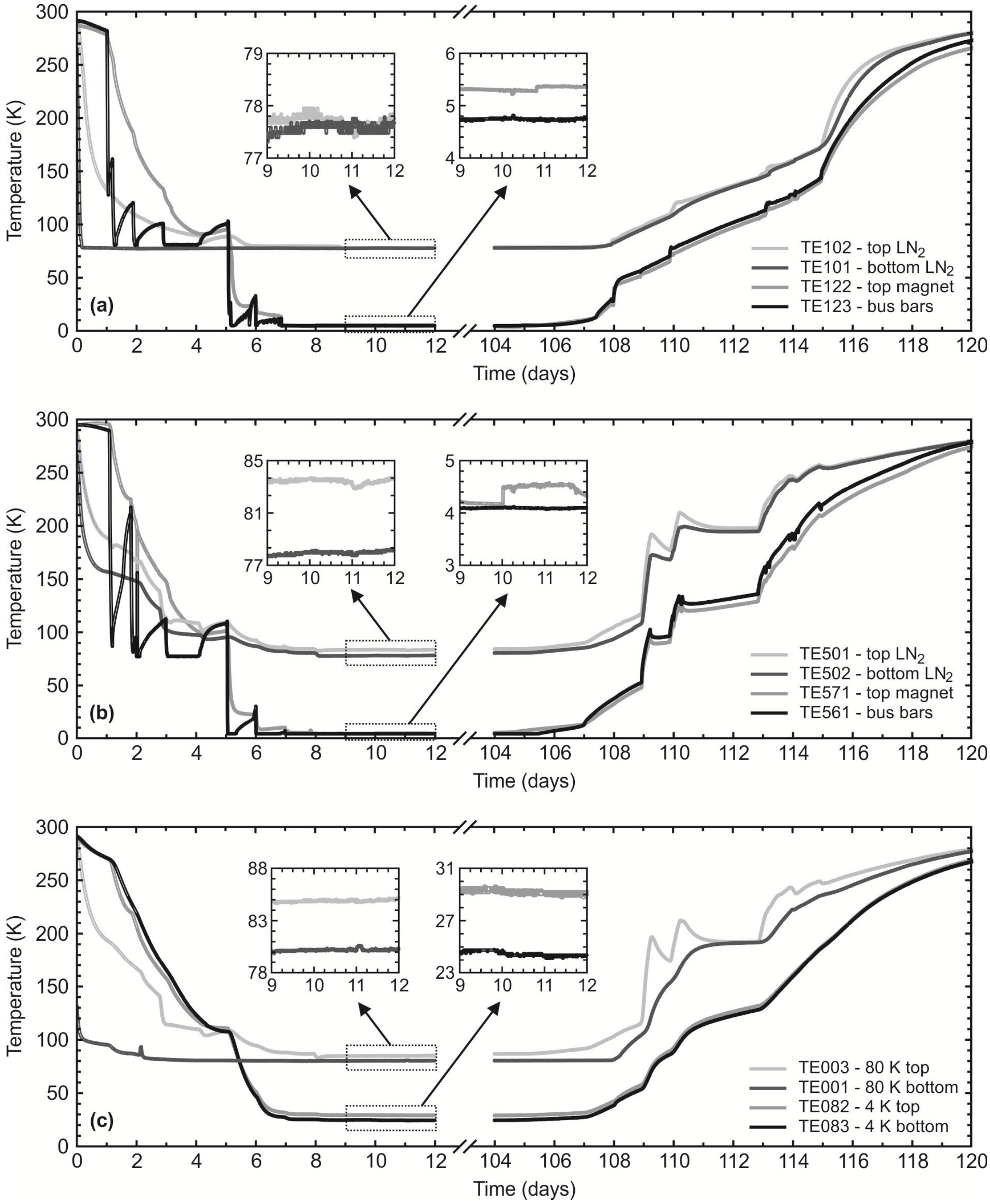

FIGURE 2. Temperatures versus the time during cool down, operation and warm up of a) the 1-T cryostat, b) the 5-T cryostat and c) the central region. The locations of the temperature sensors are indicated in Fig. 1.

down this area to 4.3 K. The temperatures of the 1-T and 5-T traps are measure to be 12 K and 18 K, respectively. Analyzing the conductive heat load through the wiring of the traps at 4.3 K showed that the thermalization is not sufficient to remove this heat load, resulting in a thermalization temperature equal to the measured trap temperatures. In future runs, the thermalization of the trap wiring will be adjusted.

After cool down, the insulation vacuum was in the 10^{-7} mbar range while the ultra-high vacuum reached a value in the 10^{-13} mbar range. For the first time, both superconducting magnets were ramped up together. This resulted in a quench of the 5T magnet at a current of 165 A, just below its nominal current of 170 A, while the 1-T magnet was fully ramped up to its nominal current of 85 A. During the quench, the temperature sensors at the outside of the 5-T magnet did not exceed 5 K. Because of the quench, it is decided to operate the 5-T magnet at a current of 150 A.

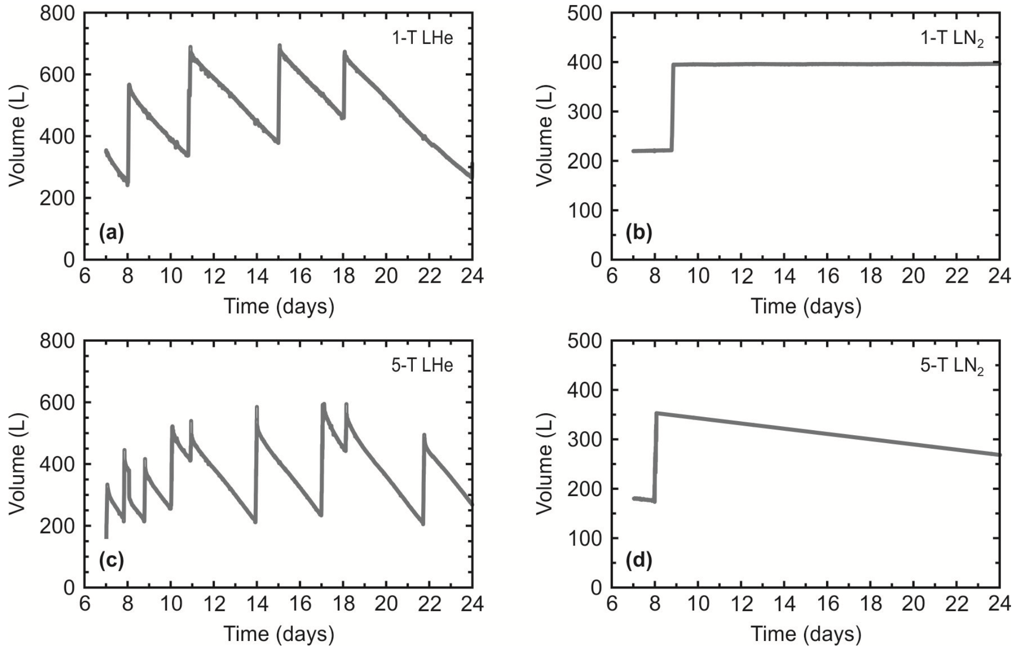

FIGURE 3. Cryogen volume versus time during normal operation of AEgIS. a) LHe level and b) LN_2 level of the 1-T magnet cryostat, and c) LHe level and d) LN_2 level of the 5-T magnet cryostat.

Figure 3 gives the volume of the cryogens in the various vessels versus time during a period of 3 weeks of operation. The 1-T cryostat LHe consumption fluctuates from 58 $L \cdot day^{-1}$ to 73 $L \cdot day^{-1}$ with an average of about 66 $L \cdot day^{-1}$ (Fig. 3a), which corresponds to a constant heat load of 2.0 W. The 5-T cryostat LHe consumption (Fig. 3c) is slightly higher with an average of about 84 $L \cdot day^{-1}$, which corresponds to a constant heat load of 2.5 W. The main heat load to the 1-T LHe vessel is caused by radiation and the magnet system, while the main heat load to the 5-T LHe vessel is due to radiation, the magnet system and conduction through the trap wiring. The latter one is calculated to be 1.1 W, which explains the higher consumption of the 5-T vessel. The fluctuations in consumption are caused by instrumentation inside the apparatus that is switched on and off during this period. The LHe vessels of the 1-T and 5-T cryostat have to be refilled once in the five and once in the three days, respectively. A similar LHe consumption is observed when the magnets are off. This indicates that the current leads are cooled well by the cold gaseous helium flow.

It can be observed in Figs. 3b and 3d that the LN_2 consumption is relatively low. The volume of LN_2 in the 1-T cryostat is not decreasing, while the 5-T cryostat is consuming 5 $L \cdot day^{-1}$. The larger consumption of the 5-T cryostat is caused by the thermalization of the central region and the entire trap wiring to this LN_2 vessel. It can be estimated that the radiative heat load to the LN_2 vessels is larger than the measured consumption. At the chimney, copper braids connect the vacuum barrier to the LN_2 vessel to precool the barrier (Fig. 1). Most probably, the evaporated nitrogen gas is re-condensed by the available cooling enthalpy of the helium gas via this thermal link. This is also indicated by the increase in LN_2 consumption with about 10 $L \cdot day^{-1}$ when the LHe vessels are empty (not shown in Fig. 3). Heaters will be placed on the LN_2 vessels to increase the consumption and in that way prevent air from flowing into the vessels.

DEVELOPMENT OF THE ULTRA-COLD TRAP

A challenging part in the design of the cryogenic system is the cooling of antihydrogen to 100 mK. It is difficult to cool the antihydrogen itself, since after formation it is directly forced out the Penning trap by an electrical field. Therefore, its constituents (especially the antiprotons) are cooled to 100 mK in a 120 s trapping period just before the antihydrogen formation. This is done in an ultra-cold Penning trap consisting of multiple high-voltage electrodes. Eisel [6] investigated various electrode designs with the focus on the thermal link between the electrodes and the mixing chamber. This link must be thermally well conducting and electrically insulating taking into account

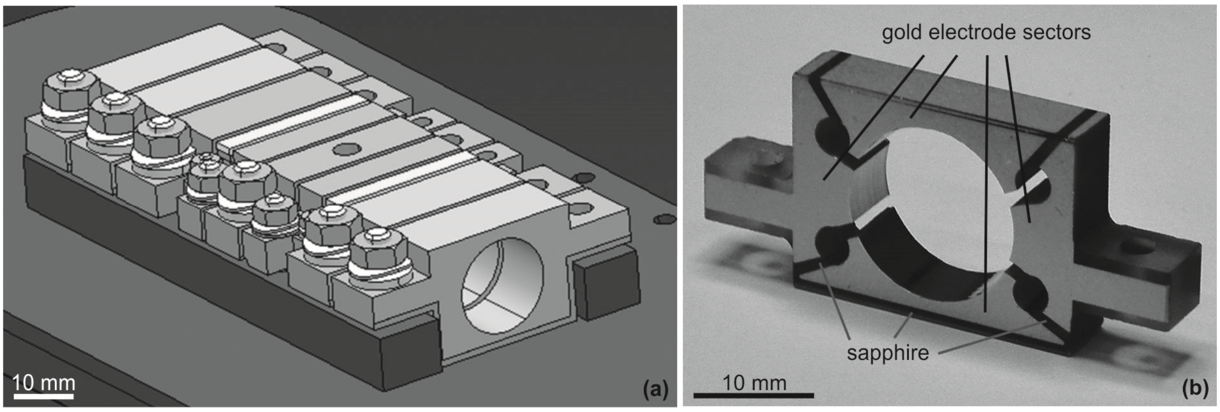

FIGURE 4. a) 3D drawing of the ultra-cold trap mounted on the mixing chamber of the dilution refrigerator. b) Photograph of one of the high-voltage electrodes of the ultra-cold trap.

that it is placed in ultra-high vacuum and in a high magnetic field. Figure 4 shows a 3D drawing of the ultra-cold trap mounted on the mixing chamber of the dilution refrigerator and a photograph of the current design of the electrodes. The electrodes are made of a sapphire base with four gold sputtered electrode sectors on it. The electrode will be screwed to the mixing chamber with a layer of indium in between to increase the thermal contact. The 1-T magnetic field will keep the indium in its normal state. Currently, this electrode design is experimentally tested at operation conditions in the CERN central dilution refrigerator.

CONCLUSIONS

In autumn 2012, the first part of the AEgIS cryogenic system, consisting of a 1-T magnet cryostat, a 5-T magnet cryostat and a central region cryostat, is assembled and successfully commissioned. The apparatus is cooled down in eight days using 2500 L of LHe and LN_2. During operation, the average consumption is 66 $L\cdot day^{-1}$ and 84 $L\cdot day^{-1}$ for the 1-T and 5-T cryostat, respectively. No difference in the consumption is observed with the superconducting magnets on or off. The temperature sensors at the Penning traps located in the bore of the magnets measured 12 K to 18 K, which is higher than expected. This is caused by badly thermalized wires of the traps at 4 K. The thermalization of the wiring will be improved in future runs. The antihydrogen will be cooled down to 100 mK in an ultra-cold trap consisting of multiple high-voltage electrodes made of sapphire with gold plated electrode sectors.

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