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Design and testing of 100 mK high-voltage electrodes for AEgIS

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Abstract

The AEgIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) experiment at CERN has as main goal to perform the first direct measurement of the Earth's gravitational acceleration on antihydrogen atoms within 1% precision. To reach this precision, the antihydrogen should be cooled down to about 100 mK to reduce its random vertical velocity. This is obtained by mounting a Penning trap consisting of multiple high-voltage electrodes on the mixing chamber of a dilution refrigerator with cooling capacity of 100 μW at 50 mK. A design of the high-voltage electrodes is made and experimentally tested at operating conditions. The high-voltage electrodes are made of sapphire with four gold sputtered electrode sectors on it. The electrodes have a width of 40 mm, a height of 18 mm and a thickness of 5.8 mm and for performance testing are mounted to the mixing chamber of a dilution refrigerator with a 250 μm thick indium foil sandwiched in between the two to increase the thermal contact. A static heat load of 120 nW applied to the top surface of the electrode results in a maximum measured temperature of 100 mK while the mixing chamber is kept at a constant temperature of 50 mK. The measured total thermal resistivity lies in the range of 210-260 $cm^2 \cdot K^4 \cdot W^{-1}$, which is much higher than expected from literature. Further research needs to be done to investigate this.

1. Introduction

The AEgIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) experiment at CERN aims at performing the first direct measurement of the Earth's gravitational acceleration on antihydrogen atoms within a precision of 1% [AEgIS collaboration (2007)]. The results will be used to verify the prediction of general relativity

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that the gravitational interaction of matter and of antimatter should be identical. The main principle is a measurement of the vertical deflection of a pulsed, cold, antihydrogen beam in the gravitational field of the Earth. To reach the desired precision, the antihydrogen needs to be cooled down to below 100 mK to reduce its random vertical velocity according to the Maxwell-Boltzmann distribution [Kellerbauer et al. (2008)]. This will be obtained by mounting a Penning trap consisting of multiple high-voltage electrodes on the mixing chamber of a dilution refrigerator operating at 50 mK. For a more detailed description of the AEgIS experiment, the reader is referred to AEgIS collaboration (2012), Kellerbauer et al. (2008), Doser et al. (2012). The AEgIS cryogenic system is discussed in more detail in Derking et al. (2014).

This paper discusses the design of the high-voltage electrodes, the thermal link to the mixing chamber and the measured thermal performance of an electrode and the electrode-mixing chamber interface at operating conditions. The paper starts with the principle of cooling of antihydrogen to 100 mK in section 2. The high-voltage electrode design is given in section 3. The thermal performance of the high-voltage electrodes is measured in a dilution refrigerator and the results are discussed in section 4. The paper ends with a conclusion in section 5.

2. Cooling of antihydrogen to 100 mK

For AEgIS to succeed, it is essential that the antihydrogen is cooled to a temperature below 100 mK. The antihydrogen is produced inside the AEgIS experimental apparatus by combining antiprotons with positronium in a Rydberg state. The positronium itself is produced by bombarding a cryogenic nanoporous material with an intense positron pulse which is produced by a Surko-type source and accumulator. The antiprotons are delivered by the antiproton decelerator of CERN. Because of its limited lifetime, after formation, the antihydrogen is directly forced out of a Penning trap consisting of multiple high-voltage electrodes by an electrical field. This makes it difficult to cool the antihydrogen itself. Therefore, its constituents (especially the antiprotons) are cooled to below 100 mK in a 120 seconds trapping period just before the antihydrogen formation takes place. This is obtained by embedding the antiprotons in a cloud of electrons and coupling these electrons to the high-voltage electrodes via dissipative circuits, so that the antiprotons cool down to the temperature of the surrounding electrodes [Doser et al. 2008]. To cool the high-voltage electrodes to below 100 mK, they will be mounted to the mixing chamber of a dilution refrigerator with a cooling capacity of 100 µW at 50 mK. A dilution refrigerator is selected, because it is the only cooling technique able to produce continuous cooling capacity in the required temperature range.

3. High-voltage electrode design

The ultra-cold Penning trap will consist of multiple high-voltage electrodes that will be independently charged and uncharged to maximum ±1 kV. A challenging part in the design is to cool the Penning trap, and thus the high-voltage electrodes, to 100 mK taking into account the following requirements. Some of the electrodes should be electrically split into four sectors and the middle electrode should contain a hole in its top surface through which the Rydberg state positronium can enter. The electrodes need to conduct thermally well while withstanding a high-voltage of ±1 kV between neighboring electrodes and the sectors within one electrode. The trapped particles should only see electrically conducting surfaces. Furthermore, the electrodes must be made of radiation hard materials, and should be in compliance with the ultra-high beam vacuum ($< 10^{-12}$ mbar) and a 1-T magnet field of high homogeneity. These requirements mean that only low-outgassing materials, leak-tight joints and non-magnetic materials could be used, and exclude the use of most of the glues.

T. Eisel (2011) investigated two different designs for thermalizing the electrodes to the mixing chamber. In the first design (sandwich design), the high-voltage electrode was electrically insulated from the mixing chamber by a monocrystalline sapphire plate. In this design phonons are the main heat carriers from the electrode to the mixing chamber. This design minimizes the amount of metallic material to be charged, resulting in minimal charging times and Joule heating. Furthermore, all mechanical components of the mixing chamber as well as the helium mixture inside are electrically at ground potential, which makes further electrical insulation unnecessary. After testing various sandwich designs, T. Eisel (2011) found that polishing the sapphire results in a lower thermal boundary resistance. By vapor depositing a 3 µm thick indium layer, the thermal boundary resistance was reduced even further.
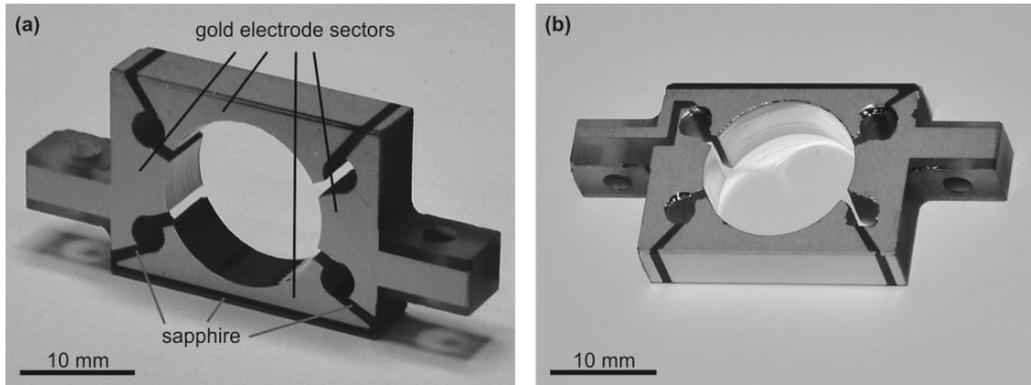
Fig. 1. Photographs of one of the high-voltage electrodes for the ultra-cold Penning trap. The electrode is made of monocrystalline sapphire and contains four gold deposited sectors. (a) Front view and (b) back view with the electrode upside down.

In the second design (rod design), the high-voltage electrode was thermally and electrically connected to the mixing chamber via a metallic pin made of oxygen free high conductivity (OFHC) copper. A sintered Al_2O_3 ceramic piece electrically insulates the pin from the mixing chamber lid, and thus from its neighboring electrodes, but the sintered heat exchanger inside the mixing chamber is at high voltage. The advantage of this design is that in the relevant temperature range the thermal conductivity of metals is dominated by free electrons and is therefore much higher than that of dielectric materials in which phonons are the dominating heat carriers. T. Eisel (2011) experimentally showed that the rod design is capable of transferring approximately a ten times higher heat load than the sandwich design. However, the drawback of the rod design is that the helium mixture should electrically insulate the electrode from the mixing chamber and the other electrodes. Because the break down voltages of the helium mixture at operating conditions is unknown, the risk of unintended break down is too large and therefore the rod design is abandoned by the AEgIS collaboration.

We have decided to make the electrodes of a sapphire base. Monocrystalline sapphire is selected because of its relatively high thermal conductivity in the relevant temperature range of 50-150 mK compared to other dielectrics [Pobell (2007)]. Fig. 1 shows photographs of one of the high-voltage electrodes. The electrode has a width of 40 mm, a height of 18 mm, a thickness of 5.8 mm and the diameter of the inner hole is 14 mm. The high-voltage electrode sectors are produced by subsequently depositing a 50 nm thick adhesion layer of titanium and a 750 nm thick layer of gold on the sapphire surface. The sectors are electrically separated from each other by leaving uncovered sapphire in between. Four small holes are placed in such a way that the trapped particles do not face these sapphire surfaces as they should only see electrically conducting surfaces. The gold layer is structured in such a way that all sectors could be electrically connected at the side ears. To decrease the thermal resistance at the electrode-mixing chamber boundary, the sapphire at the bottom surface of the electrode is polished and also subsequently covered with a 50 nm thick adhesion layer of titanium and a 750 nm thick gold layer. The sapphire at the surfaces facing the trapped particles is polished too.

The high-voltage electrodes will be mounted with M2.5 screws to the mixing chamber with a 250 μm thick indium foil in between. The 1-T magnetic field in which the Penning trap is mounted in AEgIS will ensure that the indium stays in its normal state.

4. Measured thermal performance of the high-voltage electrode

The thermal performance of the high-voltage electrode is measured in the temperature range between 50 to 200 mK on a dilution refrigerator. Fig. 2 gives photographs of the electrode mounted on the mixing chamber of the dilution refrigerator. As shown, the electrode is pressed with M2.5 screws to a copper block with an indium foil of 250 μm thickness sandwiched in between. To increase the thermal contact an indium cold weld is made by retightening the screws at room temperature for several days with a force higher than the yield strength of indium.

Fig. 2. (a) The high-voltage electrode is pressed to a copper block and equipped with RuO_2 temperature sensors and heaters. The location of various temperature sensors and heaters is indicated. Heater Q_{sl} is located at the backside of the electrode at a similar position as sensor T_{sl}. (b) The high-voltage electrode is mounted in a dilution refrigerator and surrounded by a heat shield (only one part shown).

This allows the indium to creep and wet the surfaces. Before mounting, the copper piece and the indium foil were cleaned with acetone. The copper piece is pressed to the mixing chamber lid with a 250 μm thick indium foil in between. Three RuO_2 temperature sensors were glued to the electrode using Stycast® 2850FT, one RuO_2 sensor was screwed to the copper block and another one is mounted inside the mixing chamber. The RuO_2 temperature sensors were calibrated against a reference thermometer from Lakeshore Cryotronics Inc. Two resistors used as heaters are glued to the top (Q_t) and to the left side (Q_{sl}) of the electrode and another is mounted to the copper block. The location of the temperature sensors and heaters is indicated in Fig. 2(a). A copper shield thermalized to the copper block is enclosing the electrodes during the measurements to minimize the radiative heat load, as shown in Fig. 2(b). To bring the indium to the normal conducting state, a magnetic field of 33 mT is applied during the measurements simulating the situation in AEgIS where the Penning trap is mounted in the bore of a 1-T superconducting magnet.

During the measurements, a static heat load (Q) is applied to the top or to the left side of the electrode. The static heat load is increased in small steps and during each step the temperature sensors are monitored. This is done

Fig. 3. Temperature of various sensors versus the applied heat to the top of the high-voltage electrode via heater Q_t. The location of the temperature sensors is shown in Fig. 2. T_{mc} refers to the mixing chamber temperature.
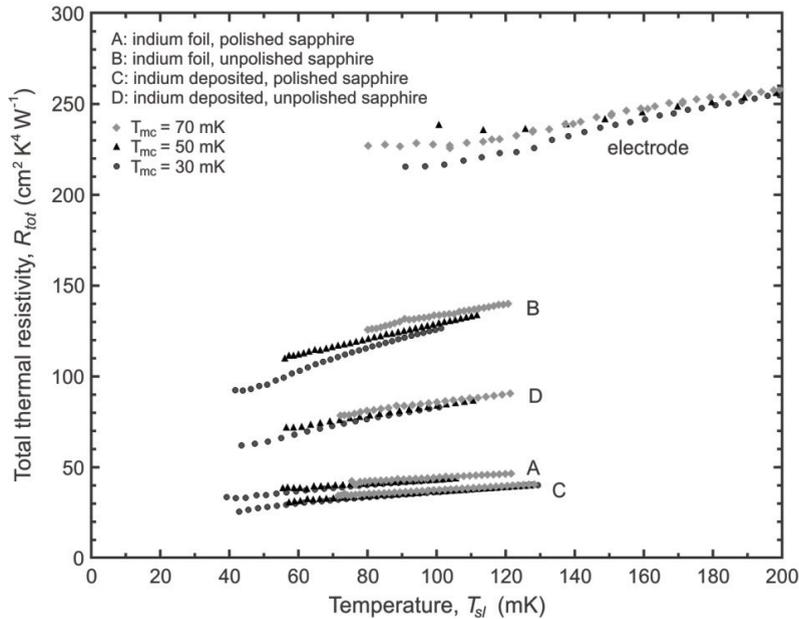
Fig. 4. Total resistivity of different Sandwich cases measured by T. Eisel (2011) and of the high-voltage electrode versus the electrode temperature (T_{sl}) for mixing chamber temperatures (T_{mc}) of 30, 50 and 70 mK. The heat is applied to heater Q_{sl}, see Fig. 2.

for a mixing chamber temperature (T_{mc}) of 30, 50 and 70 mK. Fig. 3 gives the measured temperatures versus the applied heat load to the top of the electrode via heater Q_t for a constant mixing chamber temperature of 50 mK. As shown, for an applied heat load of 120 nW the top sensor measures 100 mK, which is the maximum allowable temperature for AEgIS. For this applied heat load, the temperature difference between sensors T_t and T_{sl} is about 15 mK indicating that the temperature difference over the sapphire is relatively large compared to the maximum allowable temperature difference of 50 mK. In future designs, this can be reduced by making the electrode base wider in that way increasing the cross-sectional area along the height of the electrode.

To compare the results to these of T. Eisel (2011), we have plotted the total thermal resistivity (R_{tot}) versus the temperature at the side of the electrode (T_{sl}) in Fig. 4, while varying the heat applied to the left side of the electrode via heater Q_{sl}. This will exclude the major part of the temperature difference over the sapphire electrode itself in the calculation of the total thermal resistivity, making a better comparison to the results of T. Eisel possible. Because the temperature differences are higher than the absolute temperature, the total thermal resistivity is calculated by [Matsumoto et al. (1977)]

$$R_{tot} = \frac{A}{4\dot{Q}}\left(T_{sl}^4 - T_b^4\right) \tag{1}$$

where A is the bottom area of the electrode, $\dot{Q}$ is the applied heat and T_b is the temperature of the copper block. As the high-voltage electrode has a polished sapphire surface with a deposited gold layer, a total thermal resistivity corresponding to the case of polished sapphire with deposited indium (case C in Fig. 4) could be expected. However, as shown in Fig. 4, the measured total thermal resistivity in the range of 210-260 $cm^2 \cdot K^4 \cdot W^{-1}$ is much higher. The reason for this is not fully understood. In the current design, two interfaces could cause the reduced total resistivity. At the gold-sapphire interface the heat is mainly transported by phonons (metal-dielectric interface). T. Eisel (2011) has shown that a deposited indium layer reduces the thermal boundary resistance most probably due to the fact that indium particles are deposited onto the sapphire surface under vacuum preventing the trapping of

other particles. It was expected that the deposited gold layer shows a similar behavior, but it seems that this is not the case. So, maybe other boundary effects are occurring at the gold-sapphire interface. This should be investigated further.

At the indium-gold interface free electrons are the dominant heat carriers (metal-metal contact). After demounting the electrode, it was observed that the indium foil was only cold welded to two small areas and not over the full bottom surface of the electrode. Although heat transport by free electrons is much higher than by phonons, the reduced area could result in an increase in the thermal boundary resistance. Simulating the bending of the electrode under the applied force of the screws showed that the electrode slightly bends in the middle. This results in an applied force at this point lower than the yield strength of indium, what explains that the indium is only cold welded at the left and the right sides. In future designs, the bending of the electrode and the way of mounting the electrode should be taken into account to ensure a good indium cold weld at the full bottom surface of the electrode.

5. Conclusion

To cool down antihydrogen to 100 mK in a Penning trap for the AEgIS experiment at CERN, a design of a high-voltage electrode is made and experimentally tested at operating conditions. The high-voltage electrodes are made of sapphire with four gold sputtered electrode sectors on it. The electrodes have a width of 40 mm, a height of 18 mm and a thickness of 5.8 mm. The electrodes are mounted to the mixing chamber of a dilution refrigerator. To increase the thermal contact, the bottom of the sapphire is polished and an indium foil of 250 µm thickness is used as intermediate layer. A static heat load of 120 nW applied to the top of the electrode resulted in a temperature of 100 mK at the top of the electrode while the mixing chamber was kept at a constant temperature of 50 mK. The measured total thermal resistivity lies in the range of 210-260 $cm^2 \cdot K^4 \cdot W^{-1}$, which is much higher than expected from literature.

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