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A 2.5 m long liquid hydrogen target for COMPASS

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ABSTRACT

A 2.5 m long liquid hydrogen target has been developed for the COMPASS experiment at CERN to investigate the nucleon spin structure via the Deeply Virtual Compton Scattering (DVCS) process. To recognize exclusive DVCS events, produced photons and slow protons need to be detected. In order to do so, the material budget around the target has to be minimal. A 0.125 mm thick Kapton® target cell and a 1 mm thick carbon fiber vacuum chamber with a Mylar® window have been constructed and tested. Finally, the target system was successfully employed during the DVCS pilot run in COMPASS at the end of 2012. The objective of this paper is to give a detailed description of this newly developed liquid hydrogen target apparatus.

1. Introduction

The COMPASS experiment at CERN has been taking data since 2002 using either muon or hadron beams with a polarized solid target, liquid hydrogen or heavy nuclear targets. Some of the most recent results on the nucleon spin structure and hadron spectroscopy are described in Refs. [1–7]. The COMPASS collaboration has submitted a proposal for new measurements including a study of Generalized Parton Distributions (GPDs) using a liquid hydrogen target in combination with a muon beam of 160 GeV/c [8]. The GPDs provide a novel description of the nucleon. This 3-dimensional "nucleon tomography" correlates transverse spatial and longitudinal momentum degrees of freedom of partons. Certain GPDs can be extracted from the cross-section of the DVCS reaction with μ^+ and μ^- beams, which are polarized along opposite directions described as $\overleftarrow{\mu}^{+} p \rightarrow \mu^{+} p \gamma$ and $\overrightarrow{\mu}^{-} p \rightarrow \mu^{-} p \gamma$. Since the cross-section is very small, a target as long as 2.5 m is required to guarantee a large enough luminosity. Besides reducing the material budget, it is also important to obtain a clear signature of the DVCS events. For this purpose two new detectors, a Recoil Proton Detector (RPD) and an Electromagnetic CALorimeter (ECAL0), have been built. The RPD, which surrounds the target, has a large polar and full azimuthal angular acceptance of proton detection. Protons at a 90° emission angle are relatively slow and have a momentum of about 260 MeV/c [8]. The ECAL0 is positioned directly downstream of the target and enlarges the polar angular acceptance for photon detection. The new target apparatus was installed and commissioned together with the RPD and an ECAL0 prototype in the COMPASS spectrometer for the pilot run of 2012, which lasted 45 days. Section 2 discusses the design and the construction of the target apparatus, while Section 3 describes a study of the quality of the isolation vacuum. Section 4 is about the installation of the target apparatus and the (real time) monitoring. Section 5 discusses the operation during the pilot run. Finally, Section 6 summarizes the results and gives the plan of the runs with the target apparatus.

2. Target apparatus

The target apparatus comprises of a long cylindrical target cell with a diameter of 40 mm, a vacuum chamber with an end cap, a refrigerator system consisting of a cryocooler with a cooling power of 30 W at 20 K and five 1000 l hydrogen tanks. To reduce the material budget of the target system, thin Kapton® and Mylar® sheets are used to construct the target cell and a thin-walled

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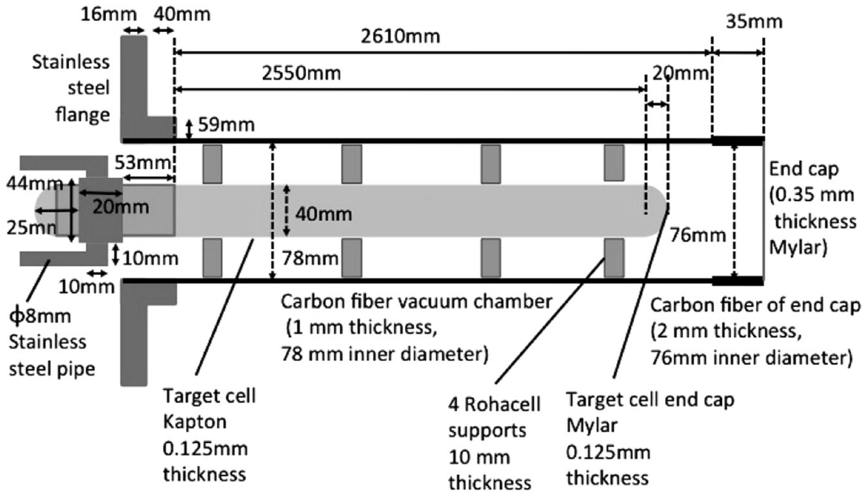

Fig. 1. A schematic side view of the target cell and vacuum chamber.

Carbon Fiber Reinforced Plastic (CFRP) pipe acts as a main part of the vacuum chamber (see Fig. 1).

2.1. Target cell

The target cell has a cylindrical shape with a diameter of 40 mm, a length of 2668 mm and a volume of 3.3 l. It is made of 0.125 mm thick Kapton® sheet and its end cap is a hemisphere made of 0.125 mm thick Mylar®. At the downstream side, the 40 mm diameter Kapton® tube[1] is glued to the end cap using Araldite®. At the upstream side, a 95 mm long stainless steel cylinder, which has a thicker ring part, is glued to the tube with a 10 mm overlap, also using Araldite®. The ring has two pipes of 8 mm inner diameter connected to it: one pipe at the bottom of the ring for the liquid hydrogen entry and the other at the top acting as a return line for the gaseous hydrogen. These pipes, together with four 10 mm thick Rohacell® support pieces, keep the cell in the center of the vacuum chamber, which is used for alignment with the particle beam. The upstream side of the stainless steel cylinder is enclosed by another 0.125 mm thick hemispherical-shaped Mylar® end cap. The cell is covered with thirty layers of 11 μm thick aluminized Mylar® foils acting as superinsulation.

Since the target cell is considered to be a pressurized vessel, safety requirements prescribe pressure tests to be performed. The target cell needs to withstand a pressure of three times the maximum inner pressure during operation, which is 2 bar in absolute pressure. Pressure tests have been carried out on test samples of the target cell, each of them being 500 mm long and having a 40 mm diameter. Out of six samples, two were chosen randomly to be used in the pressure test. Increasing the inner pressure stepwise, the rupture pressure was measured to be 6.8 bar for both samples [9].

2.2. CFRP pipe

The CFRP pipe, 1 mm thick and 80 mm in outer diameter, consists of ten layers of two different types of CFRP sheets made of carbon fibers.[2] The design of the pipe is referred to Ref. [10]. These sheets are 0.1 mm thick and the fibers are oriented in only one direction. The first type is Mitsubishi Plastics HYEJ25M80PD and is used for eight layers. The fibers of two out of these eight layers are oriented in longitudinal direction, while the other six layers have their fibers oriented in circumferential direction. The Young's modulus is 780 GPa which makes the chamber strong enough to avoid buckling due to forces from the outside. The second type is Mitsubishi Rayon HYEJ12M40J-25 and is used for two layers. These layers have their fibers oriented in the longitudinal direction. The Young's modulus is twice lower than the first type's: 390 GPa to be more flexible and improve rollability. Both types of sheets are composed of carbon and epoxy following Table 1. The average density of the carbon (epoxy) is 2.07 (1.20) g/cm^3. The volume ratio of the carbon (epoxy) is 56.6 (43.4)%.

Table 1
The compositions of the CFRP pipe material.

CFRP sheet type	# of layers	Carbon density (g/cm^3)	Epoxy density (g/cm^3)	Carbon weight fraction	Epoxy weight fraction
Mitsubishi Plastics HYEJ25M80PD	8	2.15	1.20	0.680	0.320
Mitsubishi Rayon HYEJ12M40J-25	2	1.82	1.20	0.745	0.255

The usage of the two types of sheets and the present configuration of the orientation of the fibers give the availability to fabricate the vacuum chamber strong enough to withstand an external pressure of 3 bar.

The vacuum chamber pressure tests were performed as follows. In total, eight CFRP pipes were produced, each of them being 2675 mm long and having an 80 mm outer diameter. One of them was chosen randomly to be used in the pressure test. The pipe, enclosed by an aluminium blind cap, was vacuum pumped and pressurized on the outside. The pressure was increased to 3 bar in absolute pressure for 2 min. Not a single anomaly could be found.

To obtain proper functioning of the vacuum chamber, difficulties concerning thermal radiation and outgassing should be solved. A silver coating with nano silver particles on the internal surface of the pipe addresses both points. The advantage of this coating is that it is suitable to be applied in narrow spaces. The nano silver particles sinter at room temperature because they are dissolved in a solvent which evaporates at room temperature [11]. The emissivity of silver is 0.03, comparing with CFRP of about 0.9. The silver coating reduces the thermal radiation heat transfer together with

[1] Produced by Precision Products Group Inc.
[2] Produced by Sankyo Manufacturing Co., Ltd.

the aluminized Mylar® foils. The silver coating was applied in the following procedure:

1. Mounting caps with a hole at both ends of the pipe.
2. Mounting the pipe horizontally on a bench.
3. Pouring the silver solution of 50 ml containing 12.8 g silver inside the pipe.
4. Rotating the pipe in circumferential direction at ninety revolutions per hour.
5. Waiting a few hours until the solvent evaporates at room temperature.
6. After stopping the rotation, waiting a few days until the pipe dries.

The thickness of the silver coating was evaluated to be 1.8 μm from the weight of the silver.

The upstream side of the CFRP pipe is slid into a stainless steel flange and the two are glued together with Araldite®. A 40 mm long overlap between flange and CFRP pipe was chosen to ensure proper fixation.

2.3. End cap of the CFRP pipe

The end cap of the CFRP pipe consists of a 35 mm long, 2 mm thick CFRP cylinder and a Mylar® window (see Fig. 2). The Mylar® window is made of a 0.35 mm thick Mylar® sheet formed at 100 °C for 30 min, using a press machine to make a 15 mm long overlap with the CFRP cylinder for gluing. The edge of the CFRP cylinder is curved with a 1 mm radius to avoid cutting the Mylar® when the inside is under vacuum and the window is thus pushed inwards. The most difficult part of the gluing process is to avoid Stycast1266 ® to penetrate into the CFRP cylinder, forming a potentially dangerous sharp edge. In addition to the glue, the Mylar® window is also fixed with a Kevlar string with Araldite®.

The Mylar® window and its connection to the CFRP cylinder needed to be pressure tested as well. A pressure test was performed on a sample of the Mylar® window glued to an aluminium flange. Requiring a pressure difference of 3 bar, first the internal pressure was stepwise increased up to 4 bar, while the external pressure was kept at atmospheric pressure. This condition was maintained for 10 min. Secondly, the external pressure was increased similarly to 4 bar, keeping the internal pressure at atmospheric pressure. This new condition was also maintained for 10 min. These procedures were repeated five times. No obvious leak was found, neither any mentionable damage was present. The Mylar® window was however slightly deformed. Another test was performed to make sure that the window bears even under serious conditions. The previously mentioned internal pressure was increased stepwise by 1 bar each 5 min. When the pressure reached 11 bar, it was maintained for 20 min. Again, no obvious leaks, neither any damage was found to be present. The results of the tests were promising and it was concluded that the window can be confidently used.

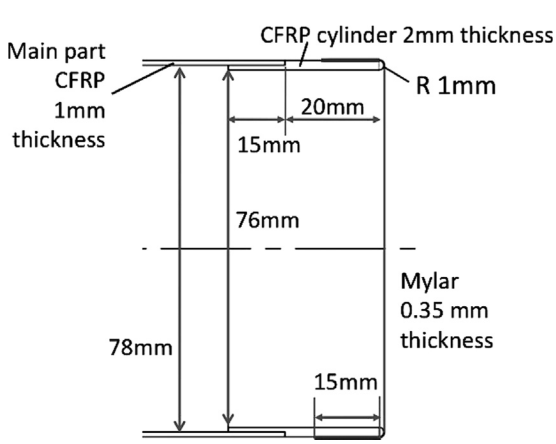

Fig. 2. End cap of the chamber.

2.4. Refrigerator system

The piping and instrumentation diagram of the COMPASS hydrogen target system is shown in Fig. 3. The refrigerator system consists of a helium cryocooler[3] with a cooling power of 30 W at 20 K, a hydrogen phase separator with a volume of 6 l and five hydrogen gas buffer tanks of 1000 l each. The phase separator is connected with a direct line to the tanks. The system is equipped with a heater that is placed on the cryocooler cold head. The heater power is controlled to regulate hydrogen pressure. The pressure is measured by a piezoresistive sensor[4] with an accuracy of $\pm 0.3\%$ including zero offset. This sensor is placed on the numerical gas control panel (see Fig. 3). A diffusion pump maintains the isolation vacuum and has a pumping speed of 150 l/s. Two level detectors are mounted in the phase separator, one at the bottom and one at the top. Once liquid hydrogen starts to condense in the phase separator, it is naturally transported to the target cell by gravity via the inlet pipe. Gaseous hydrogen returns to the phase separator via the outlet pipe. A pneumatic valve controlled by pressurized helium gas is mounted in the outlet pipe. This valve enables emptying the target cell in 10 min. An "empty target" mode is realized by closing this valve: hydrogen gas created in the target pushes the liquid hydrogen back to the phase separator via the inlet tube. It is used for background studies in the experiment.

3. Isolation vacuum study

To study the performance of the vacuum chamber from an 'outgassing' point of view, the deterioration of the isolation vacuum was observed before the installation of the target cell. To measure the deterioration rate, the pressure inside the vacuum chamber was lowered by pumping with a turbo pump. The pump was connected to the chamber via a 1 m long, 25 mm inner diameter pipe. The conductance of the pipe defines the pumping speed of 2 l/s. Once a certain value of the pressure was reached, the chamber was closed and the pressure was measured repeatedly for about 10 min. Then, pumping was restarted. This procedure was repeated to give the deterioration rate as a function of the pumping time as shown in Fig. 4. It shows the deterioration rate for three different vacuum chamber samples. The deterioration rate strongly depends on how long the chamber is pumped and reaches an asymptote of about 1×10^{-4} mbar · l/s. It is assumed that the deterioration can only be caused by outgassing of the internal surface of the CFRP pipe, diffusion through the Mylar® end cap window and leak through the CFRP pipe. The results show that outgassing from the internal surface of the CFRP pipe is decreasing over time, while transmission through the Mylar® window remains more or less constant. Since the asymptotic value is consistent with the calculated value of diffusion of water vapor through the Mylar® window, by using its specific permeability [12], the diffusion through the CFRP pipe itself is negligible. Independently, the leak rate of the vacuum chamber was also measured with a helium leak detector. The measured value was as low as about 2×10^{-6} mbar · l/s, reaching the specified requirements.

[3] SUMITOMO Cryogenics, CH-110LT-F70H.
[4] General Electric Company, UNIK 5000.

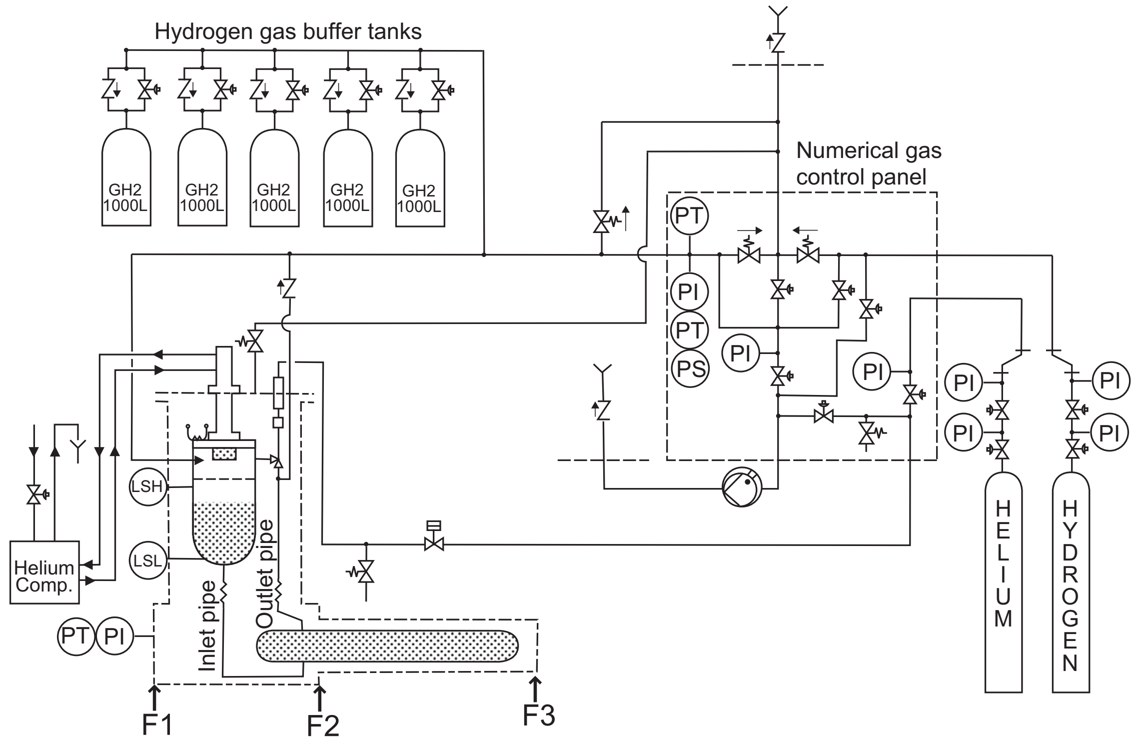

Fig. 3. Piping and instrumentation diagram of the COMPASS hydrogen target system with pressure transmitter (PT), pressure indicator (PI), pressure switch (PS), and level switch high/low (LSH/L). F1, F2 and F3 are the reference positions for the exact positioning and alignment during installation. The diffusion pump system for the isolation vacuum is excluded here.

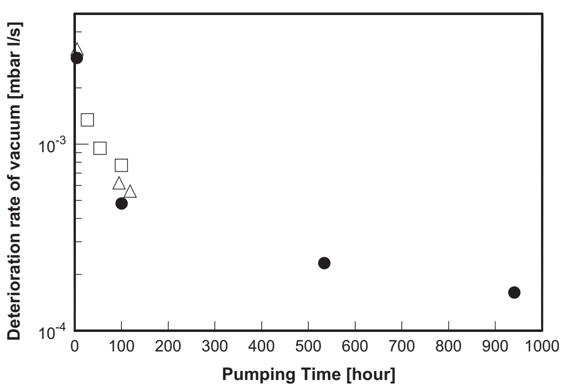

Fig. 4. Deterioration rate of the isolation vacuum of the vacuum chamber as a function of pumping time. The deterioration rate is the sum of outgassing of the internal surface of the CFRP pipe and diffusion through the Mylar® end cap window. Three different samples were measured independently, as indicated by the three types of symbols. The sample represented by the open squares was used in the experiment.

During operation the deterioration of the vacuum is also caused by hydrogen diffusing through the Kapton® sheet. Permeability of the target cell was also measured using a helium leak detector. At a temperature below 120 K, the measured value was 3×10^{-7} mbar · l/s. Since the permeability of Kapton® for hydrogen is lower than that for helium, the permeability of the hydrogen is negligible. Thus, it is clear that the diffusion of water vapour through the Mylar® window forms the bottle neck in reaching a low enough pressure in the vacuum chamber.

The vacuum pressure was estimated to be 2.2×10^{-6} mbar once the target is cooled down. This value can be obtained when a 130 l/s effective pumping speed is applied during operation in the experiment with the second Mylar® window at the upstream side described in Section 4. When the cryocooler is working in addition, the obtainable vacuum pressure will be even slightly lower. This value is acceptable for effective target deployment of the target apparatus in the COMPASS experiment during physics runs (data taking).

4. Target apparatus in experimental hall

The vacuum chamber with the target cell inside was connected to the refrigerator with bolts and an O-ring was used to seal the connection. The target apparatus was installed in the COMPASS experimental hall.

4.1. Installation

In the experimental setup, an additional round 0.175 mm thick, 80 mm diameter Mylar® sheet is mounted at the upstream side of the target apparatus and is fixed between two flanges with an O-ring. The target cell is inclined by 2 mm over the full length to evacuate the hydrogen gas automatically to the outlet pipe.

4.2. Target control and monitoring

The target control system monitors and controls the different parts of the target apparatus: the isolation vacuum pump, the heater, the cryocooler and the valve to empty the target. If a problem is detected, either for the isolation vacuum, the cryocooler, the diffusion pump or the hydrogen pressure, the target control system switches off the cryocooler automatically, such that the hydrogen will evaporate and the gas is recovered to the tanks. At the same time, an acoustic alarm sounds. The hydrogen gas pressure, temperature of the return line from the target cell and the isolation vacuum are also independently monitored by the COMPASS Detector Control System (DCS) via a PLC

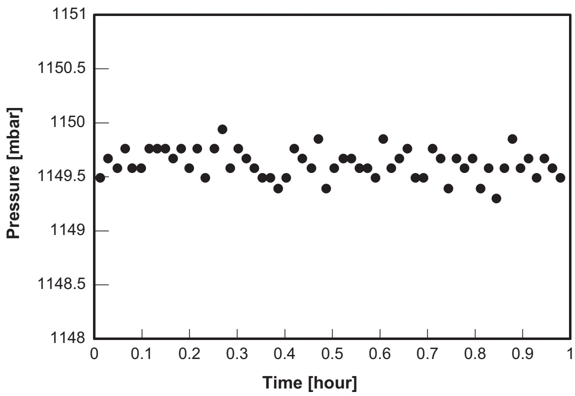

Fig. 5. Hydrogen pressure as a function of time. The data shown represent a sample of 1 h on the 22nd day after the cryocooler started.

system[5] [13]. When the values of these parameters are out of a predefined range, the DCS gives an alarm signal. The authorized persons who are responsible for the target apparatus have the possibility to set additional alarm settings and parameter limits in the DCS. Shift crew members, who are not necessarily target apparatus experts, can recognize problems with the target apparatus via the DCS. The mentioned parameters are captured every 2 s via PVSS® and the values are stored in the COMPASS DCS Oracle database.

5. Operation of the target

To reduce the influence of the outgassing from the inner surface of the vacuum chamber the diffusion pump had been kept running for two weeks to reach a pressure of 1×10^{-5} mbar in the vacuum chamber, before the cryocooler was started. To be sure that the hydrogen volume (target cell, phase separator and gas tanks) does not contain any undesired contents, a strict procedure has to be followed. First the volume has to be purged. After pumping, the space is filled with helium gas and flushed four times. Then, the volume is filled with hydrogen, pumped and filled again. Finally the hydrogen volume contains hydrogen gas at a pressure of 1855 mbar. At this stage, the cryocooler is switched on.

The hydrogen pressure decreases as the temperature decreases. Lowering the pressure from 1855 to 1160 mbar took about 13 h. At the start of the pressure regulation at about 1160 mbar the heater power was 2.5 W and it stabilized at about 18 W at a pressure of about 1140 mbar. A stable isolation vacuum pressure of 5×10^{-7} mbar was obtained during data taking which is consistent with the calculated value of 2.2×10^{-6} mbar in Section 3, taking into account the cryocooler effect.

The DVCS pilot run took 45 days. The target apparatus has been successfully operated during this period. The hydrogen pressure varied between 1116 and 1158 mbar due to variations of pressure and temperature in the experimental hall.

The short term stability of the hydrogen pressure over a time span of 1 h was measured to be ± 0.03 mbar (see Fig. 5). The ± 0.03 mbar corresponds to $\pm 0.026\%$ of the stable pressure of 1149.6 mbar in Fig. 5. The stability is better than the sensor accuracy of $\pm 0.3\%$, as mentioned in Section 2.4. Fig. 5 depicts this very stable behavior. The shown data represent a sample of data during 1 h on the 22nd day after the cryocooler started.

The density has a direct impact on the luminosity. The density of the liquid hydrogen is a function of temperature, while the temperature T (K) of para-hydrogen[6] is given by a function of the vapor pressure P (mbar) [14]:

$$T = 16.037 + 5.0376 \times 10^{-3} \cdot P - 8.5086 \times 10^{-7} \cdot P^2 \tag{1}$$

which is valid when the pressure is within a range of 1100–1300 mbar. The liquid hydrogen density D (kg/m^3) is given by

$$D = 82.370 - 1.332 \times 10^{-3} \cdot T + 2.835 \times 10^{-2} \cdot T^2 \tag{2}$$

which is valid when the temperature is in the range of 16–24 K. During the 45 days of data taking, the average value for the vapor pressure was 1137 mbar, which corresponds to an average temperature of 20.67 K and a mass density of 70.29 kg/m^3.

In total an amount of 380.22 mol was initially injected in the hydrogen volume of the target apparatus. A total hydrogen leak of 3.33 mol was observed over 45 days. This value was calculated from the pressure drop which occurred over the test period and the temperature in the hall. The average daily leak rate was thus 0.074 mol or 0.019%. Compared with the average daily leak rate which was observed for the 400 mm long hydrogen target, which was used by the COMPASS experiment in 2008 (0.027%), this result is above expectation.

6. Summary and outlook

A 2.5 m long liquid hydrogen target made of a 0.125 mm thick Kapton® target cell and a 1 mm thick CFRP vacuum chamber has been developed for operation in the COMPASS experiment at CERN. Its design, construction, test and operation were all very successful. Mechanically the target apparatus fulfills all requirements and passed all the tests without any problems. However, before the DVCS pilot run started, it was observed that outgassing of the internal surface of the CFRP pipe deteriorates the isolation vacuum. To reduce the outgassing, the vacuum chamber needs to be pumped during about two weeks to obtain a vacuum pressure of 1×10^{-5} mbar before cooling. During the pilot run data taking period, the vacuum pressure reached a satisfactorily low value of 5×10^{-7} mbar. The liquid hydrogen pressure stability over a time span of 1 h was ± 0.03 mbar. The apparatus has performed very well during 45 days at the end of 2012 and will be used again in the DVCS program which is foreseen to take place in 2016 and 2017.

Acknowledgments

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