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The polarized deuteron target at COMPASS in 2022

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The COMPASS experiment at CERN used a upgraded transversely polarized deuteron target with a muon beam of 160 GeV/c for SIDIS measurements in 2022. The deuteron target material of ^{6}LiD installed in 3 cells was polarized by the DNP method with a 2.5 T magnet, a dilution refrigerator and three 70 GHz microwave oscillators. During the data-taking the target operates in a transversely oriented magnetic dipole field at 0.6 T. This frozen spin operation mode without DNP process leads to a slow depolarization. Nevertheless, it was important to reach 40 % polarization that is sufficient for spin asymmetry measurement. The newly installed 3 microwave oscillators played a significant role to increase the polarization. We obtained deuteron polarizations of more than 40 % in each cell for two days. The relaxation time of the deuteron polarizations during the data taking period was measured to be about 5000 h at 0.6 T and below 100 mK.

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1. Introduction

Sivers and Transversity functions of Transverse-Momentum-Dependent Parton-Distribution-Functions have unique information of the transverse spin structure of the nucleon. We collected a significant amount of data for semi-inclusive DIS (SIDIS) on transversely polarized protons with a polarized NH_3 target in 2010 [1]. On the contrary we obtained data for polarized deuterons only for short periods in 2002 and 2004 with a small acceptance magnet. Thus, the statistical uncertainties of the deuteron transverse spin asymmetries were considerably larger than those of the corresponding proton asymmetries [2]. We planed to obtain more deuteron data to improve the statistical uncertainties in 2022.

Recently the transverse spin structure of the nucleon has attracted attention in relation to the theory of Beyond Standard Model (BSM) of elementary particles. Some of the BSM theories expects an electric dipole moment (EDM) of quarks, which is forbidden in the standard model [3]. The nucleon EDM is expressed as $d_N = \delta u \cdot d_u + \delta d \cdot d_d$, where δu, δd are the quark tensor charges and d_u, d_d are the quark EDM. This means that the tensor charge is an essential information in determining the upper limit the EDM. The tensor charges are derived by integrals with respect to x of the Transversity of the quarks. Due to the large uncertainty of the Transversity for the d-quark, the tensor charge estimation by phenomenological analysis gives large uncertainty [4].

2. Apparatus

The Polarized Target (PT) apparatus in 2022 has been used since 2002 [5]. It consists of several systems with a large cooling power ^{3}He-^{4}He dilution refrigerator, a magnet system, three microwave generators, a target container with three separated target cells and multiple NMR detection system in order to monitor the deuteron polarization of ^{6}LiD (Fig. 1).

The dilution refrigerator is able to maintain temperatures between 100 to 300 mK during the DNP (Dynamic Nuclear Polarization) and below 100 mK during the frozen spin mode within the data-taking period [6]. The mixing chamber, where the target material is placed, has almost a volume of 5 litres. Eight mechanical booster pumps, connected in series giving 13500 m^3/h pumping speed, provide about 100 mmol/s flow rate to keep the refrigerator running.

The magnet system consists of a solenoid and a dipole superconducting magnet providing a magnetic field of 2.5 T and 0.63 T, respectively [5]. The solenoid magnet supplies the magnetic field for longitudinal polarizations during the DNP. 16 trim-coils are installed to ensure a field homogeneity $\Delta B/B$ below 50 ppm in the target region over an approximate distance of 130 cm. The dipole magnet is used for transverse polarization and rotating the target spin. By an interplay with the solenoid and dipole magnetic fields the target spin is rotated into the needed transverse direction with respect to the muon beam, that takes about 40 minutes. Once the material is polarized, the refrigerator is operated in the frozen spin mode. In this mode, the direction of the target spin can be rotated with negligible losses of the polarization. The magnet system was installed in 2005 and has a large acceptance of $\pm$ 180 mrad.

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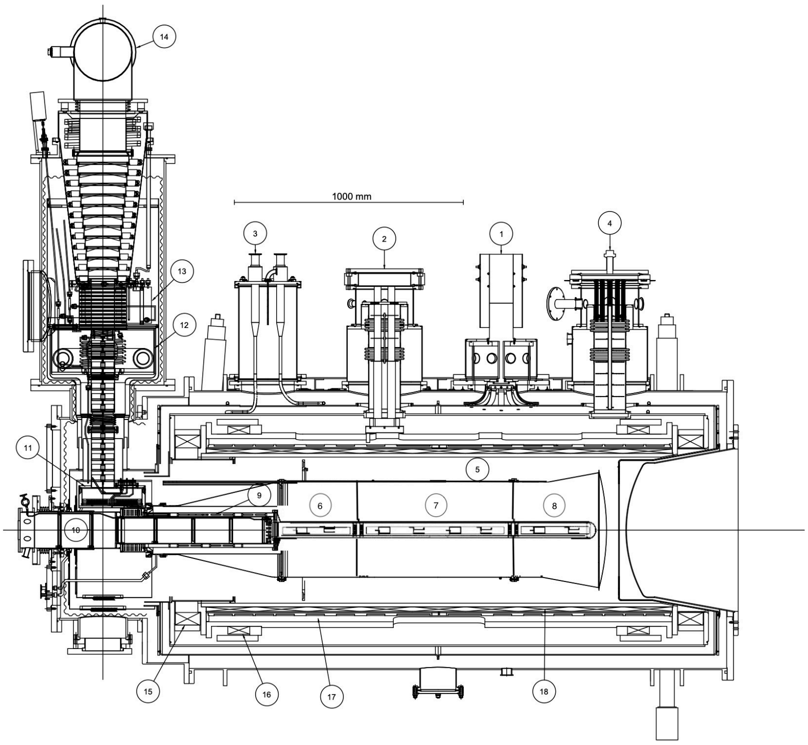

Figure 1: Side view of the COMPASS polarised target in SIDIS physics data taking in 2022: ① cryocooler for magnet thermal radiation shield, ② current lead turret, ③ liquid nitrogen precooling inlet and outlet connections, ④ liquid helium transfer and instrumentation turret, ⑤ microwave cavity, ⑥ upstream cell, ⑦ central cell, ⑧ downstream cell, ⑨ step heat exchanger, ⑩ target holder isolation vacuum and radiation shields, ⑪ still or helium-3 evaporator, ⑫ helium-4 evaporator, ⑬ helium-4 gas/liquid separator ⑭ helium-3 pumping port, ⑮ upstream end compensation coil, ⑯ dipole magnet, ⑰ trim coils and ⑱ solenoid magnet.

The ^{6}LiD used as deuteron target material in 2022 was produced in 2001 [7]. The material has been stored in a liquid nitrogen dewar for more than 20 years. The material was installed into a three-cell-container, which is 30-60-30 cm long with a diameter of 3 cm. The distance between adjacent cells is 5 cm. The upstream and downstream cells are polarized in the same direction and the central cell is polarized in the opposite direction to the other cells in order to cancel the false asymmetry due to time-dependent effects originating from acceptance variations.

Each cell requires about 100 mW in the beginning of the DNP operation. Considering the microwave attenuation, at least 2 W microwave power is required. Three microwave oscillators[1] produced by ELVA-1 are newly installed to adjust microwave power and frequency for each cell independently. The provided power by the new oscillator is up to 4 W. Remote control of them is enabled either via ethernet with SNMP or HTTP, or via USB using a provided PC Tool. The oscillators are integrated in the Detector Control System (DCS) via SNMP which provides a single user interface for control and monitoring.

Continuous wave NMR is used to determine the deuteron polarization [5, 8]. The upstream and downstream cells have 3 NMR coils and the central cell has 4 coils. The coils are mounted on

[1]Model : SYN-E/69.8/70.2/-2W and SYN-E/69/71/-2W

the outer surface of the cells.

3. Polarization measurement

The calibration of the deuteron polarization in ^{6}LiD is based on the TE NMR signal obtained at 0.99, 1.29 and 1.48 K with 2.5 T. The slope of the red line in Fig. 2 is the called enhancement factor. It took a few days for each points because of the long relaxation time. The statistical accuracy was about 1 % for each data point. The ^{6}Li nucleus can be regarded as being composed of a spinless α particle plus a proton and a neutron carrying the total spin-1 of the nucleus. Once the deuteron is polarized by DNP, ^{6}Li is also polarized at the same time and the polarization can be calculated by the EST concept [7].

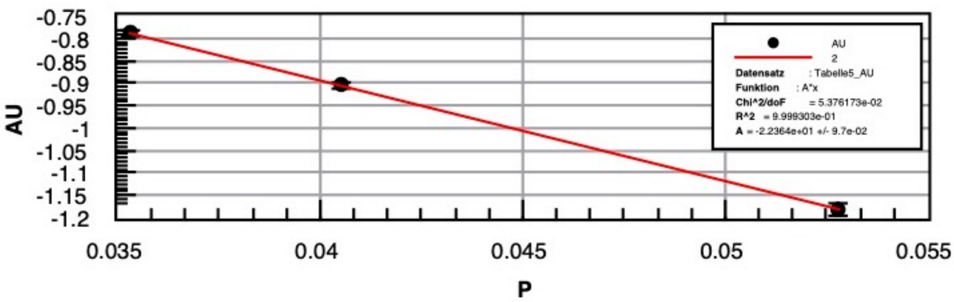

Figure 2: Plot of the area unit of the NMR signal of coil #5 (central cell) versus the polarization [%]. The polarizations can be calculated for the different temperatures and the magnetic field at 2.5 T. For example, the deuteron polarization at 2.5 T and 0.99 K is about 0.053 %.

The physics data-taking was proceeded following the similar procedure of the runs with the NH_3 target in 2010 and 2015 [5]. The time to reach the maximum polarization of the deuteron of ^{6}LiD is almost one week, which is longer than the proton of NH_3, which takes two days [5, 7]. The physics data-taking was proceeded in a series of periods of two weeks from June to November. Each data-taking period was divided into two sub-periods with opposite configuration of the polarization in the three target cells. The deuteron was polarized for about 50 h at 2.5 T in the longitudinal direction with respect to the beam to reach about 40% polarization at the beginning of the first sub-period (see Fig.3). Subsequently, the target was cooled down to below 100 mK to be operated in the frozen spin mode. After the first sub-period, the target spin was rotated to the 2.5 T longitudinal field to measure the polarization. In the second sub-period the deuteron was polarized in the opposite spin configuration.

During the polarization build-up the optimized microwave frequencies were changed. The microwave frequencies started from about 69.990 and 70.100 GHz for positive and negative polarizations with respect to 16.334 MHz for the NMR center frequency. About 50 MHz of the frequency had to be adjusted respectively until the DNP operation is finished. In addition microwave frequency modulation of $\pm$ 10 MHz amplitude with 1000 Hz was applied to shorten the polarization build-up time. The microwave power was also needed to be reduced from 3 to 0.1 W to optimize the polarization.

The relaxation times during the physics data-taking period were measured as about 3000 h (5000 h) for positive (negative) polarization.

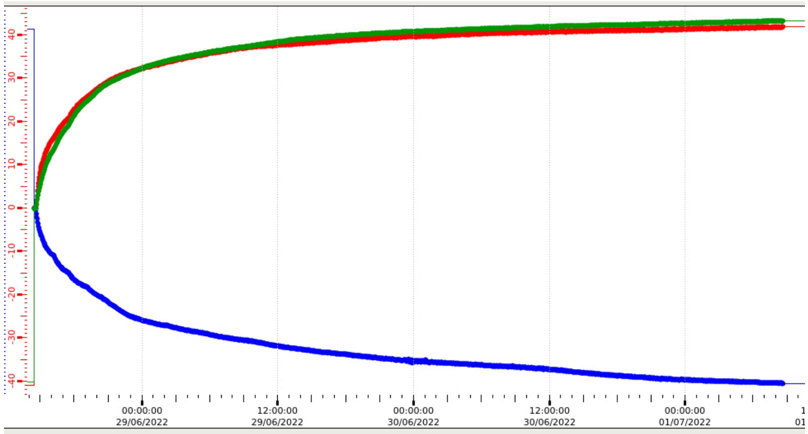

Figure 3: Example of the polarization build-up curve plotted by the COMPASS DCS. The red (green) line shows the positive polarization of the upstream (downstream) cell. The blue line shows the negative polarization of the central cell.

4. Conclusion

The upgraded COMPASS polarized target system was applied for the SIDIS run in 2022. We successfully polarized the deuteron target which was sufficient to collect physics data with respect to the polarization of 40 % and five days for one sub-period with the newly installed microwave system.

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