On the large COMPASS polarized deuteron target

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The spin structure of the nucleons is investigated in deep inelastic scattering of a polarized muon beam and a polarized nucleon target in the COMPASS experiment at CERN since 2001. To achieve high luminosities a large solid polarized target is used. The COMPASS polarized target consists of a high cooling power ^{3}He/^{4}He dilution refrigerator capable to maintain working temperature of the target material at about 50 mK, a superconducting solenoid and dipole magnet system for longitudinal and transversal magnetic field on the target material, respectively, target cells containing polarizable material, microwave cavities and high power microwave radiation systems for dynamic nuclear polarization and the nuclear magnetic resonance system for nuclear spin polarization measurements. During 2001–2004 experiments superconducting magnet system with opening angle ±69 mrad, polarized target holder with two target cells and corresponding microwave and NMR systems have been used. For the data taking from 2006 on an important upgrade of COMPASS polarized target has been done. In a new target system the new large acceptance superconducting magnet with opening angle ±180 mrad and three cells target holder with corresponding microwave and NMR systems have been implemented. The spin reversal by magnetic field rotation to decrease possible systematic error is incorporated. New three cells target holder configuration leads to a further reduction – by an order of magnitude – of possible instrumental false asymmetries. The new large acceptance COMPASS polarized target system with ^{6}LiD target material for deuteron polarization was successfully used in the COMPASS 2006 run. Preliminary figures of the maximum average longitudinal deuterium polarizations in three target cells obtained at the begining of the COMPASS 2006 run were $+54\,\%/-52\,\%/+56\,\%$, respectively. In the experiments with polarized proton target the irradiated NH_3 material is planned to be used.

Key words: COMPASS; Polarized target

1 Introduction

One of the aims of the COMPASS fixed target experiment at CERN [1–5] is to study in detail how nucleons and hadrons are made up from quarks and gluons. In particular, the spin structure of the nucleons is investigated by studying spin dependent processes of deep inelastic scattering (DIS) of longitudinally polarized muon beams and longitudinally and transversally polarized proton and deuteron targets — the COMPASS muon programme. The gluon contribution $\Delta G/G$ to nucleon spin, spin dependent structure functions g1, flavor decomposition of spin distribution functions, transverse spin physics as well as Λ - hyperon spin physics are being investigated. To perform such measurements a new state-of-the-art COMPASS spectrometer including the largest ever used polarized solid state target system [5-7] was built at CERN.

In the COMPASS muon programme the cross section asymmetries $A_{\rm phys} = \Delta\sigma/2\bar{\sigma}$ are being measured, where $\Delta\sigma$ is the difference between cross sections of a given process for two different beam-target spin configurations and $2\bar{\sigma}$ are spin averaged cross sections. In the experiment the cross section asymmetries are obtained from the measurements of corresponding counting rate asymmetries $A_{\rm exp}$. For longitudinally polarized beam and longitudinally polarized target

$$A_{\rm exp} = \left(N^{\uparrow\uparrow} - N^{\uparrow\downarrow}\right) / \left(N^{\uparrow\uparrow} + N^{\uparrow\downarrow}\right) = P_{\rm b} \cdot P_{\rm t} \cdot f \cdot A_{\rm phys}\,, \tag{1}$$

where $A_{\rm phys}$ is the cross-section asymmetry that would be directly measured for a pure target material and the target and beam 100 % polarized. $N^{\uparrow\uparrow}$ is the counting rate for parallel and $N^{\uparrow\downarrow}$ for antiparallel spin orientations of the beam and the target. $\rm P_b$ is the beam polarization and $\rm P_t$ is the target polarization. The dilution factor f is the ratio of the polarizable nucleons to the total amount of nucleons in the target material. Expression similar to Eq. (1) can be written when transversally polarized target is used.

In order to obtain high statistical accuracy maximizing luminosity together with large acceptance are important goals of the spectrometer design. With the present muon beam intensity only a polarized solid-state target with a high fraction of polarizable nucleons can provide the required luminosity. The measurements of quark polarizations both longitudinal and transverse require a large range in momentum transfer and thus the large muon scattering angle to be covered. The final layout of COMPASS spectrometer covers an opening angle of ± 180 mrad with a luminosity of almost $5 \cdot 10^{32}\,\rm cm^{-2}\,s^{-1}$. Apart from the luminosity, the beam and the target polarizations and the dilution factor have to be taken into account to estimate the statistical accuracy of the measured double-spin cross-section asymmetries. For a given beam polarization $\rm P_b$ the quantity $\rm P_t \cdot \mathit{f}$ which depends on target material must be maximized.

The longitudinally polarized positive muon beam with the beam momentum 160 GeV/c, longitudinal polarization -76 % and the muon flux $1.2 \times 10^{7}\,\rm s^{-1}$ [2×10^{8} /spill (4.8 s/16.2 s)] is used in COMPASS muon programme experiments. To reach the luminosity of high precision experiment ($\approx 5 \cdot 10^{32}\,\rm cm^{-2}\,s^{-1}$) a target thickness of about $60\,\rm g/cm^{2}$ is needed. A solid state polarized target is thus required. The

COMPASS solid state polarized target based on the dynamical nuclear polarization method (DNP) has been designed to meet these requirements. It incorporates several elements previously used in polarized target of the CERN SMC experiment [8].

COMPASS polarized target consists of a high power ^{3}He/^{4}He dilution refrigerator, a superconducting magnet system, target cells containing polarizable material, microwave cavities and high power microwave radiation systems for DNP and nuclear magnetic resonance (NMR) system for nuclear spin polarization measurements. In the COMPASS muon programme experiments during 2001–2004 former SMC superconducting magnet system with opening angle ±69 mrad, polarized target holder with two target cells and corresponding microwave and NMR systems have been used. Since 2006 an important upgrade of COMPASS polarized target has been realized. In the new target system a large acceptance superconducting magnet with opening angle ±180 mrad and three target cells with corresponding microwave and NMR systems have been implemented. This new large acceptance COMPASS polarized target system was used successfully in the COMPASS 2006 run with ^{6}LiD deuteron polarized target.

2 Polarized target systems

The twin cells COMPASS polarized target used in the experiments during 2001–2004 is shown in Fig. 1. The triple cells polarized target used in the experiments since 2006 is shown in Fig. 2.

2.1 Solid state polarized proton and deuteron targets

While electron spins can be aligned in a magnetic field of a few T and give rise to a large polarization at thermal equilibrium for a low enough temperatures, only negligible nuclear spin polarization can be reached under the same field-temperature conditions. The use of the hyperfine fields acting on nuclei in solids at low temperatures is one of the solutions how to transfer the electron spin polarization to nuclear spins. Solid state target polarization relies on dynamic nuclear polarization when the proper polarization states are selected by external microwave field. This process requires a material containing some amount of paramagnetic centers in the target material, a temperature below 1 K and a strong and homogeneous magnetic field. Taking into account the degree of polarization which can be achieved (polarization P_t in Eq. (1)), the fraction of polarizable nuclei (dilution factor f in Eq. (1)) and also some additional characteristics as the density of the material, the packing factor of the target material in the target cell, and the spin relaxation time of the spin polarized system, the deuterated lithium (^{6}LiD) and the irradiated ammonia (NH_3) have been chosen as the target materials for polarized deuterium and polarized proton targets, respectively, for COMPASS muon programme experiments [6, 7].

In deuterated lithium (^{6}LiD) a degree of polarization higher than 40 % can be reached. This material has a very favorable composition [7, 10]. Since ^{6}Li can be considered to a good approximation as a deuteron (spin 1) and ^{4}He nucleus (spin 0) the fraction of polarizable material (deuterons) f is of the order of 0.5. The irradiated ammonia NH_3 which is planned to be used as a polarized proton target in COMPASS experiments has less favorable dilution factor f, about 0.15, but can be polarized to the degree higher than 80 %.

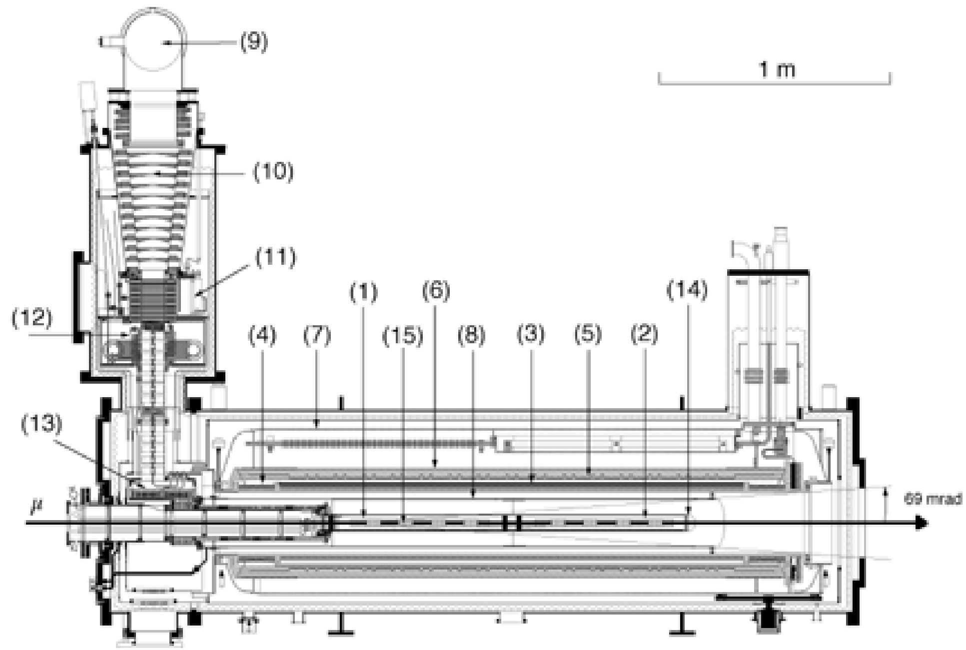

Fig. 1. Side view of COMPASS polarized target apparatus with two cells polarized target holder and superconducting magnet system with the opening angle ±69 mrad from the upstream end of the target cell. (1) upstream target cell, (2) downstream target cell, (3) solenoid coil, (4) compensation coils, (5) 16 correction coils, (6) dipole coil, (7) liquid helium vessel for the magnet, (8) microwave cavity, (9) ^{3}He pumping port, (10) ^{3}He precooler, (11) separator, (12) evaporator, (13) still, (14) mixing chamber and (15) NMR coils.

2.2 The dilution refrigerator

A powerful dilution ^{3}He/^{4}He refrigerator designed for CERN SMC experiment [11, 12] is used in COMPASS to cool the large amount of polarized target material down to the temperature of about 50 mK and to keep this temperature as long as necessary for the experiment. The large cooling power of the refrigerator can cope with the high amount of microwave power during the DNP process where more than 350 mW are used for polarization build up at the temperatures 200–300 mK. When the desired polarization is achieved at the temperatures 200–300 mK the microwave systm is switched off. The refrigerator can decrease and maintain the temperature of the target at about 50 mK in the spin frozen mode to slow down the spin relaxation time.

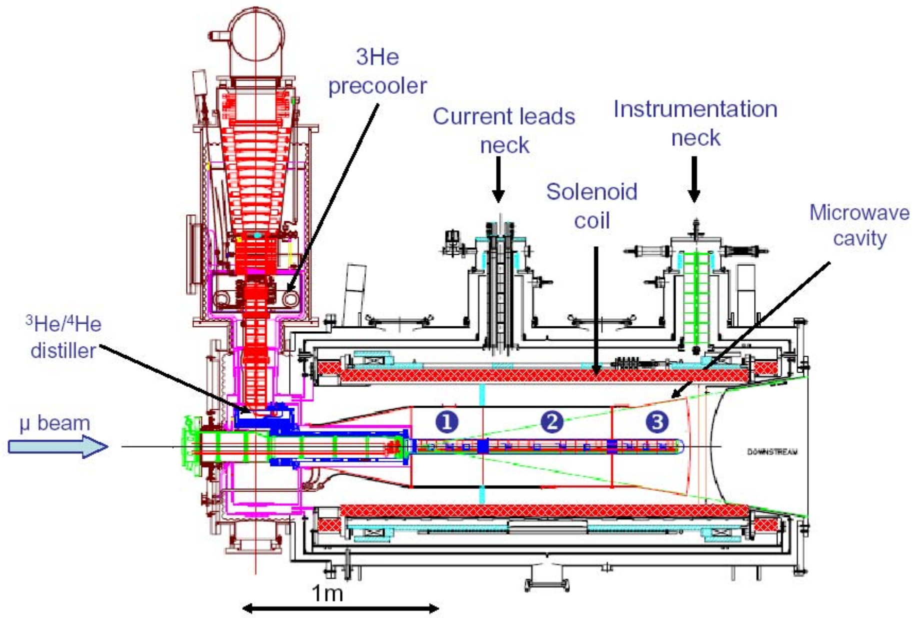

Fig. 2. Side view of new COMPASS polarized target apparatus with three cells polarized target holder and superconducting magnet system with the opening angle ±180 mrad from the upstream end of the target cell. (1) upstream target cell 300 mm, (2) central target cell 600 mm, (3) downstream target cell 300 mm.

2.3 Twin and triple cells target

At COMPASS experiments the spin asymmetries were measured using the target divided into two (experiments 2001–2004) and three (experiments from 2006 on) cells, which are exposed to the same beam flux but polarized in different directions. This helps to reduce sufficiently systematic errors caused by the different spectrometer acceptance for different target cells and time variation of the spectrometer efficiency and beam intensity.

The twin cells target has two target cells, the upstream and downstream cell. Each of the cells has a diameter of 30 mm and a length of 600 mm and cells are separated by 100 mm gap. The diameter was chosen to be consistent with the beam size of $\approx 3\,\sigma$. The target material in both cells can be polarized in the opposite directions to each other. Therefore the data taking can be done with opposite directions of the target polarization in particular cells at the same time. The variation in spectrometer acceptance for reaction products originating from the two identical cells is the source of false asymmetry which can be removed to a large extent by reversing regularly the cells polarization. In the COMPASS experiments this is usually done every 8 hours.

A new COMPASS target system functioning from 2006 which has been implemented together with the new target magnet has three target cells. In this configuration the central cell is twice as long as the two external cells and its target material is polarized in opposite direction in comparison with external cells. Each cell has a diameter 30 mm. The length of the central cell is 600 mm and the length of each of the two externall cells, upstream and downstream cell, is 300 mm. The cells are separated by 50 mm gap. The simulations show that such a configuration leads to a further reduction by an order of magnitude of a false asymmetry. The possibility to reverse regularly the cells polarization during the experiments is also maintained here.

2.4 Superconducting magnets

The superconducting magnet system used during 2001–2004 (see Fig. 1) consists of the solenoid and the dipole magnets and has the opening angle ±69 mrad. The solenoid produces a 2.5 T magnetic field along the beam direction with an axial homogeneity better than 20 ppm in a volume 1500 mm long and 50 mm in diameter. Sixteen correction coils are used to trim the magnetic field. This magnetic field is used for longitudinal target polarization and in particular to investigate the longitudinal target cross section asymmetries. The transverse holding field of 0.5 T is produced by the dipole saddle shaped coil and deviates from its nominal value inside the target volume at most by 10 %. This transverse magnetic field is used for transversal target polarization and in particular to investigate the transversal target cross section asymmetries. Both magnets have their own control systems allowing to set the solenoid and the dipole currents remotely and to perform the rotation of resulting field on the target automatically. In the experiment this is used for the change of the target spin orientation, namely for the spin reversal. Adiabatic spin reversal by rotating the magnetic field on the target material can be achieved in about 33 min.

The original design of the COMPASS spectrometer [1] included a large aperture superconducting solenoid and dipole magnets providing the magnetic field needed to establish and to maintain the polarization of the target. The solenoid has been designed to ensure ±180 mrad acceptance for the most upstream edge of the polarized target. The new large acceptance magnet system consisting of 2.5 solenoid and 0.62 T dipole magnets has been built and is now operational. The measured field uniformity of the superconducting solenoid about 3.5×10^{-5} is excellent. New automatic cryogenic control system of the magnet and the user magnet slow control have been implemented. Adiabatic spin reversal by rotating the magnetic field can be accomplished.

2.5 Microwave system

The ^{6}LiD target material was used as the deuterium polarized target in COMPASS experiments both during 2001–2004 and in 2006.

In order to polarize two target cells material in opposite directions at the same time during experiments 2001–2004 two independent microwave systems were used.

The DNP is achieved by irradiating the paramagnetic centers in the target material with microwaves at frequencies of 70.2–70.3 GHz. The densities of paramagnetic centers is of the order 10^{-4}–10^{-3} per nucleus. An additional low frequency modulation of microwave frequency of about 10 MHz helps to enhance the polarization. The polarization process produces the heat warming the mixing chamber of the refrigerator to about 200–300 mK. A deuteron polarization P_t higher than 40 % is reached within one day in the 2.5 T magnetic field with the ^{3}He flow of 80–120 mol/s in the ^{3}He/^{4}He dilution cryostat. The maximum polarization difference between the oppostitely polarized upstream and down streams cells $|P_t$ (upstream)—P_t (downsream)$|$ higher than 100 % is reached in five days. During the data taking in longitudinal mode the solenoid-dipole field direction is rotated as a rule three times a day to invert the nuclear spin magnetization direction. When the solenoid field becomes close to zero the transverse dipole field of 0.5 T is reached to preserve the polarization. In addition the sign of the polarization in target cells is inverted two or three times per year by rebuilding the polarization by microwave frequencies. This process takes several days. During the data taking in transverse mode the nuclear spin direction is kept by the dipole field of 0.42 T and the transverse polarization can be only reversed by retuning the microwave frequencies. The polarization is measured again in the longitudinal 2.5 T field after the end of the transverse data taking. The relaxation rate for the polarization in frozen spin mode with the temperature below 90 mK is about 0.7 % per day in the 0.42 T magnetic field [13].

The new microwave cavity was constructed for the three cells target system to match the large acceptance of the new solenoid and to provide the proper polarizing environment and enough resonant microwave excitation power for the new three segments target. The design of the new microwave cavity was optimized in order to achieve the highest possible polarization. The precautions were taken to have new cavity microwave leak tight between cells and to achieve the best possible spatial microwave uniformity in the target material. In the three cells target the target materials in the central cell on one side and in two externall cells on the other side are polarized in opposite directions. This system has been successfully used during the experiments in 2006 with ^{6}LiD target.

2.6 Nuclear magnetic resonance system

The nuclear spin polarization is measured with a continuous-wave nuclear magnetic resonance (NMR) system [6, 7]. Several NMR coils are distributed along the target cells and tuned to the deuteron Larmor frequency at 2.506 T. They are driven simultaneously by a radiofrequency synthetizer with the frequency sweep of ±50 kHz around the deuteron Larmor frequency 16.38 MHz. Although the maximum of 10 NMR signals in the system can be detected at the same time 4 NMR coils have been mounted inside each target cell of two cells system to probe different parts of the cells in the 2002, 2003 and 2004 runs. In addition to the 8 coils one more coil has been mounted in the downstream cell. In the three cells target arrangement used in the 2006 run 4 NMR coils have been mounted inside central cell and 3 NMR coils have been mounted inside each external target cell to probe different parts of the cells.

The mixing chamber is filled with ^{4}He to perform the thermal equilibrium calibration of the polarization [14, 15] in a 2.5 T solenoid field at the temperature in the region 0.9–1.5 K. The spin magnetization of ^{6}LiD reaches good thermal equilibrium at this temperature in about 15 h [16]. The polarization of the target material can be calculated from the helium temperature measured with ^{3}He vapor pressure [17, 18]. The area of the measured NMR signal is used to determine the polarization during DNP when the spin system is not anymore in thermal equilibrium with helium in the mixing chamber. The ^{6}LiD has a single NMR line about 3 kHz wide [19]. After the thermal equilibrium calibration procedure the ^{4}He is removed and the dilution cryostat filled with ^{3}He/^{4}He mixture again.

3 Polarization results

The measurement of the polarization of the target was performed according to the procedure described in Ref. [7]. Results of the deuteron polarization measurements during data taking with ^{6}LiD target material, two cells polarized target system and the superconducting magnet with the opening angle ±69 mrad in 2004 run are shown in Fig. 3.

Preliminary figures of the maximum average deuterium polarization at the begining of the COMPASS 2006 run with ^{6}LiD target material and the new large acceptance polarized target system with the opening angle ±180 mrad were in upstream, central and downstream target cells $+54\,\%/-52\,\%/+56\,\%$, respectively. More detailed analysis of the polarization results from the 2006 run will be done at the end of the run.

When the polarized target has been prepared for the 2006 experiments the deuteron polarization of about 40 % was achieved within one day and about 45 % within two days of DNP in all three cells of the new large acceptance COMPASS polarized target.

Finally the deuteron polarization higher than 50 % was achieved within several days of DNP. Comparison of the preliminary deuteron polarization results in the new target system for the 2006 run with those of the 2004 run indicates that the maximum polarization obtained in the new system is slightly higher and the polarization build up is slightly faster than those figures achieved in 2004 run. This is probably due to the optimization of different parts of the new system.

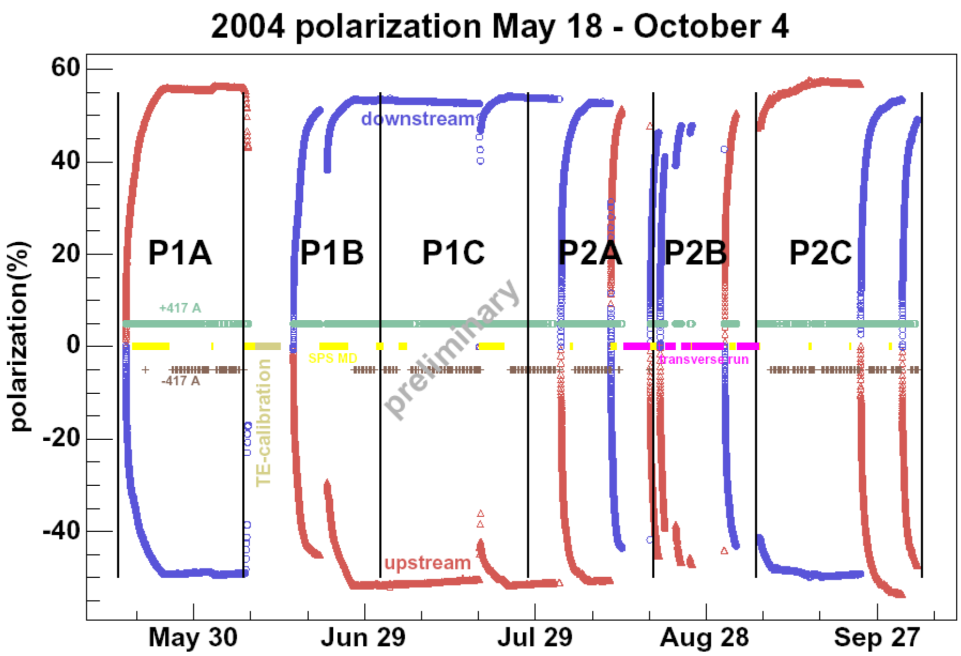

Fig. 3. Deuteron polarization in the upstream and downstream target cells during data taking in 2004 run with ^{6}LiD target material, two cells polarized target holder and the superconducting magnet system with the opening angle ±69 mrad.

4 Summary and outlook

The large COMPASS polarized target has been successfully running since 2001 in a very reliable way. In the COMPASS muon programme experiments during 2001–2004 superconducting magnet system with opening angle ±69 mrad, polarized target holder with two target cells and corresponding microwave and NMR systems have been used.

For the data taking from 2006 on an important upgrade of the COMPASS polarized target has been realized. In a new target system the new large acceptance superconducting magnet with opening angle ±180 mrad and three target cells holder with corresponding new microwave cavity and NMR systems have been implemented. New magnet has an excellent homogeneity and works reliably. New microwave cavity has optimized design to achieve the highest possible polarization of the target. In the new three cells target configuration design where the central cell is twice as long as the two external cells the target material in central cell is polarized in opposite direction than in the external cells. The simulations show that such an arrangement leads to the reduction by an order of magnitude of false asymmetries caused by the variation of the spectrometer acceptance for the reaction products originating in the different part of the polarized target. The possibility to reverse regularly the cells polarization during the experiments reduces further possible false asymmetries.

New large acceptance COMPASS polarized target system has been used successfully in the COMPASS 2006 run with ^{6}LiD deuteron polarized target. Preliminary figures of the maximum average deuterium polarizations in three target cells obtained in the COMPASS 2006 run were $+54\,\%/-52\,\%/+56\,\%$, respectively.

Further improvements of the COMPASS polarized target system will include the optimization of the procedure for proton target polarization build up when the NH_3 material is used for the experiments with polarized proton target in both longitudinal and transverse mode.

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