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Recent activities of the Bonn polarized target group

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The next generation of double polarization experiments at the Bonn accelerator facility ELSA with the Crystal Barrel Detector and the Bonn Frozen Spin Target will be performed with an elliptically polarized photon beam. Elliptically polarized photons allow the simultaneous measurement of different polarization observables in one target-detector setup. In order to exploit all the possibilities of this approach, the Bonn Polarized Target Group has developed a new concept for an internal holding coil for the frozen spin target, a so-called combined holding coil. This magnet design allows a variable field orientation between 0° and 90° and thus an individual polarization orientation between longitudinal and transverse target polarization during data acquisition in the scattering experiment. In the following we report on the current activities of the Bonn Polarized Target Group on the topic of internal superconducting holding magnets.

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1. Introduction

For more than 50 years, single and double polarization experiments with a polarized solid target have been performed at the accelerator facility of the Physics Institute in Bonn. The starting point for the development of a polarized target for the 2.5 GeV synchrotron was the more than complex recoil polarization experiments in pion photoproduction at that time, which were subject to large statistical and systematic errors. The target asymmetry, on the other hand, is clearly and simply defined as

$$T = \frac{1}{f} \cdot \frac{1}{P_t} \cdot \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}.$$

It results from the difference between the counting rates in the up and down directions divided by their sum, weighted by the dilution factor and the polarization of the target nucleons. These are two well-defined quantities: the dilution factor is the number of polarizable nucleons relative to the total number of nucleons in the target, and the polarization of the target nucleons is measured by NMR. Both parameters can be accurately determined with only a small systematic error. With the development of the porpyrexide-doped alcohol target samples at CERN [2], also in 1968, the decision to establish a polarized target working group at the Physics Institute of the University of Bonn was not difficult. Since then, the goal of the working group has been the continuous development and improvement of the polarized target and its components for single and double polarization experiments at the Bonn accelerator facility ELSA and for external experiments at CERN and MAMI. In all developments the focus has always been on optimizing and maximizing the figure of merit

$$FoM = n_T \cdot f^2 \cdot P_t^2$$

and the luminosity

$$\mathcal{L} = I \cdot n_T$$

of the target and the combination of target and detector system for the intended scattering experiments. Finally, to enable new and innovative polarization experiments. In the course of the work, significant contributions were made to the development of the ammonia target materials NH_3 [3] and ND_3 [4] (production, investigation and first use of ND_3 in scattering experiments) as well as to the systematic investigation and preparation of ^{6}LiD [5] as a target material. In addition, the principle of the frozen spin target was extended in such a way that polarization experiments with detector systems of large angular acceptance were already possible in the 1990s with the development and first use of the technology of "internal holding coils" [6]. The principle of the horizontal frozen spin target with internal holding coil developed by us [7] was used for the first time in 1998 for the measurement of the GDH sum rule at MAMI [8] and ELSA [9]. Due to the successful and convincing concept, the principle was transferred by other target groups from Mainz [10], Jlab [11] and JINR Dubna [12] to their own target systems.

The concept of internal coils has been continuously developed by us in recent years, and I would like to report here on the current activities of the working group in this area.

PoS(SPIN2023)221

2. Frozen Spin Principle

The principle of the frozen spin target is based on the fact that both the electron and the nucleon (proton) relaxation times T1 in the solid-state target material are a very strong function of the temperature and the magnetic field. T1 characterizes the polarization decay after switching off the DNP mechanism (switching off the microwaves). Typical T1 values for protons (but also deuterons) are minutes at a temperature of 1K and days below 100 mK. The principle of operation of the frozen spin target is that the target material is dynamically polarized in a high magnetic field, typically 2.5 T, and in a temperature range of about 0.2 to 0.3 K. Once the target material is optimally polarized, the microwaves are turned off and the temperature of the refrigerator is lowered to below 60 mK. Due to the long relaxation time T1, the polarization of the nucleons is frozen (frozen spin mode). In the next step, the magnetic field in the target region can be reduced to a value at which the polarization decay is acceptable for the scattering experiment (holding field). It should be noted that T1 is also a characteristic value of the target material used. This means that the relaxation time can vary considerably under otherwise identical conditions for temperature and magnetic field. For example, at T = 70 mK, B = 0.4 T, a T1 of about 200 h is obtained for D-butanol and a T1 of about 1500 h is obtained for ^{6}LiD [13]. This holding field can be generated by a variety of external or internal magnets. They are optimally adapted to the requirements of the scattering experiment and the detector used. On the other hand, the need for low temperatures for long relaxation times is one of the inherent limitations of the frozen spin process. It has to be considered that the maximum acceptable beam intensity is limited by the Kapitza resistance of the target material. At target temperatures below 80 mK, heat dissipation and heat transfer rates are very low. The maximum intensity that can be handled with satisfactory target performance (relaxation times) is on the order of 10^8 particles/sec. The boundary condition of low beam intensity makes the frozen spin target the ideal instrument for polarization experiments at tagged photon beams and thus for photoproduction experiments at the Bonn accelerator facility ELSA. Nevertheless, and this is a characteristic of the frozen-spin principle, one always needs a sophisticated rail system to move the polarization magnet and/or detector system into the polarization mode of the target or into the data taking mode (frozen-spin mode) of the scattering experiment.

Since the early 1990s, the Bonn Polarized Target Group has focused on the further development of target technologies with special emphasis on the frozen spin target and in particular on the development of thin superconducting coils as internal holding or polarizing magnets implemented in the dilution refrigerators of the frozen spin target.

3. Internal ‘holding magnets’

The principle of internal magnets (internal holding coils) is relatively simple: usually the low temperature of the innermost heat shield of the dilution refrigerator is used as a coil mandrel on which a superconducting wire is wound to form a magnet in the target area. Since the magnetic field required to maintain polarization in the frozen spin mode is on the order of 0.5 Tesla, thin superconducting wires can be used. Depending on the number of turns, low double-digit currents are sufficient to generate the field. The field direction and thus the polarization direction is determined to a first approximation by the geometry of the dilution refrigerator. Since the coil is

PoS(SPIN2023)221

always wound on the cylindrical geometry of the heat shield, the simplest coil shape is a solenoid [6] [14].

3.1 Internal 'longitudinal holding coil'

In a horizontal dilution cryostat, whose axis of symmetry coincides with the beam axis of the scattering experiment, this solenoid generates a longitudinal magnetic field in the target area, which in turn specifies a polarization direction in the beam direction (longitudinal polarization). In this application, the holding coil must be kept as thin as possible to allow the secondary particles generated by the scattering process to penetrate the coil while the beam itself remains unaffected by the magnet. Depending on the thickness of the coil mandrel (heat shield) and the superconducting wire used, a coil thickness of less than one millimeter is possible. Another advantage for the scattering experiment is the homogeneous mass distribution of the holding coil for the detection of the reaction products. Since the internal coils are relatively small, compact magnets, the magnetic field drops to a few gausses over a few centimeters. The stray field therefore has virtually no effect on detector components positioned close to the cryostat. The concept of the internal holding coils, especially the solenoids, allows the polarized target to be used in detector arrangements with large solid angular acceptance [7].

3.2 Internal 'transverse holding coil'

If transverse polarization is required in a horizontal dilution cryostat, as described above, the solenoid must be replaced by two dipoles arranged in the form of "racetrack coils" (cosine theta magnets), which generate a transverse magnetic field. Unlike the solenoid, a racetrack coil requires twice as many turns to produce the same field. The shape of the race-track coils and the higher number of turns automatically lead to a much more inhomogeneous mass distribution and therefore to a much higher radiation length for the reaction products produced in the scattering process. Nevertheless, even with these coils, a maximum total thickness of about 2 mm can be achieved in the area of the dipoles. This is just thin enough to ensure a sufficient detection probability for the escaping particles.

The frozen spin target scheme with horizontal dilution cryostat and internal longitudinal (solenoid) or transverse (race-track) holding field has been used very successfully in various polarization experiments around the world.

Less frequently, frozen spin targets with vertical dilution cryostats and internal holding coils have been used in scattering experiments. The solid angle acceptance of these systems is clearly limited and ϕ-symmetry is not given. In the two polarization experiments performed, these limitations did not play a role, and in these systems the holding field was generated by a Helmholtz-type internal holding coil. Two short solenoids were wound on the heat shield in close proximity. Since the holding field again follows the axis of symmetry of the vertical cryostat, a magnetic field perpendicular to the production plane of the scattering process was obtained and thus a transverse polarization for measuring the target asymmetry [15] [16] [17].

PoS(SPIN2023)221

3.3 Internal 'combined holding coil'

However, regardless of whether a frozen spin target with a horizontal or vertical dilution cryostat is used for a double polarization experiment, a change of the polarization direction, e.g. from transverse to longitudinal polarization, always requires a change of the internal holding coil. This change usually requires a modification of the cryostat used: the cryostat has to be warmed up, opened and the magnet system has to be replaced. After that the cryostat can be cooled down and the data acquisition can be continued with the new polarization direction. This change takes at least 1 week and requires a relatively large technical effort. In addition, the interruption of the data acquisition due to the conversion results in a new data set with all necessary calibrations for the target and the detector at the start of the new measurement. How much easier would it be if the polarization direction in the target material could simply be rotated during data acquisition?

This idea could be ideally combined with the intention to measure double polarization observables with elliptically polarized photons in the future [18]. Since an elliptically polarized phonon beam results from photons with linear rather than circular components, it is possible to simultaneously measure polarization observables associated with these polarization states. Since these polarization observables require different field orientations, it would be useful to change the field/polarization direction of the target nucleons during the scattering experiment.

To that end, a combined holding coil is being developed which pairs longitudinal and transverse coil functionalities within a single configuration. The most straightforward arrangement for such a pairing is to simply concentrically nest the solenoid and racetrack geometries (Figure 1). The primary concern for this configuration is maintaining sufficient field strength without excessively increasing the radiation length material budget. The current single-purpose coils available for use at ELSA (which serve as an initial basis for this design) each have four layers of windings. An ideal combined coil would achieve the dual-purpose without greatly exceeding that number across both coils.

The initial step in attaining that is generating an optimizable model. The basis coils were originally developed using finite element analysis which models blocks of current densities. For the purpose of fine optimization, though, we elected to model our coils computationally using MatLab. Using the Biot-Savart law

$$B(r) = \frac{\mu_0}{4\pi}\int_C \frac{Idl \times r'}{|r'|^3}$$

we calculate each individual winding. The element of interest in this equation is the current path l. The x and y components of l are trivially selected by their theta dependence ($R\cos(\theta)$) and $R\sin(\theta)$). The z component, however, defines the coil shape.

For a solenoid, the z component can either be modeled as a series of discrete circular loops ($z = z_0$) or as a continuous spiral

$$z = \theta\frac{D}{2\pi} + z_0.$$

Checking the result between the two techniques found them to be negligibly different within the target region. With this, we found we can reduce the solenoid by 2 layers while still (barely) meeting the minimum field requirement.

PoS(SPIN2023)221

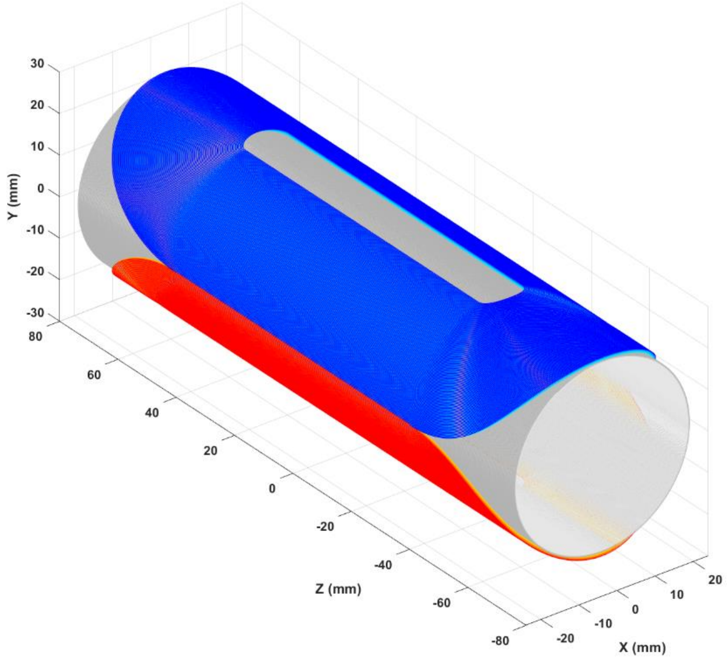

Figure 1: Combined holding coil configuration showing longitudinal solenoid coil (grey) and transverse racetrack coils (blue and red).

PoS(SPIN2023)221

The racetrack coil, however, presents a more interesting geometry. Ideally, it would be composed of straight lines (down the length of the mandrel) connected by semicircular connections (around the mandrel perimeter). However, the superconducting magnet wire has physical limitations in its bending radius which necessitates a gentler transition between straight sections and connecting arcs. The original transverse coil layers were wound flat then bent over the mandrel generating a smooth curve. We chose to emulate this by modeling the connecting arcs as ellipses wrapped around the polar axis

$$z = a\sqrt{1 - \left(\frac{\theta - k}{b}\right)^2} + h$$

(with appropriate handling of the various quadrants). The result of this parameterization was checked against a standard 3d modeler (Opera3D) and found commensurate. Additionally, like the solenoid, we also tested its sensitivity to single loops and continuous winding calculations.

Optimizing the racetrack geometry presents several options. Analyzing the central field contribution of each winding based on its angular position and layer number allows us to clearly understand the relationship between coil geometry and field strength (Figure 2). From there, decisions can be made regarding the relative importance of material budget, material uniformity, field uniformity, and absolute field strength. The current transverse coil traded maximum field strength and material uniformity for field uniformity and material budget. Choosing differently, we can reduce the layer number to 3 by extending the upper layers to match the angular coverage of the lowest one (increasing the material uniformity) and still reach the required field strength - albeit less uniformly.

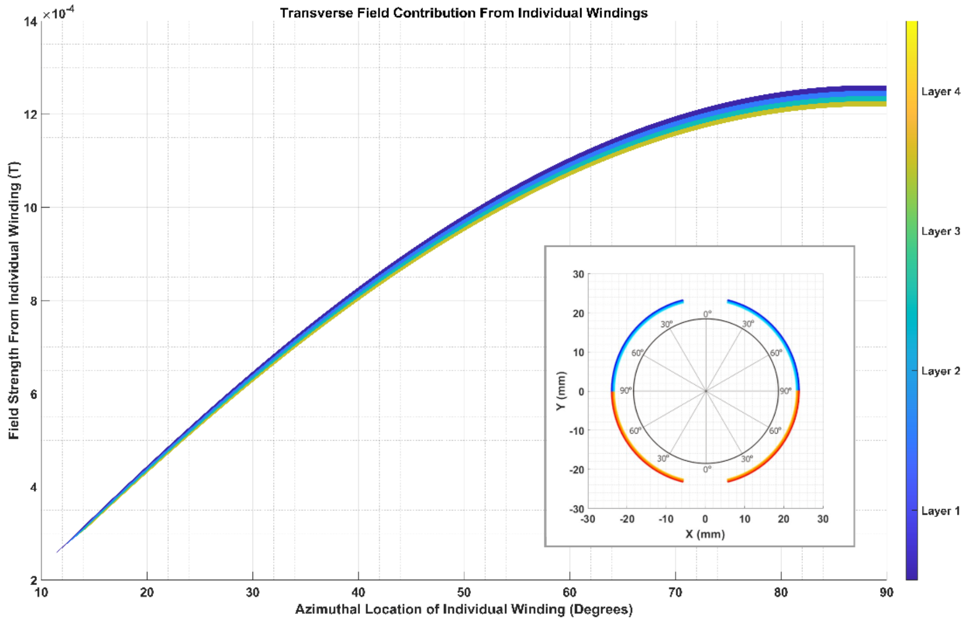

Figure 2: Contribution of each racetrack winding based on its position within the coil.

Altogether, we anticipate being able to produce a combined holding coil with only 1 additional layer compared to current coils. The next steps are to manufacture and test a prototype coil using the impressive winding facilities at the University of Bonn. Additionally, we can consider the opportunity of arbitrary angle polarization using this configuration. For this, however, the question of relative component uniformities becomes more relevant. Efforts are currently underway to generate a coil configuration which meets those requirements.

4. Internal 'polarizing magnets'

A disadvantage of the frozen spin target principle is the continuous polarization decrease during data taking despite the very low temperatures in the dilution cryostat. To improve the figure of merit for future polarization experiments, the thin internal holding coil of the horizontal frozen spin target should be replaced by a coil of the same geometry but with a stronger magnetic field. Ideally, the magnet should provide the field of the external polarization magnet, typically 2.5 Tesla. The advantages of this scheme of an internal polarization magnet are obvious: the target polarization can be kept at a high level by DNP even during data taking for the polarization observable measured. There is no more loss of time due to the otherwise usual post-polarization phases. We call this scheme '4π-continuously polarized target' [19].

However, the DNP process requires a high field homogeneity over the target volume, and since the magnetic field volume of the planned internal polarization magnet is of the same order of magnitude, appropriate correction windings have to be placed on the magnet. In addition to

PoS(SPIN2023)221

this necessary constraint, the overall thickness of the magnet should not exceed 2 mm to ensure particle detection of the reaction products. All this requires precise winding of thin superconducting wires on a thin-walled copper mandrel using wet winding techniques [20].
In the target laboratory of the Physics Institute of the University of Bonn, a small superconducting magnet with a nominal field of B_P = 2.5 T was successfully wound on the specially developed winding machine. The coil can be installed in the existing or future horizontal dilution cryostat. The coil was tested in a 1K ^{4}He evaporation refrigerator. We have demonstrated that both butanol and ^{6}LiD can be dynamically polarized [21]. The next step is to install the coil in the new dilution refrigerator and use it in the Crystal Barrel experiment at ELSA.

PoS(SPIN2023)221

5. Conclusion

For more than 50 years, the Bonn Polarized Target Group at the Physics Institute of the University of Bonn has been involved in the development and operation of polarized solid-state targets for and at European accelerator facilities. The focus has always been on improving and optimizing the sub-components of the polarized target in order to increase the luminosity or "figure of merit" of the scattering experiments involved. A major focus of the work in recent years has been the development of thin superconducting magnets, which are used as internal holding coils or polarizing magnets in the dilution cryostats of the frozen spin targets used. For the planned measurements with elliptically polarized photons at the Crystal Barrel Experiment at ELSA, we are pursuing the idea of a combined holding coil consisting of a solenoid and a race-track configuration. In this concept, both coils are mounted on a thin coil carrier. The combination of both coils and the individual energization of the magnets allows the experimenter to individually adjust the resulting field vector and thus the target polarization between 0° (longitudinal polarization) and 90° (transverse polarization). In combination with elliptically polarized photons, this allows the simultaneous measurement of completely different polarization observables in a single setup. Recent calculations and simulations show the feasibility of this approach. The next step will be to wind the coils and assemble the system. Finally, the system will be used in the dilution cryostat of the frozen spin target of the Crystal Barrel experiment.

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PoS(SPIN2023)221