# Design of internal superconducting holding magnet for the JLAB Hall-B frozen spin polarized target

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## Abstract

We present the results of our investigation of a series of internal holding magnets for longitudinal and transverse polarizations. These magnets will be placed inside a polarizing refrigerator designed for frozen spin targets. The studied magnets will provide the holding field in the range 0.3–0.5 T. The total thickness of the superconducting coils is of the order 0.5 mm. The frozen spin target is under construction for use in photo-nuclear experiments in concert with the JLAB Hall-B CLAS detector.
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## 1. Introduction

The JLAB Hall-B large acceptance spectrometer (CLAS) is an almost $4\pi$ detector [1] that is able to operate with both electron and tagged photon beams using a variety of targets. Considerable data have been collected using an electron beam and polarized targets [2–5]. The target [6] was longitudinally polarized using a pair of 5.0 T superconducting Helmholtz coils and was located 0.57 m upstream of the center of the CLAS detector. The on-axis bore of the magnet was 20.0 cm in diameter that provided a $\pm 55°$ open aperture for particles scattered into the forward cone. The target cell, a cylinder with 2.0 cm in diameter and 2.0 cm long, was immersed in a liquid He bath maintained at approximately 1.0 K by the $^4$He evaporation refrigerator described in Refs. [7,8]. The target material chosen was ammonia because of its high resistance to radiation damage [9,10].

Recently, three experiments using a polarized photon beam and polarized target had been approved and one letter of intent has been submitted [11–14]. The proposed projects will use both longitudinally and transversally polarized targets. Preliminary simulations have shown that the run conditions require the target to be a cylindrical cell 1.5 cm in diameter and 5.0 cm long. It should offer minimal obstruction of outgoing charged particles scattered at angles between $7°$ and $154°$, and be located at the geometrical center of the CLAS. The holding magnet should also produce minimal distortion of the trajectories of outgoing charged particles. After taking into

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account all of these requirements, a reasonable choice for a polarized target is to use the "Frozen Spin" mode which implies the separate use of both an "external" polarizing and an "internal" holding superconducting magnet. In this mode, the target material should be polarized outside the CLAS detector at $B = 5.0$ T and $T = 1.0$ K. After the maximal polarization is achieved, the cryostat is turned to the "holding" mode at $B = 0.5$ T and $T = 50$ mK and moved inside the CLAS detector. Since the new target will be used only in photonuclear experiments, in addition to ammonia, alcohols such as butanol or propandiol could also be used as a target material. At temperature $T = 50{-}60$ mK and holding field $B = 0.5$ T, the expected relaxation time for both alcohols and ammonia is about $t = 10$ days (200–300 h) [15–20].

Some equipment and instrumentation from the previous polarized target [6] will be used; however, we need a new dilution refrigerator, a polarizing magnet and holding magnets. The 5.0 T superconducting polarizing magnet has been ordered.[1] The design work on the $T = 50$ mK dilution refrigerator is underway and it will be built on site at Jefferson Lab.

The purpose of this work is to produce an optimal design of an "internal" superconducting holding magnet for longitudinally and transversally polarized targets.

## 2. Design and field map

The preliminary design of the dilution cryostat has the holding magnet wound on the inner radiation shield with a diameter $D = 4.0$ cm. Since the proposed projects require both longitudinal and transverse target polarization, we modeled both solenoid and dipole holding magnets. The internal holding system should be as "transparent" to outgoing particles as possible which implies less amount of conductor and, therefore, lower holding field. In contrast to that, the relaxation time of polarization is a strong function of the magnetic field and needs high fields to maintain polariza-

tion. Therefore we considered holding magnets with a central field $B = 0.3$, $0.5$, and $0.7$ T. To monitor the value of polarization during the experimental runs, we required a field homogeneity better than 1% over the target volume $D = 1.5$ cm and $L = 5.0$ cm. Table 1 summarizes all the models. To make our simulations to find out the optimal design of a holding magnet system, we used the Poisson/Superfish 2D package [21] and Opera-3D package [22]. To produce field lines perpendicular to the long dimension of the magnet, windings must be "racetrack"- or "saddle"-shaped. We started our studies with the simple "Racetrack" model that consists of a dipole with two flattened coils (see Table 1). With nine layers coil such a dipole can provide a central field $B = 0.7$ T with homogeneity 1% over the target volume. This model was also used to calculate a field map for the preliminary modeling of the start detector (scintillator paddles surrounding the target and providing timing information), and, to study the critical interaction between the fringe field of the holding system and the CLAS superconducting coils.

For better field performance we used "Constant Perimeter Ends curved and fitting cylinder" model for which we made an additional development. As a first step, we wrote a special program that optimized a layer configuration to fit to the "cosine" shape of current distribution (see Fig. 1). Such a design is well known to produce a perfectly uniform transverse field [23,24].

After the layer distribution had been optimized, we studied the dependence of a field homogeneity versus the dipole length (20, 24, 25, 30 cm) to find an optimal dipole length (see Fig. 2). As can be seen, it is possible to decrease a dipole length for both three- and four-layer dipoles down to $L = 25$ cm and still keep a field homogeneity in longitudinal direction better than 0.4% over a target length 5.0 cm. Decreasing the dipole length does not change the homogeneity in both $X$ and $Y$ transverse directions and it is still less than 0.5% over the target diameter $D = 1.5$ cm. In contrast to a dipole, the solenoid is less sensitive to a length variation. In our case, the solenoid with a diameter $D = 4.0$ cm and a length $L = 20.0$ cm could provide the required field parameters. Varying

Table 1
Models of holding magnet system

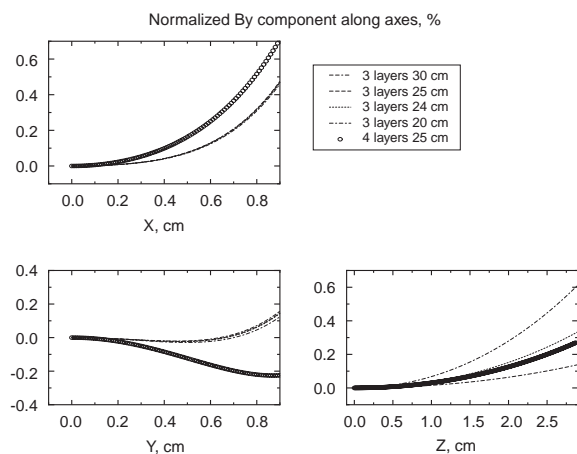| Parameters | Solenoid | | Dipole | | |
| --- | --- | --- | --- | --- | --- |
| | | | "Cosine shape" | | "Racetrack" |
| Expected central field, T | 0.3 | 0.5 | 0.3 | 0.5 | 0.7 |
| Number of layers | 2 | 3 | 3 | 4 | 9 |
| Current density, K Amp/cm$^2$ | 101.2 | 101.2 | 127.5 | 127.5 | 101.2 |
| Superconducting wire, $\varnothing$ mm | 0.112 | 0.112 | 0.14 | 0.14 | 0.112 |
| Length, cm | 20.0 | 20.0 | 25.0 | 25.0 | 30.0 |
| Diameter (or between coils), cm | 4.0 | 4.0 | 4.0 | 4.0 | 3.6 |
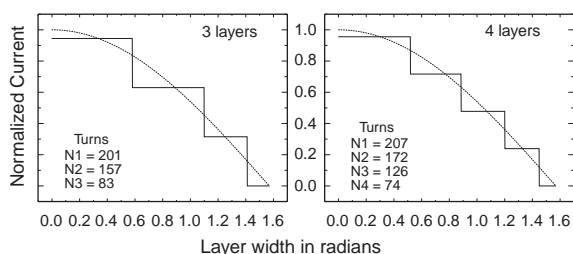


Fig. 1. Cosine shape dipoles.



Fig. 2. Field homogeneity vs. dipole length.

the number of layers, we could get a certain holding field value. Two- and three-layer solenoids provide quite similar field maps with a central field $B = 0.3$ and $0.4$ T respectively, and a homogeneity over the target cell better than 0.5%. For transverse polarization we considered three- and four-layer dipoles (see Table 1) which provided a

holding field of $B = 0.36$ and $0.48$ T, respectively, with a homogeneity better than 0.8% (see Fig. 3).

## 3. Forces acting on conductors

In terms of mechanical design, we have also calculated the forces acting on the conductors making up the magnets. For such calculations we have two main areas of interest, the "middles" and "ends" of the holding magnets. For the solenoid magnet we used the Poisson/Superfish 2D package. For the dipole magnet, the 2D package could only be used for the middle parts. For the end parts we had to use the Opera-3D package.

The two-layer solenoid was considered as one "thick" (0.24 mm) layer solenoid. In this approach both packages give only a radial component with a central field $B_c = 0.29$ T (Poisson) and $B_c = 0.3$ T (Opera) and a net force (integrated over all conductors) $F_{tot} = 782$ N (Poisson) and $F_{tot} = 828$ N (Opera). As can be seen, both Opera and Poisson calculations, give similar values. To calculate the force distribution, we considered an entire solenoid as a solenoid consisting of eight pieces. The force distribution has been calculated for both two- and three-layer solenoids and results are shown in Fig. 4. As expected, at the end of the solenoid there are tangential components of the forces acting on the conductors. Being cylindrically symmetric, such forces do not dramatically change the field homogeneity. In fact, closer to the end of solenoid, tangential components rapidly rise up which causes a motion of superconducting wires relative to each other resulting in quenching. In contrast to the solenoid, a force distribution
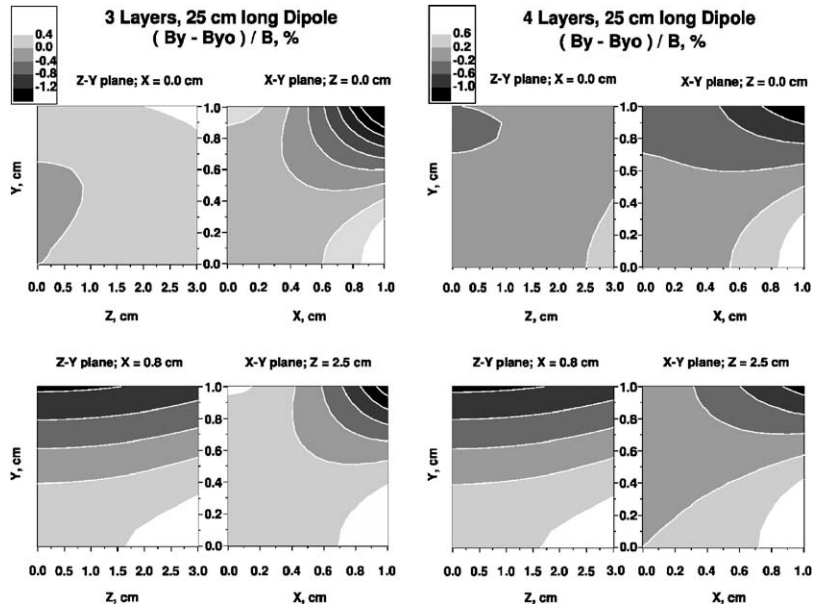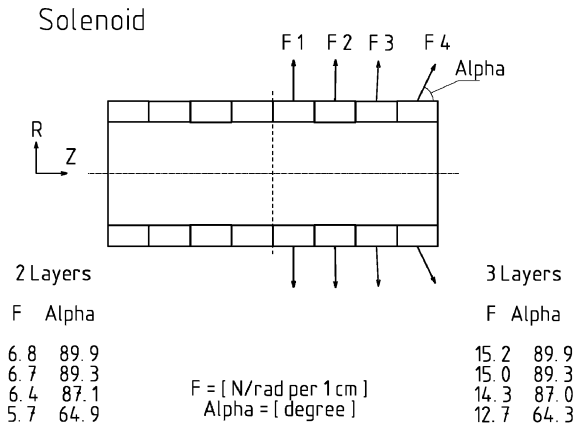
Fig. 3. Field homogeneity of dipoles.



Fig. 4. Solenoid force distribution.



Fig. 5. Dipole forces at the center.

over dipole coils is essentially asymmetric. On the middles (straight parts), forces are still two dimensional. As can be seen in Fig. 5, forces bend back $layer_1$ and $layer_2$ and squeeze $layer_3$ and $layer_4$. Table 2 summarizes all the results of calculations of the forces acting on the conductors of the dipoles. The presented values are forces integrated over a sector volume and applied to the "average" point of a sector as shown in Fig. 6. Since the field of a dipole is extremely sensitive to
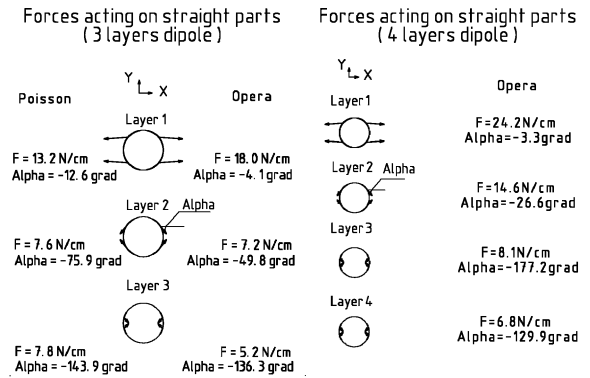
the layer configuration, forces acting on the middles will certainly result in a high distortion of the field homogeneity. In addition to that, forces acting on the end of a dipole will cause motion of the conductors resulting in distortion of the field homogeneity and quenching. For this reason, we intend to consider the monolithic holding magnet design (fully epoxy-impregnated coils) using pre-impregnated epoxy-fiberglass (or epoxy-carbonfiber) composite as described in Ref. [25].

Table 2
Forces acting on dipole conductors

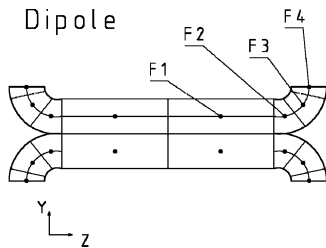| Dipole | Forces, N | | | |
|---|---|---|---|---|
| | Coil 1 | Coil 2 | Coil 3 | Coil 4 |
| Three layers | | | | |
| $|\vec{F}_1|$; $\vec{F}_1$ | 169.1; (168.7; −12.1; 0.0) | 67.7; (43.7; −51.7; 0.0) | 49.2; (−34.0; −35.6; 0.0) | — |
| $|\vec{F}_2|$; $\vec{F}_2$ | 16.7; (16.6; 0.7; 1.8) | 8.8; (8.1; −2.6; 1.7) | 6.2; (−4.8; −3.9; 0.6) | — |
| $|\vec{F}_3|$; $\vec{F}_3$ | 11.7; (10.3; 2.0; 5.2) | 6.8; (2.3; −4.3; 4.7) | 6.8; (−4.5; −4.9; 1.2) | — |
| $|\vec{F}_4|$; $\vec{F}_4$ | 8.8; (1.8; −2.1; 8.3) | 8.7; (−0.6; −6.6; 5.6) | 7.2; (−2.0; −6.8; 1.5) | — |
| Four layers | | | | |
| $|\vec{F}_1|$; $\vec{F}_1$ | 227.8; (227.4; −13.0; 0.0) | 136.8; (122.4; −61.2; 0.0) | 76.6; (−3.8; −76.5; 0.0) | 63.6; (−48.8; −40.8; 0.0) |
| $|\vec{F}_2|$; $\vec{F}_2$ | 21.9; (21.7; 0.9; 2.2) | 15.9; (15.7; −1.2; 2.2) | 6.9; (1.8; −6.4; 1.7) | 8.3; (−7.0; −4.4; 0.5) |
| $|\vec{F}_3|$; $\vec{F}_3$ | 16.9; (15.3; 3.7; 6.1) | 10.6; (7.5; −2.8; 6.9) | 8.7; (−1.0; −7.2; 4.8) | 8.7; (−6.3; −5.9; 1.0) |
| $|\vec{F}_4|$; $\vec{F}_4$ | 11.5; (3.3; 0.6; 11.0) | 10.0; (1.1; −4.4; 8.9) | 10.4; (−1.2; −8.5; 5.9) | 8.9; (−2.8; −8.4; 1.0) |



Fig. 6. Dipole forces at the ends.

## 4. Conclusions

We have found an optimal design of the "internal" superconducting holding magnet for both longitudinally (solenoid) and transversally (dipole) polarized targets. For each model, a field map and forces acting on the conductors have been calculated. The obtained results have shown that such a design can keep a field homogeneity over the target volume better then 1% which should be enough to monitor a polarization value during an experimental run. In terms of construction that is resistant against mechanical stresses, we intend to consider a monolithic holding magnet design.

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