3

Calibration of the apparatus

3.1 Magnetic Field Direction Measurement

The E05-102 experiment measured the beam-target asymmetries for three different orientation of the target spin: along the beam line (longitudinal (+)), and two horizontal transverse-to-the-beam directions (transverse ($\pm$) directions). The interpretation of the experimental results depends strongly on the direction of the target spin. Hence, it is essential to precisely know the orientation of the of the magnetic field, that holds the target spin in a particular direction. In particular, a direction of the magnetic field provided by the three perpendicular pairs of Helmholtz coils (see Sec. 2.4.4) as a function of the electric current inside them must be well understood. Contributions of the BigBite fringe-fields and Earth's magnetic field must also be considered.

The precise information on the direction of the holding magnetic field for each experimental setting was obtained by the compass calibration measurements. Two different compasses were employed. The vertical compass was considered to determine the polar (vertical) angle , while the horizontal compass was utilized to obtain the azimuthal angle of the of the magnetic field.

3.1.1 Vertical Compass Measurement

The magnetic field created by the Helmholtz coils is expected to be uniform at the target position and is linearly proportional to the electrical current ($B_{S,L,V} \propto I_{S,L,V}$). By setting currents in all three coils, the field polar angle ϕ_B can be expressed as:

$$\phi_B = \arctan\left[\frac{\sqrt{(I_S + A)^2 + R^2 (I_L + B)^2}}{K (I_V + E)}\right], \tag{3.1}$$

where I_S, I_L, I_V are the currents in the small, large and vertical coils. Parameters R and K are the scaling constants. Since we are interested in the ratio of the three currents only two such factors are needed. Parameters A, B, and E, correspond to the residual fields, which are present even when currents in all coils are zero. They represent the cumulative contributions of the Earth's magnetic field and BigBite spectrometer in each direction.

In order to determine the precise value of the angle ϕ_B for every current setting used during the experiment (demonstrated in Fig. 2.21),parameters R, K, A, B and E need to be determined. They were obtained from the measurements of angle ϕ_B at different current settings using vertical compass.

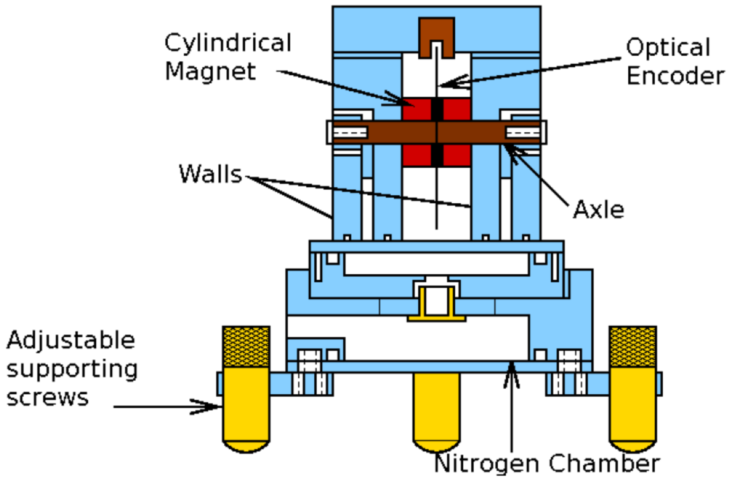

Figure 3.1 — Schematics of the vertical compass device. The main part of the compass is cylindrical magnet with the digital encoder for reading vertical angle of the magnet. The datum is transfered to the computer via USB cable. The compass is floating on thin layer of nitrogen gas, which is constantly blowing from the adjustable platform. This enables compass to rotate frictionless in both, horizontal and vertical direction. Figure is taken from [65].

The schematics drawing of the vertical compass is shown in Fig. 3.1. The compass was developed at the Department of the Physics and Astronomy at the University of Kentucky [65]. The main part of the compass is a magnetic cylinder with a digital optical encoder for reading the vertical deviations of the magnet. The resolution of the encoder disk was 0.09°. The compass was placed on top of the adjustable platform which was installed inside the target enclosure. The platform was adjusted in a way, that the center of the compass coincided with the center of the target. A nitrogen gas was blown into the system through the inlet and accommodated the compass to move frictionless in both horizontal and vertical direction.

The measurement was done in two steps. After the magnets were set to an appropriate values, compass was left free to align with the magnetic field. Once aligned, the encoder reading N_1 was noted. Then compass was rotated in the horizontal direction for 180° and locked at that angle. In that position the second encoder reading N_2 was recorded. The polar angle in the coil coordinate system was then determined from equation:

$$\phi_B\left(I_S, I_L, I_V\right) = \frac{2000}{\pi} \cdot \frac{N_1 - N2}{2}\,.$$

The measurements were performed for ten different current settings. All the measurements were preformed with the BigBite magnet turned on and are gathered in table 3.1. The measured points were later fitted to the Eq. (3.1) in order to determine the unknown free parameters [66]. The results are shown in table 3.1.

3.1.2 Horizontal Compass Measurement

The azimuthal angle of the magnetic field at a given combination of currents in the three pairs of Helmholtz coils is obtained from the formula:

$$\theta_B = \arctan\left[\frac{R\left(I_L + B\right)}{\left(I_S + A\right)}\right], \tag{3.2}$$

Table 3.1 — [Top:] Vertical compass measurements performed during the commissioning phase of the E05-102 experiment. All measurement were performed with BigBite magnet turned on. The uncertainty of the measured angles was estimated to be $\approx 10^{-4}$ rad. [Bottom:] The free parameters from Eq. (3.1) determiend for E05-102 experiment. Fitting analysis was performed in collaboration with Andrej Leban [66].

Measurements for $I_L = 0.0$ A

I_S [A]	I_V [A]	N_1	N_2	ϕ_B [rad]
7.0	0.0	1990	11	1.5543
5.0	10.0	1462.5	537	0.7269
0.0	14.0	997.5	1002	0.0035
-5.0	10.0	534	1466	0.7320
-7.0	0.0	7	1994	1.5606

Measurements for $I_S = 0.0$ A

I_L [A]	I_V [A]	N_1	N_2	ϕ_B [rad]
-7.0	0.0	3972	1959	1.5610
-5.0	10.0	518	1411.5	0.7018
0.0	14.0	983	947	0.0283
5.0	10.0	1438	491	0.7438
7.0	0.0	1955	3976	1.5543

Parameters

Parameter	K	R	A [A]	B [A]	E [A]
Value	0.5504	0.9873	-0.0195	0.1575	0.1681
Uncertainty	0.0081	0.0187	0.0667	0.0419	0.0605

where I_S and I_L are again currents in the small and large vertical coils, while the parameters A, B and R have the same meaning as in the vertical case.

The parameters A, B and R are a priori unknown and need to be determined. This time a horizontal compass was utilized. It is constructed of a magnetized 40 cm long iron needle (dipole magnet), mounted on a support frame. The compass is again positioned at the center of the target enclosure at the height of the beam line. In the presence of the horizontal field (parallel to the needle) the compass turns in the direction of the magnetic field. The angle of the needle with respect to the beam direction was obtained by measuring the absolute position of the both ens of the needle. The position measurements were performed by the survey group using high precision 3D laser positioning system. After the compass rotated to a particular direction, a metal survey ball equipped with a mirror was positioned on each end of the needle and illuminated by a laser in order to determine their coordinates. Using this laser technique, a position of the survey ball can be determined with a very high precision. However, the resolution of the compass measurement is limited by the accuracy of placing a survey ball on the tip of the compass needle and was estimated to be $\approx 3\times 10^{-4}$ rad, assuming that coordinates of the needle ends are known to ± 1 mm. Furthermore, error on the position of the needle tips can also lead to a non-zero offsets at the center of the compass. Fortunately this does not cause any issues, since magnetic field is believed to be uniform at the target position.

Knowing the needle coordinates, the azimuthal angle of the magnetic field could be determined from:

$$\theta_B = \alpha_{Coil} + \arctan\left(\frac{x_2 - x_1}{z_2 - z_1}\right), \qquad (3.3)$$

where indexes 1 and 2 denote the left and right end of the needle, respectively. In

Eq. (3.3) we also had to consider, that survey measurements were performed in the Hall coordinate system, while the Eq. (3.2) calculates the angle in the Coil coordinates system (see Fig. 2.21). Hence, a rotation for a constant angle $\alpha_{Coil} = 143^\circ$ is required to transform azimuthal angles from Hall coordinate system to the Coil coordinate system. Only then measured angles can be used for further calculations.

A series of horizontal compass measurements was performed at different values of the I_S and I_L. Furthermore, the calibration was performed with BigBite magnet on and off, to estimate the influence of the BigBite fringe fields on the target field. The obtained measured points are shown in table 3.2. The measurements were then

Table 3.2 — Horizontal compass measurements performed during the commissioning phase of the E05-102 experiment. Measurement were performed with BigBite magnet turned on and off. The uncertainty of the measured angles was estimated to be $\leq 3 \times 10^{-4}$ rad.

BigBite On

I_S [A]	I_L [A]	z_1 [cm]	x_1 [cm]	z_2 [cm]	x_2 [cm]	θ_B [rad]
4.2	-5.6	-5.08	231.36	8.53	-225.24	-0.8952
-1.0	-6.9	163.58	164.09	-160.76	-157.66	-1.7144
-5.6	-4.2	230.12	-1.63	-226.93	10.15	-2.5216
-6.9	1.0	124.34	-194.29	-136.74	180.47	2.8251
-4.2	5.6	-8.92	-235.87	-3.86	221.07	2.2055
1.0	6.9	-169.16	-168.16	155.83	153.44	1.4259
5.6	4.2	-234.87	-11.25	222.11	-4.57	0.6604
6.9	-1.0	-149.41	170.82	135.21	-186.50	-0.2524

BigBite Off

I_S [A]	I_L [A]	z_1 [cm]	x_1 [cm]	z_2 [cm]	x_2 [cm]	θ_B [rad]
4.2	-5.6	-8.52	229.46	1.88	-227.36	-0.9023
-5.6	-4.2	225.13	0.12	-231.79	4.20	-2.5048
-4.2	5.6	-4.84	-238.88	-3.00	217.99	2.2125
5.6	4.2	-235.88	-3.15	220.98	-3.36	0.6453

fitted to the Eq. (3.2) in order to obtain free parameters. For the fitting least-squares minimization technique was considered [66]. Determined parameters are shown in table 3.3. The analysis was done separately for data with BigBite magnet energized and BigBite turned off. However, the comparison of the fitted paramaters shows no significant difference between the two cases. This suggests that BigBite fields clamp successfuly protects target from the unwanted BigBite magnetic fringe fields.

3.1.3 Final Compass Results

Free parameters A, B and R in Eqs. (3.1) and (3.2) were determined independently for the horizontal and vertical compass measurement. However, both methods are investigating the same system. Consequently, in ideal case parameters A, B and R obtained with horizontal and vertical compass should be identical. Therefore, we can combine

Table 3.3 — The free parameters of the horizontal compass Eq. (3.2), determined for E05-102 experiment. Fitting analysis was performed in collaboration with Andrej Leban [66]. Results show no significant difference between BigBite-On and BigBite-Off results.

Parameters

Parameter	R	A [A]	B [A]
BigBite On	0.9975 ± 0.0023	0.032 ± 0.024	0.193 ± 0.170
BigBite Off	0.9793 ± 0.0442	0.054 ± 0.266	0.082 ± 0.324

results from tables 3.1 and 3.3 and calculate the mean values of the parameters. They are shown in table 3.4. The obtained mean values can now be applied to Eqs. (3.1) and

Table 3.4 — The final values of the parameters used in Eqs. (3.1) and (3.2) to calculate polar and azimuthal angles of the target holding magnetic field. The determination of the parameters was performed in collaboration with Andrej Leban [66]. Parameters A, B and R are the mean values of the vertical and horizontal compass results. Parameters K and E were obtained with vertical compass only.

Final Parameters

Parameter	K	R	A [A]	B [A]	E [A]
Value	0.5504	0.99745	0.0248	0.1565	0.1681
Uncertainty	0.0081	0.00130	0.0123	0.0377	0.0605

(3.2) in order to determine the true orientation of the field for the current settings considered in the experiment. Together with the angles, corresponding errors also need to be determined. The major contributions to the error come from the uncertainties of the fitted parameters. Since these parameters and their errors are not independent [67], the upper limit for the error can be estimated as:

$$\Delta\theta_B \leq \left|\frac{d\theta_B}{dR}\right|\Delta R + \left|\frac{d\theta_B}{dA}\right|\Delta A + \left|\frac{d\theta_B}{dR}\right|\Delta B\,,$$

$$\Delta\phi_B \leq \left|\frac{d\phi_B}{dK}\right|\Delta K + \left|\frac{d\phi_B}{dR}\right|\Delta R + \left|\frac{d\phi_B}{dA}\right|\Delta A + \left|\frac{d\phi_B}{dR}\right|\Delta B + \left|\frac{d\phi_B}{dE}\right|\Delta E\,.$$

The final results are gathered in table 3.5. For clarity, the angle values are displayed in the hall coordinate system. The orientations of the target spin corresponding to each magnetic field configuration were also calculated.

3.2 Calibration of the Beam Current Monitors

The raw BCM readout is given in terms of counts in the scaler modules. The total number of counts (BCM-Counts) corresponds to the collected charge, while the scaler count rate ($(\mathrm{BCM}-\mathrm{Rate}) = d(\mathrm{BCM}-\mathrm{Counts})/dt$) corresponds to the beam current.

Table 3.5 — True orientation of the magnetic field, calculated for each target orientation setup considered in E05-102 experiment. The θ_B^{Hall} is the azimuthal field angle, while the ϕ_B^{Hall} is the polar angle (zero when pointing in the vertical direction), given in the Hall coordinate system. Corresponding angles θ_{Spin}^{Hall} and ϕ_{Spin}^{Hall} for the target spin orientations are also calculated. The displayed errors represent the upper limits for the angle uncertainties.

Field/Spin Direction

Field Orient.	I_S [A]	I_V [A]	I_L [A]	θ_B^{Hall} [°]	ϕ_B^{Hall} [°]	Spin Orient.	θ_{Spin}^{Hall} [°]	ϕ_{Spin}^{Hall} [°]
Vert. (+)	-0.130	-13.529	-0.065	282.1 $\pm$15.04	1.1 $\pm$0.29	Vert. (-)	102.1 $\pm$15.04	178.9 $\pm$0.29
Vert. (-)	0.028	13.020	-0.218	93.7 $\pm$24.00	179.4 $\pm$0.30	Vert. (+)	-86.3 $\pm$24.00	0.6 $\pm$0.30
Long. (+)	-5.81	0.168	-4.622	0.6 $\pm$0.33	91.5 $\pm$0.29	Long. (-)	-179.4 $\pm$0.33	88.5 $\pm$0.29
Long. (-)	5.93	0.168	4.061	179.8 $\pm$0.34	91.5 $\pm$0.30	Long. (+)	-0.2 $\pm$0.34	88.5 $\pm$0.30
Trans. (-)	-4.238	0.168	5.527	269.6 $\pm$0.30	91.5 $\pm$0.30	Trans. (+)	89.6 $\pm$0.30	88.5 $\pm$0.30
Trans. (+)	4.286	0.168	-6.001	89.5 $\pm$0.29	91.5 $\pm$0.29	Trans. (-)	-90.5 $\pm$0.29	88.5 $\pm$0.29

Following relations are used to determine beam current (I_{Hall-A}) and collected charge (Q_{Hall-A}) from each of the six BCM signals ($x = u_1, u_3, u_{10}, d_1, d_3, d_{10}$):

$$I_{Hall-A} = \frac{dQ_{Hall-A}}{dt} = \frac{(BCM - Rate)_x - O_x}{C_x} \quad (3.4)$$

$$Q_{Hall-A} = \frac{(BCM - Counts)_x - (Time) \times O_x}{C_x}, \quad (3.5)$$

where C_x and O_x are calibration constants and (Time) represents the total time of the data taking. Parameter C_x is a multiplicative factor in units of As^{-1} and basically transforms the raw scaler reading to the meaningful physical quantities. In addition, the offset parameter O_x corrects for the presence of the dark current in the electronics, which leads to the non-zero current readings when the beam is turned off.

The calibration constants C_x and O_x for all six BCM signals were determined using a dedicated data set (E05-102 run number #2268). This particular run consists of three sequences of zero and non-zero current, which allows a simultaneous determination of both calibration parametes. Fig. 3.2 shows the raw scaler reading for three BCM signals u_1, u_3, u_{10}. During this special run, electron beam was delivered only to the Hall A. This allows us to compare our BCM readings directly to the beam current at the injector. The value of the beam current there is precisely known ($\sigma_{I_{Injector}} < 0.05\,\mu A$) and is instered into our data stream as an EPICS variable (IBC0L02). Combining this information with our raw BCM data in formula (3.4), calibration constants were determined. Results are gathered in table 3.6. Once knowing the calibration parameters, we were able to indipendently determine beam current, that entered Hall-A, employing each of the BCM signals (see Fig. 3.2). The resolution (sigma) of the reconstructed beam current was limited with the spread of the scaler data (BCM-Rate) and was estimated to $\sigma_{I_{Hall-A}} < 0.6\,\mu A$.