3D HALL PROBE CALIBRATION SYSTEM AT INSERTION DEVICE MAGNETIC MEASUREMENT FACILITY AT BNL *

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Abstract

Hall probes are commonly used to measure local magnetic field, however they need to be calibrated. This paper describes the accurate 3D Hall probe calibration system developed by the NSLS-II Insertion devices group. The calibration system and the calibration curves are presented. An Arepoc 3D Hall probe used to characterize the Insertion Devices (IDs) has been calibrated. The probe contains three sensors oriented perpendicular to each other in order to measure three components of the magnetic field. The three Hall sensors are mounted on a circuit board and their active area dimensions are 0.05 mm x 0.05 mm with a linearity error up to 1 T less of 0.2%.

INTRODUCTION

The 3D Hall probe calibration system consists of a GMW dipole electromagnet, a precision magnet power supply system, a nuclear magnetic resonant teslameter (NMR) and a motorized probes supporting stage.

In order to perform an absolute and precise calibration, the Arepoc 3D Hall probe must be positioned in a known magnetic field. The coordinate frame of the probe is indicated in Fig. 2. Sensor 1 is perpendicular to z direction (longitudinal direction), sensor 2 is perpendicular to x direction (horizontal direction) and sensor 3 is perpendicular to y direction (vertical direction).

HALL PROBE CALIBRATION SYSTEM

GMW dipole electromagnet (see Fig. 1) and a low noise and high stability Danfysik System 8500 Power Supply are used to create a constant and uniform magnetic field in the region around the point midway between the coils. The maximum magnetic field obtained with a current of 140 A at pole gap of 30 mm is of about 2.148 T and the uniformity achieved is of 110 ppm in 10 mm^3. The magnet and the power supply are water cooled.

A Metrolab PT-2025 NMR Teslameter System (Fig. 1) precisely measures the absolute magnetic field produced by the GMW dipole magnet. It is based on the nuclear magnetic resonance effect and achieves 5-ppm absolute accuracy and 1mG resolution for measurements in the range from 430 G to 137 kG. A multiplexer with different NMR probes is used, because the magnetic field value could be in one of several probe's ranges. So the proper NMR probe needs to be chosen and positioned within the magnetic field in the right position. A motorized *NMR Probe Supporting Stage* (see Fig. 3) is used to manage the NMR probe and to position it in the center of the electromagnet.

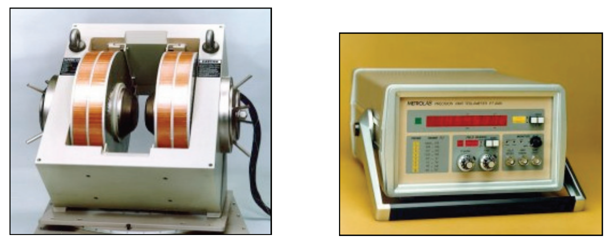

Figure 1: GMW dipole electromagnet and metrolab NMR teslameter.

An integrated digital multimeter is used to measure the Hall voltages of the sensor under calibration and a *Hall Probe Supporting Stage* (see Fig. 4), needed to move and rotate the probe during the calibration, provides precise controlled linear and angular motions in all required directions.

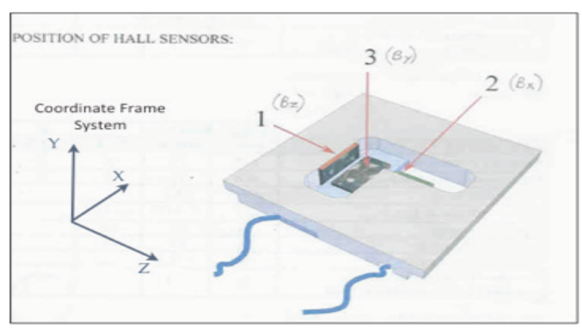

Figure 2: Coordinate frame system.

The control system written in LabView coordinates and automates the calibration measurements.

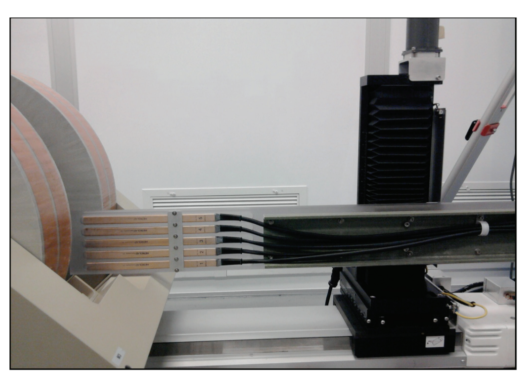

Figure 3: NMR probe supporting stage.

*Work supported by DOE contract DE-AC02-98CH10886
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The system is linked to a PC via GPIB for the NMR teslameter and a serial interface for the power supply and motion control system.

The control system synchronizes the readings of the sensor's voltage with the NMR probe signal and collects and processes the measurement data.

CALIBRATION PROCEDURE

Hall probe's output signal is a voltage that is proportional to the strength of the magnetic field in which the probe is placed. The calibration curve is a function that relates the Hall voltage to the strength of the field. For a 3D Hall probe is necessary to determine separate calibration curves for each of the three sensors. Knowing the calibration curve, you will be able to use the probe to measure the strength of an arbitrary magnetic field in the calibration range. The system calibration procedure includes the following steps: *System Setup*, *Alignment* and *Calibration.*

In the System Setup step the connections of all devices must be checked and powered on. After the setup, the system needs to be properly aligned before calibration scan can be executed. Alignment of the sensors into the electromagnet consists in three following steps:

- Align the NMR probes in the center of the electromagnet.
- Align the Hall probe in the rotating stage.
- Adjust the probes so that they are parallel to the electromagnet surfaces.

Imperfect alignment obviously leads to an underestimate of the field. Therefore is important to align the Hall probe as well as possible. Instead alignment is not an issue for the NMR probe, which measures the total magnetic field.

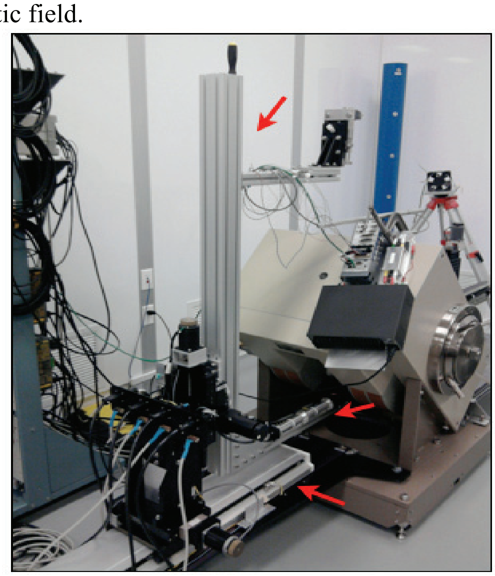

Figure 4: Hall probe supporting stage

The angular alignment of the Hall sensors with the transverse magnetic field of the electromagnet is made rotating the sensor around the z-axis and the y-axis until to maximize the reading of the multimeter (Hall probe voltage). In this way the deviation of the sensor from the perpendicular field direction can be reduced, because it is very sensitive to misalignment.

The calibration positions of the sensors along to the direction of the magnetic field of the electromagnet are obtained by rotating the probe of 90˚ around the axis of sensor. If the sensors are precisely perpendicular to the direction of magnetic field of the electromagnet then the maximum Hall voltage is measured. In this way for each sensor in the proper calibration position were determined the alignment angles.

A Hall sensor is not only sensitive to perpendicular magnetic field component $\mathbf{B}_\perp$, but also to the parallel component $\mathbf{B}_\parallel$. If magnetic field vector is not precisely orthogonal to the Hall probe, an additional voltage is added to the Normal Hall voltage (V_{NH}), due the field component in the plane of Hall sensor. This is known as Planar Effect (V_{PHE}) [1].

$$\begin{aligned} V_{NH} &= GR_H IB_\perp \\ V_{PHE} &\propto IB_\parallel^2 Sin(2\xi) \end{aligned} \tag{1}$$

For low magnetic field (< 2T), the basic equation describing the relation between the local electric field **E,** the local current density **J** and the flux density **B** in a Hall sensor is given, neglecting the anisotropy effect, by

$$\mathbf{B} = \rho J - R_H(\mathbf{J}\times\mathbf{B}) - M\rho\mathbf{B}\times(\mathbf{B}\times\mathbf{J}) \tag{2}$$

where ρ is the material resistivity, R_H is the Hall coefficient an M is the transversal magnetoresistance coefficient. The Hall voltage and the Planar effect are calculated from equation 2 and for materials with a low carrier mobility, the equation that describing the Planar Hall voltage may be written as [3]:

$$V_{PHE} = \frac{M\rho}{2t} IB^2 Sin^2\Theta Sin(2\xi) \tag{3}$$

where t is the plate thickness, I is the applied current, Θ is the angle between B and axis perpendicular to the sensor and ξ is the angle between $\mathbf{B}_\parallel$ and the current.

To remove this error during the calibration, two configurations are considered: *Normal* and *Reverse* position. The *Reverse* position is obtained with a rotation of 180˚ around the orthogonal direction of the magnetic field of electromagnet. In *Reverse* position the polarity of the magnetic field and the Hall voltage changes sign, but does not change the planar Hall voltage, because is proportional to the square of the field. So the difference of the two voltages removes the Planar Effect:

$$\begin{aligned} V_{NH} &= \frac{V^{Norm} - V_H^{Rev}}{2} \\ V_{PNH} &= \frac{V^{Norm} + V_H^{Rev}}{2} \end{aligned} \tag{4}$$

The calibration step, for each sensor, can be described with the following operations:

1. Select the current on the Magnet Power Supplies System.
2. Choose the relevant probe according to the magnitude of the field.
3. Place the proper NMR probe at the center of the electromagnet.
4. Start the measurement scans with NMR teslameter in *Automatic Mode*: This mode sweeps the radio frequency over the whole range of the FINE potentiometer. This represents a variation of ± 5 % of the frequency actually selected by the COARSE potentiometer [2].
5. Read the NMR magnetic field locked.
6. Place the Hall sensor in the center of the electromagnet at alignment angles. Read the *Normal Hall Voltage.*
7. Rotate the sensor of 180º around the orthogonal direction of magnetic field in order to have the *Reverse* position.
8. Read the *Reverse Hall Voltage.*
9. Change the current of electromagnet and repeat the previous steps for whole calibration range.
10. Rotate the sensor of 90˚ respect to each other, in order to have the next calibration position and repeat previous steps.

The calibration was performed in the measurements range ± 1.9 T. The calibration at zero field was done using a zero-gauss chamber.

AREPOC CALIBRATION CURVE

The magnetic field from Hall probe voltage measurements can be written as: $B=f(V)$, where B is magnetic field, V is the voltage of Hall sensor and $f(V)$ is a nonlinear function: $f(V)=K_0+K_1V+\ldots+K_nV^n$.

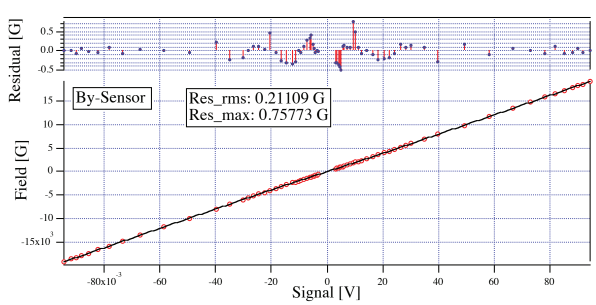

Figure 5: Calibration curve of By-sensor.

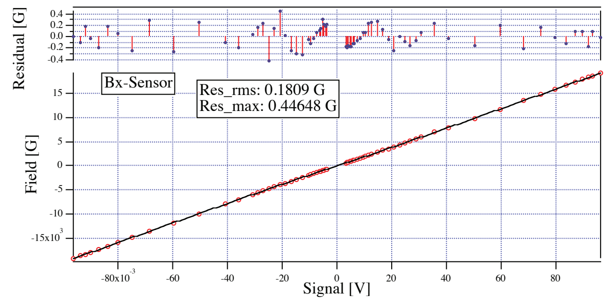

Figure 6: Calibration curve of Bx-sensor.

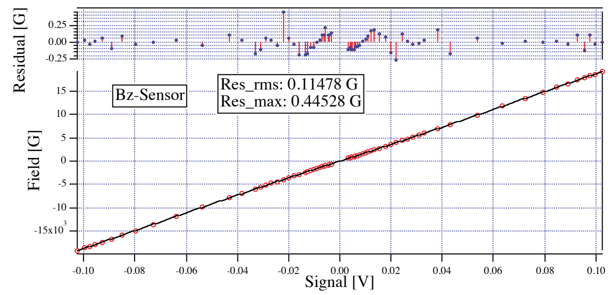

Figure 7: Calibration curve of Bz-sensor.

A polynomial fit of $B=f(V)$ was done to determine the coefficients (see Fig. 5, 6 and 7). Using the equation 4, the voltage due to the Planar Hall effect was cancelled. The best order of the polynomial fit is the minimum value that does not involve significant changes to the residual. The main nominal parameters of the probe (current 10 mA) are shown in table 1.

Table 1: Main Nominal Parameters

Sensors	**Sensitivity [mV/T]**	**Offset Voltage [µV]**
By-Sensor	63.3	< 60
Bx-Sensor	64.7	< 100
Bz-Sensor	66.9	< 20

CONCLUSION

The 3D Hall probe calibration system has been successfully used to calibrate an Arepoc 3D Hall probe. The system works very well and is capable of calibrating probes with high degree of accuracy.

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ISBN 978-3-95450-138-0