TEMPERATURE-DEPENDENT CALIBRATION OF HALL PROBES AT CRYOGENIC TEMPERATURE*

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Abstract

Short-period superconducting undulators (SCUs) are presently being developed for the Advanced Photon Source. Field measurements of the SCUs will be performed at 4.2 K and near 300 K, so temperature-dependent calibration of the Hall probes is necessary. The sensitivity of the Hall probes has been measured at temperatures from 5 K to 320 K over a magnetic field range of ±1.5 T. It was found that the sensitivity increased as the temperature decreased from 300 K to about 150 K. A specially designed probe assembly, with three Hall sensors for measuring both the horizontal and vertical field components, has been calibrated. The techniques for doing the calibration and the measurement results at various temperatures will be presented.

INTRODUCTION

A Hall sensor with excitation current perpendicular to an external magnetic field produces a Hall voltage, due to the Lorenz force, that is transverse to the excitation current. This voltage depends on the field strength, the excitation current, temperature, and material properties of the Hall sensor.

Field measurements of the superconducting undulators (SCUs)[1,2] at the Advanced Photon Source (APS) need to be done initially in a vertical cryostat in a liquid helium (LHe) bath. The sensitivity of the Hall sensor is relatively constant from 4.2 K to 50 K, so temperature compensation of the measured Hall voltage is not crucial. After installation of the SCU in the production cryomodule and before installation in the storage ring, the SCU will be measured using a "warm-bore" horizontal measurement system with the Hall probe at approximately 300 K. Because the actual temperature can vary along the warm-bore chamber, and the slope of the Hall sensitivity is quite steep near 300 K, accurate temperature measurements and calibration curves are required.

The Hall probe assembly shown in the Fig. 1 was designed to measure the horizontal and vertical fields at the mid-plane of the SCU. The Hall probe assembly was custom-made by AREPOC S.R.O., Bratislava, Slovakia. It has three Hall sensors mounted to a ceramic substrate. The sensors designated C4 and C5 measure the vertical field and C6, the horizontal field. The two vertical field sensors allow the ability to calculate the mid-plane field even if the probe axis is not centered on the mid-plane. All three Hall sensors were calibrated over a temperature and field range of 5 – 320 K and ±1.5 T.

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EXPERIMENTAL SETUP

An electromagnetic dipole was used for the calibration field of the Hall probe assemblies. The actual field is read with a nuclear magnetic resonance (NMR) probe. The sensitivities of the sensors provided by the vendor, with an excitation current of 10 mA, are listed in the Table 1. The sensors C4 and C6 are mounted back to back on a ceramic plate attached to a circular holder that is also ceramic. The distance between the active portions of C4 and C6 was measured using the technique described in [3] and found to be 1.018 mm. The C5 probe is mounted orthogonally to C4 and C6 in order to simultaneously measure the horizontal and vertical fields of the SCU.

Figure 1: Hall probe assembly.

The Hall probe assembly was attached to the cold head of a custom-built cryostat from Janis Research. Apiezon N grease was used between the cold head and the assembly holder to provide good thermal contact, and a Cernox temperature sensor from Lakeshore, attached near the C5 sensor, was used to measure the probe temperature. The temperature of the probe was controlled by transferring LHe into the cryostat. The Hall probe was located in the vacuum layer of the cryostat.

The cryostat was attached to a goniometer to provide alignment of the Hall sensors to the calibration dipole field. The voltage output of the Hall sensors was measured with a multi-meter card installed in a National Instruments PXI chassis. For alignment of the C4 and C6 sensors to the calibration field the output of the C5 sensor was minimized. The horizontal field is more sensitive to angular changes and thus provides a more accurate way to align the probe assembly. When calibrating the C5 probe, the output of the C4 and C6 sensors were minimized.

Table 1: Comparison of Measured and Vendor Provided Hall Sensor Sensitivities at 300 K

Probe	Vendor mV/T	Measurement m/T	Current mA
C4	68.2	68.3	10
C5	67.2	67.3	10
C6	68.5	68.7	10

RESULTS

Figure 2 shows the NMR field as a function of Hall voltage for sensor C4 at 300 K. The measured data can be described by the following expression:

$$B = \sum_{n=0}^{N} K_n (U - U_0)^n = K_1(U - U_0) + K_2(U - U_0)^2 \ldots + K_N(U - U_0)^N, \tag{1}$$

where U_0 is Hall offset, and K_1 is the main coefficient that shows the slope of the Hall output. The K_1, referred to as K, corresponds to the inverse sensitivity of the Hall sensor. The K of each probe at each temperature is calculated from the measured calibration data using the least squares fitting method. As shown in Fig. 2, the K value for C4 is 14.651 T/V. Since the measured characteristic curves of the other two probes were very similar with only different K values, only the curve for C4 is shown.

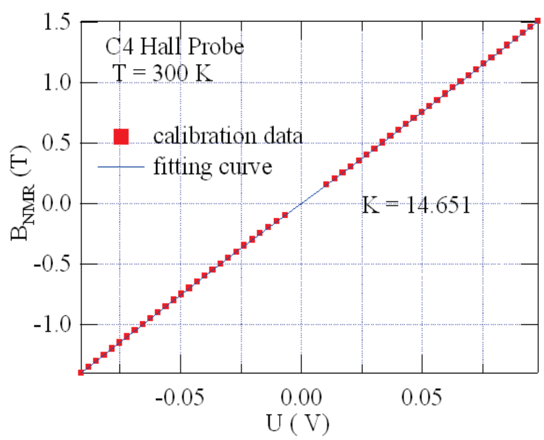

Figure 2: The field dependence of the Hall probe C4 output voltage at 300 K.

Each Hall sensor was first calibrated at 300 K and compared with the measured sensitivity provided by the vendors, as shown in Table 1. The measured sensitivity from the calibration at 300 K differed by only about 0.1 % relative to the vendor's sensitivity for each probe. This also confirmed the alignment of each probe at 300 K. The probe alignment near 5 K was confirmed by reading the maximum output. The calibration measurements were then performed at 16 different temperatures from 5 K to 320 K.

As shown in Fig. 3, the measured Hall voltage showed nonlinearity with field at each temperature point and the nonlinearity increased with decreasing temperature. It was found that the temperatures of the Hall sensors were changing with field at 5 K. It was also found that the resistance of the hall sensor was field dependent, thus the power dissipation from the excitation current also was field dependent. The Hall probe resistance was measured at fixed temperatures of 5 K and 300 K in the field range of ±1.5 T.

Along with the assembly that contained sensors C4, C5, and C6, AREPOC provided a second assembly with three additional sensors C1, C2, and C3. This second assembly was manufactured at the same time as the first and exhibited similar characteristics. Sensor C3 from this assembly was used to measure the field-dependent resistance. The same excitation current of 10 mA was used for the resistance measurements. The results are shown in Fig. 4.

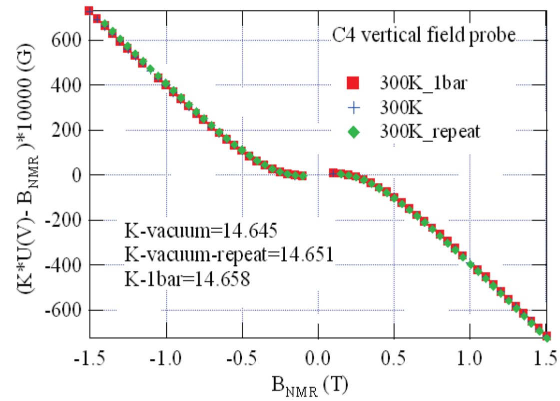

Figure 3: Field dependence of the nonlinearity of the C4 Hall sensor at 300 K. The + markers corresponds to the first calibration data and the filled diamonds are the repeated calibration data. The filled squares are the calibration data with 1 bar air pressure.

The Hall probe resistance increases up to 20 Ω with a field of ±1.5 T versus the resistance with a zero field at 5 K. It decreases to 15 Ω with a field of ±1.5 T at 300 K.

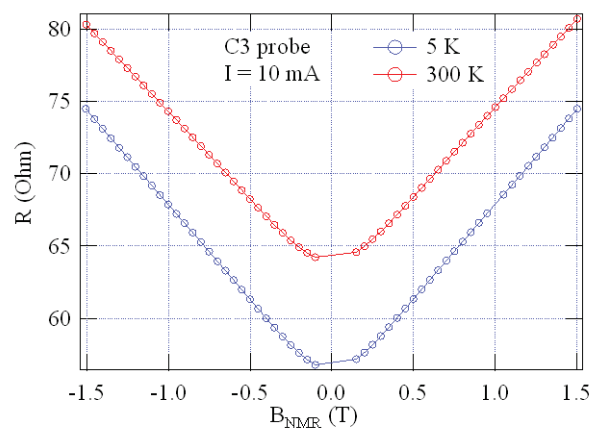

Figure 4: The field dependence of the Hall sensor resistance. The temperature was set to 5 K and 300 K and the resistance was measured across the excitation current leads with a field range of ±1.5 T.

In order to confirm the pressure effects on the Hall sensors, the calibration was performed at 1 bar, and the result was compared with in-vacuum calibration data as shown in Fig. 3. There was no significant difference found in the calibration of the Hall sensors at the two tested pressures and temperatures. The calibration process was repeated after one heat cycle at 5 K in order to check the reproducibility of the calibration. From the results of these measurements it was confirmed that all AREPOC sensors have good reproducibility at both 5 K and 300 K.

In Figure 5 the solid markers represent Hall sensitivity as a function of temperature with the Hall sensors in vacuum. The open markers represent the Hall sensitivity from 250 K to 320 K in the air. Results show a good agreement of the sensitivity within air and vacuum. Prior to the above measurements the C5 sensor's sensitivity was measured at 100 K in air. Once it was confirmed that there was no difference in the sensitivity of the C5 sensor in vacuum or air, the other two sensors were calibrated to 280 K.

The sensitivity of C4, C5, and C6 probes increased by about 5.2, 5.2, and 5.4%, respectively, at 5 K compared to the sensitivity at 320 K. Below 150 K it only changed approximately ±0.1%.

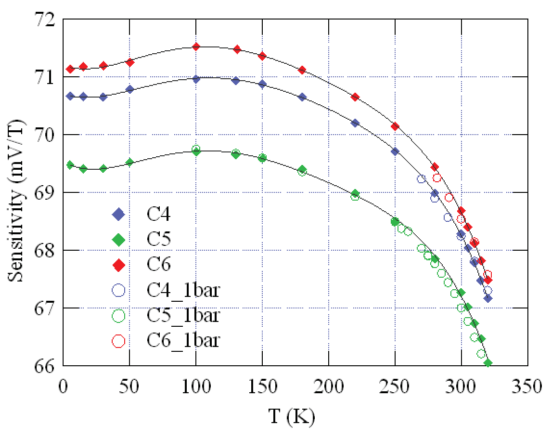

Figure 5: Sensitivities of Hall sensors C4, C5, and C6 as a function of temperature. The red and green solid diamond markers are the measured calibration data in vacuum. The open circle markers are the calibration data with 1 bar air pressure.

DISCUSSION

The calibrated sensitivities of C4, C5, and C6 probes increased with decreasing temperature. This result is consistent with our previous Hall probe calibration data [4].

The measured Hall probe resistance was about 50 Ω at 5 K in zero field and increased about 20 Ω with a field of ±1.5 T. At 300 K it increased 15 Ω within the same field range. The resistance values shown in Fig. 4 are equal to the actual Hall sensor resistance plus approximately 12 Ω due to the 3m long signal leads. Only about 20 cm of the signal leads were in the cryostat.

The effect of Joule heating on the C3 sensor was confirmed by measuring the field dependence of the Hall probe assembly temperature near 5 K. The Cernox temperature sensor responded to the increased Joule heating (due to increased Hall resistance) as shown in Fig. 6. The temperature sensor was confirmed to be insensitive to magnetic field changes, as the vendor stated, by measuring the temperature at 5 K and 300 K within the field range of ±1.5 T with the Hall probe excitation current turned off. The temperature was then measured with the Hall sensor excitation current set to 10 mA. The measured temperature increased (at zero field) by 4.8 K due to the approximately 4mW power dissipation of the Hall sensor. It increased by 0.5 K after increasing the field to 1.5 T. This means that the increased heat from the change in Hall resistance increases the probe temperature about 0.5 K from 0-1.5 T. The effect from the Hall probe heating on the probe temperature vanishes at 300 K. Fortunately, the change in sensitivity of these sensors is small at temperatures below 50 K.

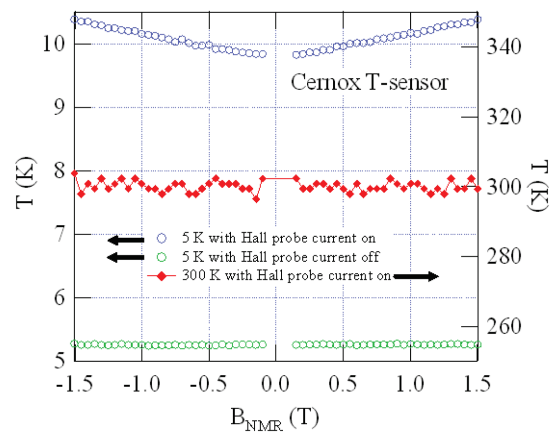

Figure 6: Hall probe assembly temperature as a function of applied field at 5 K and 300 K with Hall sensor current on and off. The temperature was stabilized at the location of the temperature sensor. The C3 sensor is about 5 mm off from the temperature sensor.

CONCLUSION

The sensitivities of the Hall sensors were measured in the range of 320 K to 5 K within a field range of ±1.5 T. It was found that the sensitivity increases with decreasing temperature. The calibration was also done in vacuum and at 1 bar air pressure. It was found that the sensitivity of the Hall probes was not affected by the different pressures.

The reason for the nonlinearity increment of the Hall sensor at low temperatures was investigated. It was found that the self-heating of the sensors changed slightly with applied field due to changes in the Hall sensor resistance.

REFERENCES

[1] Y. Ivanyushenkov et al., "Status of R&D on a Superconducting Undulator for the APS" PAC 2009, Vancouver, May, 2009.

[2] E.R. Moog, M. Abliz et al., "Development Status of a Superconducting Undulator for the Advanced Photon Source (APS)," IPAC10, Kyoto, 2010.

[3] M. Abliz, I.B.Vasserman et al., "Calibration of Hall Probes at Cryogenic Temperatures" SRI-16, ANL, http://sri2010.aps.anl.gov/program/workshop-3.

[4] Y. Ivanyushenkov, M. Abliz et al., "Calibration of Hall probes at Cryogenic Temperatures," IMMW-16, Switzerland, http://immw16.web.psi.ch/Presentations.