A Hall Probe Calibration System at Low Temperature for the TPS Cryogenic Permanent Magnet Undulator

Article *in* IEEE Transactions on Applied Superconductivity · January 2018

DOI: 10.1109/TASC.2018.2795575

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***Abstract*—A cryogenic permanent-magnet undulator (CPMU) with a 15-mm period length is being constructed for the TPS. Field measurements of this undulator will be performed with a Hall probe at cryogenic temperatures, for which a field strength and temperature-dependent calibration system is necessary. This system consists of a cryo-cooler and a heater to control the Hall probe temperature, a home-made dipole electromagnet, a nuclear magnetic resonant Tesla meter, and two angle adjusting stages. These stages will rotate the Hall probe to adjust the angular accuracy of the Hall probe axes with respect to a reference ceramic surface and to measure the planar Hall effect coefficient. A two-axis compact 0.9-mm SENIS Hall probe is used in the very small gap of 4 mm of this CPMU. Design details and performance of this system, its calibrating process, and calibration results at various temperatures will be discussed in this paper.**

***Index Terms*—Low temperature, Hall-probe calibration, cryogenic permanent-magnet undulator, magnetic field measurements in vacuum.**

I. Introduction

A HYBRID type CPMU made from PrFeB permanent magnet materials is under construction for TPS Phase-II beamlines. At a minimum operating gap of 4 mm a magnetic field of 1.32 T is expected at a temperature of 77 K [1]. Therefore, field measurements will be done at 77 K. Recently, an in-situ field measurement system [2] has been modified and upgraded to assess the magnetic field performance of the CPMU [3]. An accurate calibration of a high precision Hall sensor at low temperatures is of great significance to determine precisely its magnetic properties. According to other facility experience, the Hall probe temperature should vary only by a few degrees during measurements of magnetic arrays at 140 K [4]. However, a CPMU using PrFeB takes about six hours to cool down to 77 K [5]. During cool-down process the Hall probe will be parked outside and not contact the cold magnet arrays, so the temperature of the Hall probe may only drop by several degrees. The field measurement of the CPMU may take ten minutes, which may also cause several degrees drop. Therefore, the Hall probe temperature variations during whole process are expected in the range around room temperature.

Manuscript received August 29, 2017; accepted January 8, 2018. Date of publication January 23, 2018; date of current version February 8, 2018. This work was supported in part by the Ministry of Science and Technology, Taiwan, under contract with the Taiwan Photon Source. *(Corresponding author: Chin-Kang Yang.)*

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Digital Object Identifier 10.1109/TASC.2018.2795575

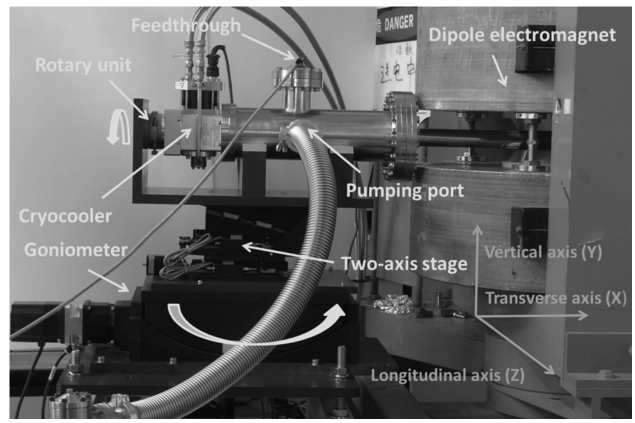

Fig. 1. Setup of the low temperature Hall probe calibration system.

At cryogenic temperatures from 4.2 K to 50 K, the Hall sensitivity is almost constant, but the Hall sensitivity varies with temperature more rapidly around room temperature. Hence accurate temperature measurements and temperature dependent calibration curves are required. A new Hall probe calibration system which is capable to be cooled down to the desired temperatures was designed, fabricated, and tested.

II. System Design and Fabrication

Fig. 1 shows the setup of this system consisting of a home-made dipole electromagnet, a precision power supply, a nuclear magnetic resonance Tesla meter, and a voltmeter to provide the field and record the Hall probe voltages. To control the temperature, a cryocooler, a heater, and a thermo-sensor are available for this system. This system has two angular and two linear degrees of freedom to align the Hall probe. The vacuum chamber has a pumping port to pump the pressure to less than 10^{-5} Torr and a feed-through to connect the signal wires from air to vacuum. All components should be suitable for high-vacuum environment without containing the Hall probe and other vacuum components, so all parts are machined free of oil and well cleaned before installation.

A. Hall Probe Holder Design

Fig. 2 shows the Hall probe holders, which holds a PT-100 sensor, a heater, and a Hall probe. The holders are of two types,

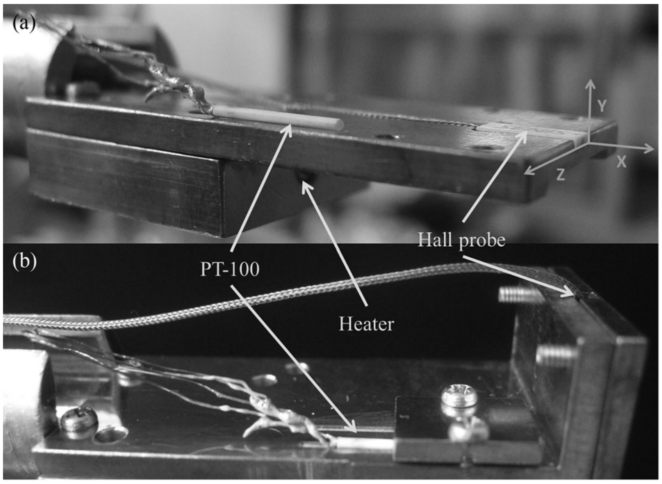

Fig. 2. Hall probe holders, heater, and PT-100 for (a) the Y channel probe, and (b) the X channel probe.

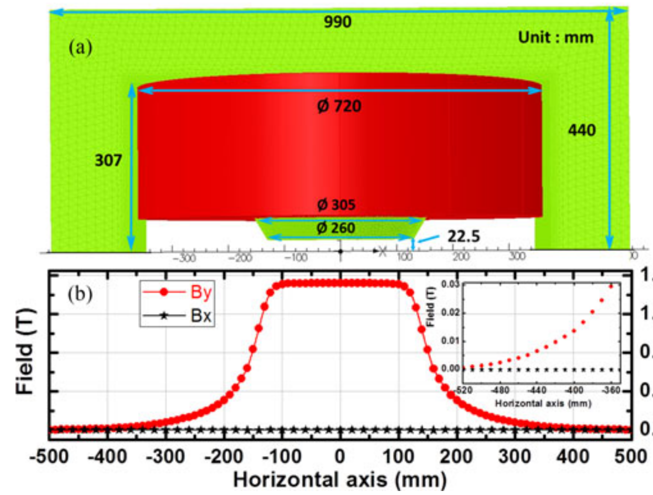

Fig. 3. (a) The upper part of the dipole electromagnet simulation model and (b) the field distribution along the horizontal axis.

as shown in Fig. 2(a) and (b), for the x and y axis field calibration and planar Hall coefficient determination. The Hall probe is held on the holder by brass screws and copper plates and connected to a cold head by a 450 mm long copper cylinder bar whose shrinkage is about 3 mm after cooling down to 6 K. Because the cryocooler will be placed horizontally, the weight on the cold head should be less than 0.5 kg to avoid damage. On the other side, the copper cylinder should be strong enough to minimize the sag caused by gravity. To reach these goals, the copper cylinder is designed as a hollow cylinder with 2 mm wall thickness.

B. Angle and Position Adjustment Components

Hall probes are sensitive to angular positions and it is estimated that the angular error should not be larger than 4 mrad to keep field errors to less than 1×10^{-5}, demanding that the angular positions for field measurements and calibrations should be preserved carefully. Therefore, the real angular probe axes with respect to the reference surface need to be determined.

The Hall sensor holder is fixed to a cold head that is attached to a rotary unit and a goniometer to measure these angles and provide alignment capabilities of the Hall probe roll and pitch angles, as shown in Fig. 1. An angular resolution of about 0.2 mrad was achieved. The goniometer is rotated by a motor and a reducer that increases the inertia torque and resolution, while the rotary unit is operated manually to reach a reproducibility of about 0.1 mrad. The rotary unit can rotate by $\pm \pi/4$ to determine the angular error and the goniometer can rotate only by a few degrees to adjust the Hall sensor angle.

C. Temperature Control System

This calibration system is not only designed to calibrate the Hall probe for a CPMU but also for superconducting undulators whose field measurement need to be done at cryogenic temperatures in the future [6]. Therefore, a cryocooler is used to cool down the Hall sensor. The cryocooler model is RDK-101D from Sumitomo, whose capacities of the 1st and 2nd stage are 5 W at 60 K and 0.1 W at 4.2 K and weighs only 7.2 kg. It is a Gifford-McMahon (GM) cooler and it is known that any magnetic field can have a serious impact on the cryocooler performance and service life [7]. The regenerator can stand a field up to 1.5 T while it should be smaller than 0.03 Tesla for the displacer motor. The magnetic field perpendicular to the moving displacer should be smaller than 0.05 T to avoid increase wear and maintenance needs.

A PT-100 thermo-sensor and a 20 W non-inductance heater, as shown in Fig. 2, are installed on the holder to control the temperature during calibration. A Lakeshore 330 autotuning temperature controller is used to measure and control the temperature. The cryocooler is installed inside the vacuum chamber to reduce the thermal conductivity of any residual gases. The chamber is made of stainless steel (316L) and annealed after machining to minimize any residual fields that might affect the field measurement.

D. Dipole Electromagnet

Fig. 3(a) shows the simulation model of the dipole electromagnet with a pole gap of 45 mm and a pole diameter of 260 mm. The 540 turn coils are made from water cooled copper tubes. The maximum magnetic field is about 1.5 T with a current of 80 A to match the 1.32 T field strength of the CPMU at a gap of 4 mm. The magnetic field produced by this dipole magnet is precisely measured by NMR probes. The magnet is powered by a low noise and high accuracy Keysight 6692 A power supply, which can produce a power of 6.6 kW and a maximum current of 110 A.

Fig. 3(b) shows the field distribution along the horizontal axis with a peak field of 1.5 T. The field strength decreases rapidly near and outside the pole edges. As mentioned, the magnetic field can cause serious problems for the cryocooler performance and service life, because its weakest part can only stand 0.03 T. To avoid any influence on the cryocooler, it is placed at the edge of the coils where the fields are smaller than 0.03 T as shown in the Fig. 3(b) inset.

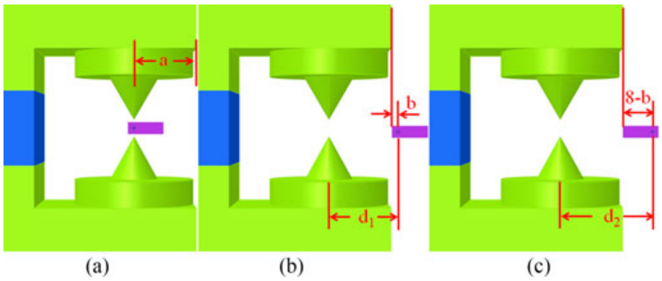

Fig. 4. Setup of the needle magnet and measurement method.

E. Needle Magnet

A needle magnet is used to determine the Hall sensor active area positions with respect to its ceramic housing. The Hall probe is first scanned to find the peak field location and this place is set as the zero position, as shown in Fig. 4(a). Then the probe is moved to the magnet edge (Fig. 4(b)), while recording this distance. After that, the probe is flipped (Fig. 4(c)) and the same process used to record the distance again. These two distances are substituted into the following equations to find out the sensor positions.

$$\mathrm{d_1 - b = a} \tag{1}$$

$$\mathrm{d_2 - (8 - b) = a} \tag{2}$$

where $\mathrm{d_1}$ and $\mathrm{d_2}$ are the distances of movement, x is the distance from the ceramic plate edge to the Hall sensor, and y is the distance from the needle to the magnet edge. Using this method can reduce the actual error to below the specification from the manufacturer of the needle magnet.

F. NMR Probe

The Hall probe is calibrated with reference to a Metrolab PT-2025 NMR and ESR probe system. It has better than 5 ppm accuracy and 1 mG resolution in the range of 0.043 T to 13.7 T and 5.5 G to 32 G. Its operating temperature range is 283 K to 313 K so these probes should therefore be outside the cool chamber. A proper probe has to be chosen and placed as close as possible to the Hall probe during calibration.

III. Measurement Results

For this Hall probe calibration system the performance of the dipole magnet and cooling system are most important. A new *two*-axis SENIS Hall probe (type C) is used to measure our CPMU due to its small external dimensions, low flicker noise, nonlinearity and low temperature coefficient of the sensitivity at room temperatures. However, this probe can operate only at a lowest temperature of 263 K, not at cryogenic temperatures, which is needed to measure a CPMU. A temperature sensor, integrated on the Hall probe chip, allows to monitor the Hall probe temperature during calibrations [8]. The alignment and calibrating process are based on well known practices followed at NSRRC [9].

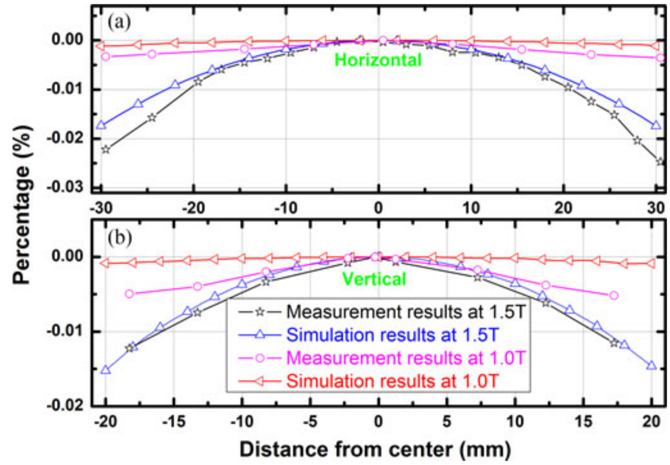

Fig. 5. Dipole magnet good field region as determined by measurements and simulation in (a) the horizontal and (b) vertical directions.

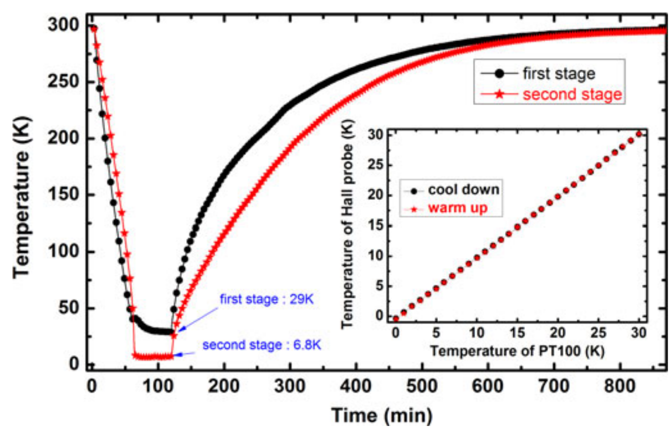

Fig. 6. Cool down and warm up test results.

A. Dipole Magnet Good Field Region Test Results

The dipole magnet is designed for a very large good field region and Fig. 5 shows the agreement between simulation and measurements.

In the horizontal direction, the field variations are smaller than 0.01% in the range of ±20 mm at a field strength of 1.5 T and ±15 mm in the vertical direction. However, at a field strength of 1.0 T the field variations are much smaller ($\sim$0.004%) even at ±30 mm. In our design, the maximum distance between the NMR and Hall probes is less than 10 mm in the horizontal direction and the field variation is only 0.1 G at a maximum field of 1.5 T and is negligible at lower field.

B. Cooling Down and Warm Up Test

Cool-down and warm up test results are presented in Fig. 6. The cooling process takes about two hours to reach the lowest temperature which for the first and second stage is 29 K and 6.8 K, respectively. The temperature comparisons of the Hall probe and PT-100 are shown in the inset of Fig. 6. There is no significant difference deu to the good thermal conductivity of the Hall probe ceramic plate [8].

TABLE I
POSITIONS AND ANGULAR ACCURACY MEASUREMENT RESULTS

Dimensions and positions accuracy	X (mm)	Y (mm)	Z (mm)
Position of the center (SENIS)	-0.5 ± 0.05	—	2.0 ± 0.1
Position of the center (measurement)	0.47	—	2.03
External dimensions of the probe (SENIS)	8.0 ± 0.1	$0.9 + 0.05$	$4.0 + 0.05$
External dimensions of the probe (measurement)	8.01	0.91	4.0
	SENIS specifications	Measurement results	
Angular accuracy of axes with respect to the reference surface	$<\pm 0.5^0$	$\sim 0.1^0$	
Planar Hall coefficient	$<0.01\%$	$\sim 0.007\%$	
	SENIS specification	Measurement results X channel	Measurement results Y channel
Offset voltage without chamber	$<\pm 10$ mV	3.57 mV	0.49 mV
Offset voltage with zero gauss chamber	——	3.26 mV	0.25 mV
Offset voltage with vacuum chamber	——	3.65 mV	0.55 mV

C. Hall Sensor Position and Angle Measurement Results

In Table I the needle magnet measurement results of the Hall probe (axis definitions shown in Fig. 2) and the specifications as given by the vendor (SENIS) are compiled. These measurement results indicate that an error of 30 μm in the distance to the ceramic plate center in the x and z axes are within specifications. The external dimensions of the ceramic plate are measured by a vernier caliper and show that it is manufactured very precise to a tolerance of only 10 μm, serving well as a reference surface.

The angular accuracy of the Hall sensor with respect to the reference surface is checked by rotating the probe. The probe was first leveled by an automatic level and then rotated to find the angle for the maximum field. As verified by measurements the angle accuracy is about 2 mrad which will cause only a 1.5 ppm field error.

The output voltage of a Hall sensor is expressed as follows:

$$V_{out} = V_{NH} + V_{PNH} = \mathrm{K_1 B_\perp I} + \mathrm{K_2 B_\parallel^2 I \sin}\,(2\varphi) \qquad (3)$$

where $\mathrm{B}_\perp$ is the horizontal magnetic field, $\mathrm{B}_\parallel$ the residual in-plane magnetic field component, I the applied current, φ the angle between the transverse field component and the applied current, and K_1 and K_2 are constants in the first approximation. The second term of (3) represents the planar Hall effect that will induce a field error. The planar Hall voltage is defined by changing the field from positive to negative and adding voltages to give a corrected voltage by eliminating the tilt owing to the inclination of the Hall sensor plane from the direction of the field [10]:

$$V_{PNH} = (V^{\mathrm{Norm}} + V^{\mathrm{Rev}})/2 \qquad (4)$$

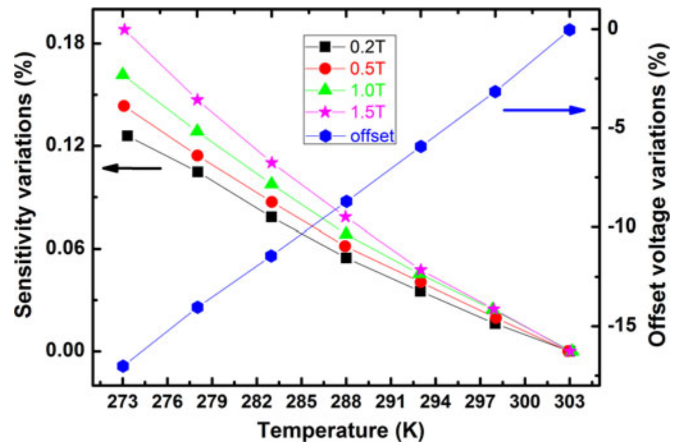

Fig. 7. Temperature dependence of the sensitivity and offset voltage.

where V^{Norm} and V^{Rev} correspond to the voltage of positive and negative fields, and V_{PNH} is the planar Hall voltage. The result reveals that the planar Hall voltage is only 0.007% of the Hall voltage, which means that the field error induced from the planar Hall effect can be kept within 0.06 G in a field of 1.5 T if the angle φ is less than 5 mrad.

The offset voltage is a parasitic output voltage when a Hall sensor is supplied with the nominal control current in the absence of a magnetic field. Some origins of this voltage are the structural asymmetry, material inhomogeneity, non- uniform doping density, and contact resistance, or external influences such as mechanical stress and variations in temperature [11]. The offset voltages are calibrated at zero field by using a zero Gauss chamber made of mu-metal, and are 3.26 and 0.25 mV for the X and Y channel. The vacuum chamber has negligible influence on the offset voltage.

D. Hall Sensor Calibration Results

Fig. 7 shows the sensitivity and offset voltage of a Hall sensor as a function of temperature. The sensitivity increases at 273 K compared to 303 K. The temperature variation is also field dependent and is 0.188% at 1.5 T while it is only 0.126% at 0.2 T. Because the resistance diminishes as the temperature decreases, the offset voltage also decreases by 17%.

Fig. 8 presents the calibration results. Only one result is shown since the observed characteristic curves of the two channels are very similar. The calibration data are fitted by the following expression:

$$B(U) = k_0 + \sum_{n=0}^{\infty} k_n (U - U_0)^n \qquad (5)$$

where U_0 is the Hall offset voltage, K_1 is the coefficient showing the inverse sensitivity of the Hall sensor, which is calculated from the measured calibration data using a least squares fit. It corresponds to a sensitivity of 5.0045 V/T that differs by only 0.09% from specifications.

The inset of Fig. 8 shows that the ESR calibration data have good agreement with fitting cure around zero field.

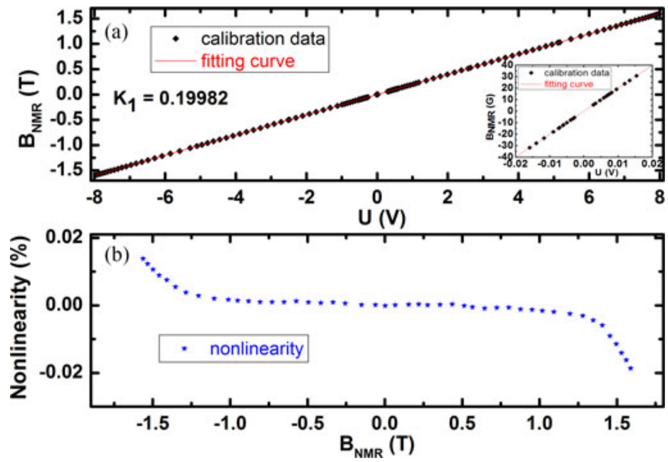

Fig. 8. (a) Field calibration data and (b) nonlinearity of the SENIS probe.

The nonlinearity is calculated by (6) and shown in Fig. 8(b).

$$(K * U(V) - B_{NMR})/B_{\max} \quad (6)$$

The result shows that the nonlinearity of this probe is negligibly small at a field of ± 1.2 T and is increasing as the field increases, but is always smaller than 0.02% up to a field of about 1.6 T.

IV. Conclusion

A system to calibrate a Hall probe at low temperatures has been developed. The dipole electromagnet has a very wide good field region and the probe can be cooled down to 6.8 K. This system is used to determine the angular accuracy and planar Hall coefficient of the Hall probe used for our CPMU as well as the calibration within a field range of ± 1.5 T and a temperature range from 273 K to 298 K. The sensitivity of this Hall probe increases by about 0.1% from room temperature to 273 K. The nonlinearity also increases with decreasing temperature. This probe has a very good performance and is ready for field measurements. However, the dipole electromagnet needs to be upgraded for future undulators with stronger field strengths and a cryogenic Hall sensor is needed to be used at cryogenic temperatures.

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