COMPENSATION OF THE PLANAR HALL EFFECT VOLTAGE USING A NEW TWO-SENSOR HALL PROBE DESIGN *

I. Vasserman, B. Berkes, J. Xu, Argonne National Laboratory, Argonne, Illinois 60439 USA,
J. Kvitkovic, Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia

Abstract

Trajectory straightness is an important parameter in defining the performance of free-electron laser (FEL) undulators, and the Hall probe is the best way to tune and measure Insertion Devices (IDs). Possibility of horizontal Hall probe magnetic field measurements in the presence of a strong vertical magnetic field have been examined at the APS during since 1997 in preparation for the tuning of the undulators for the FEL project at the Advanced Photon Source (APS). The next step of this investigation was reported at the 2004 FEL Conference [1]. Hall probe horizontal magnetic field measurements in the presence of a vertical magnetic field with a strong gradient are complicated due to the influence of the planar Hall effect (PHE) on the resulting Hall voltage. The previous test showed that the 2-axis Sentron Hall probe [2] is a possible choice. It was used for the Linear Coherent Light Source (LCLS) devices that have a fixed gap of 6.8 mm and a peak field of around 1.4 T. However, horizontal magnetic field integrals were very sensitive to the vertical position of the Hall probe**.** The new type of sensor with compensated planar Hall effect much less sensitive to the positioning is a subject of this work.

INTRODUCTION

Investigations into the possibility of using Hall probes for horizontal magnetic field measurements in applications where this field is the result of distortion of the main vertical component of the magnetic field due to geometrical mechanical errors of the device, nonuniformity of permanent magnet blocks, and so on, have been ongoing at the APS since 1997. During these investigations, proper types of probes and modes of operation were found. The next set of investigations comes from the idea of cancelling PHE voltage by using a set of two Hall sensors connected in series. The planar Hall effect (PHE) voltage causes errors in measurements because it adds an electrical field to the actual Hall field when there is a component in the field in the plane of the probe. The output voltage of an ideal Hall probe is described by the expression [3]:

$$U_x = K_1 B_x I + K_2 B_{\|}^2 I \sin(2\varphi), \tag{1}$$

where B_x represents the horizontal magnetic field, $B_{\|}$ is the component of the magnetic field in the plane of the Hall probe (B_y in our case), I is the current, φ is the angle between the direction of the in-plane components of the magnetic field and the current, and $K_{1,2}$ are constants in the first approximation. The second term in this equation corresponds to the PHE voltage. Due to the double angular dependence of the PHE voltage, rotation of the probe by 90° in φ results in a change in the sign of the planar voltage. It means that if we have two sensors with similar characteristics, rotate those 90° with respect to each other, and connect the output in series, the voltage due to the PHE will be cancelled. This has been known for a long time [4] but was never implemented. Recently, a theoretical study of PHE voltage compensation as well as some additional solutions was carried out [5]. In order to use such a probe for straightness of trajectory and field integral measurements, which are particularly important for FEL devices, contribution of the PHE voltage has to be reduced further. For example, the tolerance in variation of the horizontal first field integral gap dependence at APS is 50 G-cm over the entire gap range from 10.5 mm to 150 mm. Therefore the contribution of the PHE has to be <0.2 Gauss averaged along the 2.4-m-long device to rely on the Hall probe for these measurements.

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CALIBRATION OF THE PROBE

The first two-sensor device was developed and manufactured at the Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia, and delivered by the Arepoc s.r.o. Company. Results of the calibration are shown in Fig. 1.

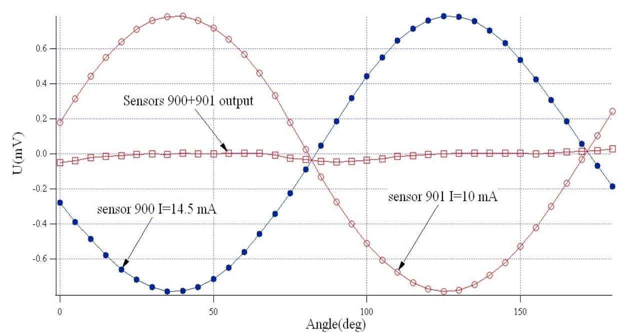

Figure 1: PHE voltage characterization for two-sensor Hall probe.

Positioning the second sensor 90° with respect to the first one was done with a precision of ≈ 3°, and currents of 10.0 mA and 16.43 mA were chosen to compensate the PHE voltages. The first test of this probe in the APS magnetic measurement facility showed much better performance than with previous probes. It was rather easy to find proper settings for one particular gap. The gap dependence of field integrals was still out of tolerance, and further tests with this probe were terminated due to damage to the probe. A new probe was ordered with a modified design that allows manual adjustment of the angle between the two sensors. A schematic of the probe design is shown in Fig. 2.

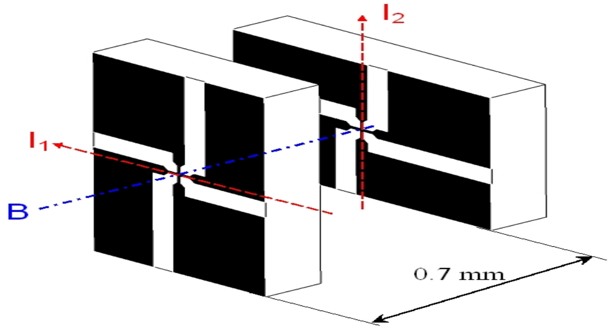

Figure 2: Schematic of the probe HHP-PHF 3-4. The 0.7-mm separation allows manual adjustment of the angle between the sensors.

All the results described below were obtained with this new probe. Initially, this probe was calibrated and the angle was adjusted using the calibration magnet in the APS magnetic measurement lab (MM1). An angular positioning accuracy of about 1° was achieved, and preliminary settings for currents were done. The calibration results look very similar to those of probe No. 902-904 shown in Fig. 1. The dependence of the planar Hall probe voltage on the magnetic field components is determined separately for probe sensors 3 and 4, respectively, using the MM1 calibration system. The total voltage output of each sensor due to the influence of the magnetic field components can be then rewritten from Eq. (1):

$$U_x = K_1 B_y I \sin\psi + K_2 B_{\|}^2 I \sin(2\varphi), \qquad (2)$$

where the first term represents the Hall voltage due to the x-component of the magnetic field when the probe plane is tilted by an angle ψ with respect to the vertical field (the exact value of this term is not important, because it will be cancelled by the procedure applied below). The second voltage term on the right side of Eq. (2) is due to the Hall sensor's in-plane response to the magnetic field component B_y (PHE voltage). Changing B_y from positive to negative and adding voltages U_+ and U_- give a corrected voltage by eliminating the tilt due to the inclination of the Hall sensor plane from the direction of B_y:

$$U_{cor} = (U_+ + U_-)/2, \qquad (3)$$

where $U_\pm$ correspond to the positive and negative directions of the in-plane magnetic field.

TEST AT THE BENCH

Further tests were performed using the APS 6-m bench and a 2.4-m-long, 3.3-cm-period Undulator A with a maximum peak field of around 0.9 T at a gap of 10.5 mm. The angular position of the probe was chosen to be close to the maximum PHE amplitude of each separate sensor. At this angle the derivative of the second term of Eq. (1) is equal to zero, so the sum of the series connected to sensors is less dependent on the angle. The dependence of the first horizontal field integral on the angle is shown in Fig. 3, and it is smaller by a factor of 50 than it was for one sensor device (see [1]).

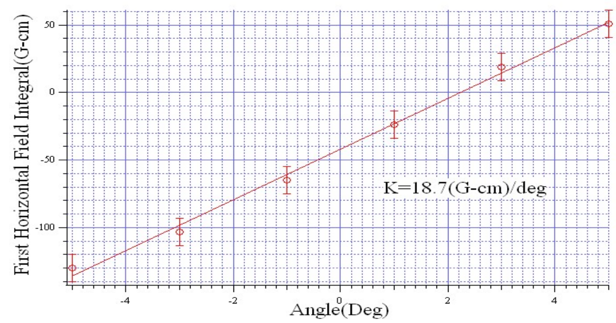

Figure 3: First horizontal field integral dependence on the angle around the *X*-axis.

The next set of tests was devoted to obtaining the gap dependence of measurements from this probe and comparing it to reference data obtained by other probes, including a moving 90-mm-long coil and a long rotating coil. The sensitivity to the level of PHE voltage compensation is very high here. Even 1 Gauss of noncompensated PHE results in a ~150 G-cm error in the first field integral. Proper compensation of PHE voltage was done by adjusting the current settings in the two sensors at minimum gap. The results of the first integral measurements after adjustment of the current settings are shown in Fig. 4.

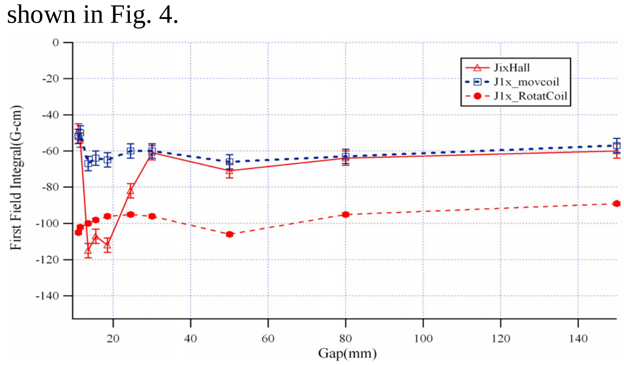

Figure. 4: First horizontal field integral dependence on gap using different sensors. Red triangles: two-sensor axial Arepoc HHP-PHF 34 probe; blue squares: short 90-mm-long moving coil; red circles: long stretched rotating coil.

Both the short moving coil and the long integrating rotating coil were used as reference measurements. The offset between the two reference measurements is explained by the different lengths of the scans (3 m for the moving coil and 4.4 m for the long rotating coil). The results using the long rotating coil at small gaps (large fields) are not very reliable, however, because the 10-conductor Litz wire used to make the coil gives variations in the width of the coil with Z. We consider the short moving coil to be the best reference data for the test. In Fig. 4 there is clearly an error in the Hall probe measurements between 13.5 mm and 24.5 mm. The error is about 50 G-cm, which is the APS tolerance for gap-dependence variation. To understand the reason for this discrepancy we look more closely at the data obtained during calibration of the probe. The sum of the output voltage obtained by the calibration system for two sensors connected in series is shown in Fig. 5 as a function of $B_{||}^2$.

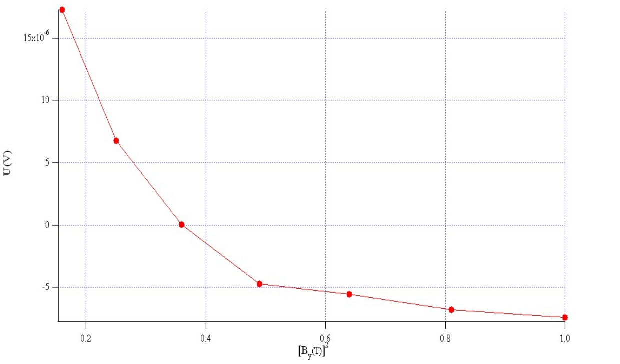

Figure 5: Sum of the output voltages of individual sensors vs. B_y^2. Precise cancellation is done at B_y =0.6T.

As can be seen, the sum of the PHE voltages is not constant and depends on the field, which means that K_2 in Eq. (1) is not a constant and different for different sensors. For perfect cancellation, the adjustment of the currents for both probes has to be done at each gap (field strength). It is adequate, however, to use only one setting over the entire gap range, because the most critical measurements are those of the angles and trajectory behavior along the device.

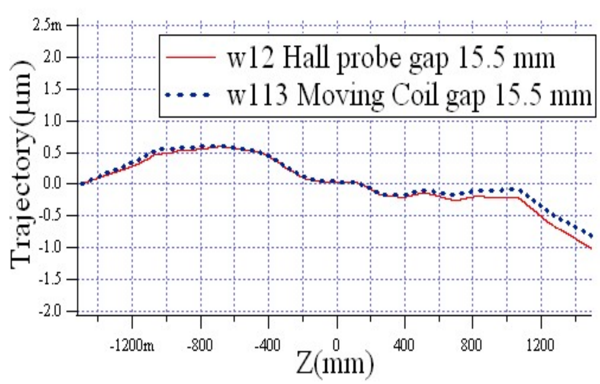

Figure 6: Comparison of second horizontal field integral measurements using the short moving coil and the Hall probe (particle energy E=7 GeV) at a gap of 15.5 mm.

The first field integral can be corrected by a local or global corrector system of the storage ring and is less critical. Comparison of the measurement data from the short moving 90-mm-long coil and the Hall probe is shown in Fig. 6, where the error in the first field integral is most visible. It is clear that Hall probe measurements are good enough to see the straightness of the trajectory and particle angles along the device, which are important parameters for some applications, such as FELs.

CONCLUSION

Compensation of the PHE voltage is important for reliable measurements of trajectory. This is especially true for IDs with small aperture, no side access, or other characteristics that are difficult to use with a complimentary magnetic measurement technique. It was shown that a two-sensor Hall probe is a good solution for this problem and, although the K_2 coefficient in Eq. (1) is not a constant, it is adequate for the trajectory even if a constant value is assumed. It is a well-known fact that K_1 is also not a constant, so calibration of Hall probes is always needed for precise field measurements. A Hall probe is the only probe that can measure a reliable map, and the possibility of using the same probe for both field maps and field integrals in both directions is appealing, especially when the possibility of using other probes is limited. Such a probe also would be useful for applications with both horizontal and vertical fields, like helical or Apple-style devices. The present work is a step in this direction. Another possibility is a proposal by one of us (BB) to use a single sensor by interchanging it between input and output wires, which works exactly the same way as the two-sensor probe but requires two scans. This is a subject of future work.

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