TEST OF HORIZONTAL MAGNETIC FIELD MEASUREMENTS IN THE PRESENCE OF A STRONG VERTICAL FIELD

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Abstract

Trajectory straightness is an important parameter in defining the performance of free electron laser (FEL) devices. Horizontal field measurements using Hall probes were tested in 1997 in preparation for the tuning of the undulators for the FEL project at the Advanced Photon Source (APS) [1]. This work is a continuation of the 1997 work, now for the demanding LCLS project. Tolerances for the Linac Coherent Light Source (LCLS) FEL undulator [2] specify a trajectory of <2 μm excursion in both (horizontal and vertical) planes for a particle energy of 14.1 GeV, which means that measurements of a small horizontal field in presence of strong (up to 1.5 T) vertical field are required. Hall probe measurements under such conditions are complicated due to the planar Hall probe effect [3, 4]. The previous test done in 1997 showed that the 2-axis Sentron probe is a possible choice. High sensitivity of horizontal field integrals to the vertical position of the sensor was observed. By positioning the probe accurately in the Y direction, this probe could be used for fast measurements and tuning of devices for LCLS undulator with a much larger magnetic field, than for the APS FEL project. Good agreement with reference moving coil measurements was obtained. The Sentron probe was recently used for LCLS prototype measurements and tuning.

INTRODUCTION

The very tight schedule for the LCLS project assumes rather little time for tuning and measurements of the 33 devices comprising the undulator. So it is important to limit the measurement technique options while tuning the device. A Hall probe is an essential part of this technique, which allows measurements and tuning of the field to obtain the best possible radiation performance of the device, including phase errors and trajectory straightness. An important part of the tuning is reducing the first (J1) and second (J2) field integrals responsible for particle trajectory angles and displacement to provide an overlap of radiation and particle beam. Measurements of integrated over device field integrals with help of rotation coil and/or stretch wire is the most reliable way of obtaining such data. The LCLS undulator consists of 3.4-m-long sections with a 6.5 mm fixed gap, which makes problematic the possibility of using such a technique, especially for horizontal field integrals measurements. Improving the accuracy of the Hall probe measurements allowing the use of the Hall probe for all tuning purposes is a main goal of this work.

SUMMARY OF 1997 TEST

Test of horizontal field measurements, using different types of Hall probes, was done in 1997 with a regular undulator A device, which is the main undulator type at the APS storage ring [1]. Two Hall probes: the usual Bell-type probe and the Sentron probe were used in this test. The main challenge with horizontal field measurements is a planar Hall-probe effect, which is associated with the angle between the vertical field and the axial probe current flow direction. The main result from the 1997 test is that it is impossible to obtain the first and second field integrals corresponding to reference measurements done by moving coil. By adjusting the angle of the Bell Hall probe around the horizontal (X) axis, either the first or second field integrals could be made equal to the reference data but not both of them simultaneously. Such an effect for the Sentron probe is rather small, as can be seen from Fig. 1. The Sentron probe is a new type of Hall probe, a so-called vertical Hall device, which is sensitive to the magnetic field parallel to the chip plane [5]. A different effect contributes to the distortion of horizontal field measurements in presence of a strong vertical field for this probe: the field integrals dependence on vertical

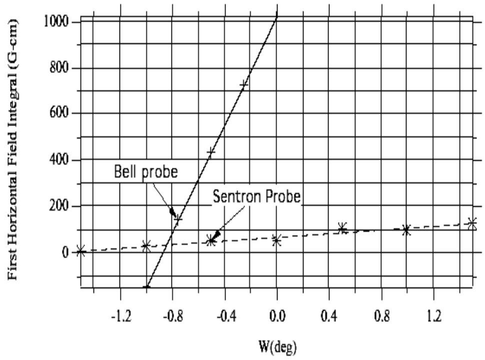

Fig. 1 Sensitivity of Bell and Sentron Hall probes to angular positioning: first horizontal field Integral vs. rotation angle around the X axis.

position (see Fig. 2). Results of the 1997 test showed a rather small dependence of the angle but strong dependence on vertical position. By choosing the proper vertical position of the Sentron probe, both first and second horizontal field integrals are found to be very close to the reference measurements done by moving coil, and such probe was used for tuning of the devices for the APS FEL project.

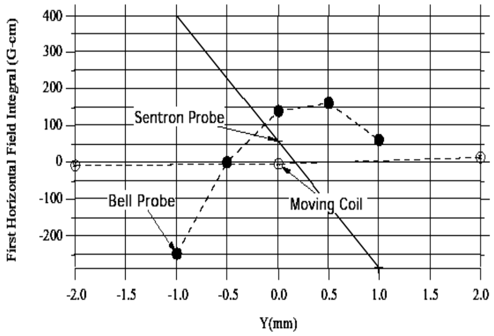

Fig. 2 Sensitivity of Bell and Sentron Hall probes to vertical position: ΔJ1/ΔY≈350 (G-cm)/mm.

NONLINEARITY OF SENTRON 2-AXIS HALL PROBE

The LCLS undulator has a much bigger vertical magnetic field (up to 1.5 T) than does undulator A. To check the possibility of using the Sentron probe in this case, a special test, using a LCLS prototype, was done. At first, the nonlinearity of the horizontal field sensor in the presence of strong longitudinal and vertical fields was investigated. The Hall probe was placed in the APS calibration magnet with a vertical field up to 1.5 T. To create a horizontal component of the magnetic field, the probe was inclined by a small (<1°) angle. The vertical field was measured by a separate probe. The vendor's calibration of the horizontal probe sensor shows a very small nonlinearity. The analog signal to the magnetic field ratio for this probe is constant with an accuracy of 0.1%. However, these measurements show that the presence of a vertical field makes a difference. Results of such measurements are shown in Fig. 3 (red crosses). The horizontal field was calculated from the measured vertical field:

$$B_x = B_y * \sin\varphi ,$$

where φ is the inclination angle of the probe.

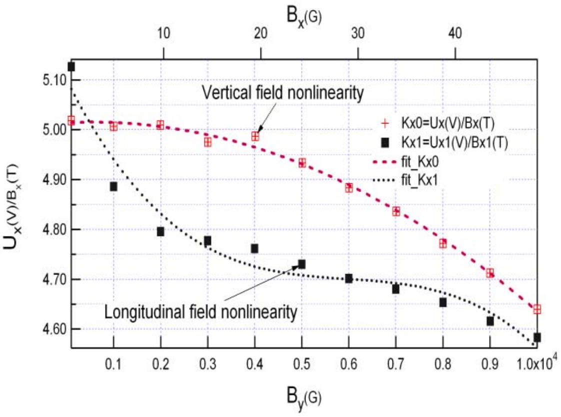

Fig. 3 Nonlinearity of a horizontal Sentron probe sensor vs. vertical and longitudinal fields.

The vendor's value for the analog-to-field ratio is 5 V/T. The nonlinearity of the Hall probe in the region of the vertical field up to 1.0 T is about 6%. The amplitude of the horizontal field for the LCLS prototype is < 10 Gauss, where the nonlinearity is small. Another, and much stronger, source of errors is the contribution of the longitudinal field. By rotating the probe around the axial axis at 90°, a longitudinal component of the field was created. The results of the test are shown in Fig. 3 (black squares). There is a clear contribution of the longitudinal component of the field, especially in the region of small (up to 300 Gauss) field, which is of most interest for us. Results of the test with the LCLS prototype are described below.

HORIZONTAL FIELD MEASUREMENTS

As was found in the test of 1997, there is a strong dependence of horizontal field integrals on the vertical position of the 2-axis Sentron probe. Sentron probe SN #367 was used for measurements of the LCLS prototype. Results of the test show the same behavior of the integral vs. vertical displacement dependence, as during 1997 test, with big quantitative difference: ΔJ1/ΔY ~1330 (G-cm)/mm. Fig. 4 shows different trajectories calculated for different vertical positions of the probe. As discussed earlier [1], these results are related to measurement errors associated with field vs. vertical displacement dependence. What is the reason for such dependence? From Maxwell's equations, we have $\partial B_y/\partial x - \partial B_x/\partial y = 0$. The results of measurements of the first vertical field integral dependence on X, $\partial J_y/\partial x$, made by moving coil and flipping coil, agree with Maxwell's equation, while the same measurements made by Sentron probe disagree. Measurements of $\partial B_y/\partial x$ are close to each other for different magnetic measurement techniques, including the Hall probe. It means that horizontal field measurements, made by an axial Hall probe, are not real and have some induced error. A possible explanation could be associated with the existence of both longitudinal and vertical magnetic fields. To find the correct vertical trajectory, a

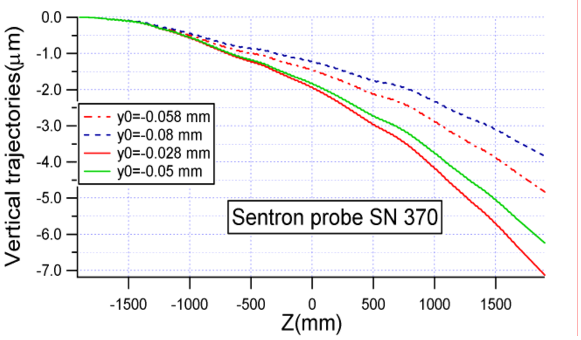

Fig. 4 Vertical trajectories calculated from Sentron Hall probe measurements at different vertical positions, E=14.1 GeV.

reference test was done using the 81-mm-long moving coil. A close match of the vertical trajectory was found for the Hall probe, using the proper vertical position of the

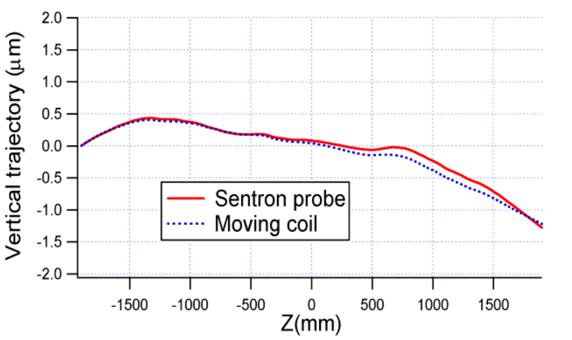

Fig. 5 Comparison of vertical trajectories measured by a Sentron probe and a moving coil.

probe. The result is shown in Fig. 5 for a particle energy of E=14.1 GeV. Comparison of moving coil measurements and Hall probe measurements of the vertical field was done as well and showed the same level of agreement as for the horizontal field. No additional adjustment was required in this case. Fig. 6 shows horizontal field data measured with probe

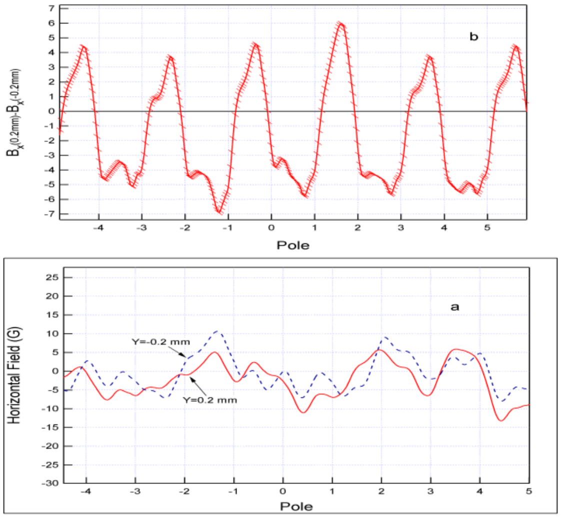

Fig. 6 a: Horizontal field for y=-0.2 mm and y=0.2 mm; b: difference of the fields B_x (0.2mm)$-B_x$ (-0.2 mm).

vertical offsets of ±0.2 mm and the difference between these two measurements. From the data shown in Fig. 6b, we can see that two types of nonlinearity exist: one is due to the contribution of the longitudinal field, and another is due to the vertical field. The undulator magnetic field in the ideal case is determined by horizontal, vertical and longitudinal components [6]:

$B_x=0$

$B_y=B_0*\cosh(ky)*\cos(kz)$

$B_z=-B_0*\sinh(ky)\sin(kz)$, where $k=2\pi/\lambda$, λ is an undulator period.

We have two possible scenarios:

a) in the case, where errors are defined by the longitudinal field, we will have horizontal field distortion $\Delta B_x=B_x(0.2mm)-B_x(-0.2mm)=0$, when the longitudinal field $B_z=0$ (pole centers);

b) in the case, where only the vertical field is responsible for the distortion, we will have $\Delta B=0$, when the vertical field $B_y=0$ (in-between the poles).

Taking this into account, we can conclude: the main contribution to field errors is due to the B_z field ($\Delta B=0$ close to the pole centers). Two neighboring poles have the zero crossing point shifted in opposite directions, which could be explained by the fact that the longitudinal field has the same sign and vertical field has the opposite sign in this location. It creates a DC component of the horizontal the field and distortion of first and second field integrals. Fortunately the effect of the vertical field is rather small for this range of magnetic field, and it is possible to find the proper Y, where the results of measurements are close enough to reference measurements, and the Hall probe could be used for measurements and tuning of vertical trajectories.

CONCLUSION

Tests of horizontal field measurements done with the LCLS prototype provided reliable results such that the Sentron probe could be used for the LCLS project horizontal field measurements and tuning. A test using a calibration magnet examined the nonlinearity of horizontal field measurements in presence of strong vertical and longitudinal fields. The most probable reason for horizontal field errors is associated with a strong longitudinal B_z field for $y\neq0$, and has to be taken into account, especially in the case of devices with a strong magnetic field. Some contribution of a strong vertical field can be observed as well.

ACKNOWLEDGMENTS

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