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A study of undulator magnets characterization using the vibrating wire technique

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ABSTRACT

The vibrating wire (VW) technique employs a stretched wire as a magnetic field sensor. Because of the wire's small diameter (~0.1 mm or smaller) and because the wire can be supported from outside the magnet, this technique is very appealing for field measurements in small gap/bore undulators with small good field regions and with limited access to the tested field. In addition, in the case of elliptical undulators, in which Hall probe (HP) measurements can be affected by the planar Hall Effect; VW technique can be used as an independent method to verify and supplement HP measurements.

In this article, we studied the potential of the VW technique for measurement of magnetic field errors and for prediction of beam trajectories in undulator magnets, using a 3.8 m long LCLS undulator as a test bench. Introducing calibrated magnetic field distortion at various locations, we measured the sensitivity and spatial resolution of the method. The method demonstrated 0.9 mm precision in localizing of the field distortion at a distance up to a few meters as well as 0.37 G cm sensitivity to the variation of the local field and 2 G cm sensitivity to the total field integral. To compare Hall probe and Vibrating wire measurements side-by-side, we measured field errors in an LCLS undulator previously characterized by Hall probe measurements. The field errors found with the Vibrating Wire technique appeared to be in good agreement with errors measured with the Hall probe. Beam trajectory distortions calculated from both data sets are also in good agreement.

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1. Introduction

The vibrating wire technique, developed in Ref. [1], employs a stretched wire as a magnetic field sensing element. In the usual setup, see Fig. 1, the wire is stretched through the region of the magnetic field to be tested and AC current with various frequencies is driven through the wire. The Lorentz forces generated by AC current flowing in the magnetic field cause the wire motion. The force distribution along the wire duplicates the magnetic field profile. If the frequency of AC current is equal to the resonance frequency of one of the wire vibration modes, this mode (standing wave) will be excited with an amplitude and phase (relative driving current) dependent on the field distribution. By measuring amplitudes and phases of various vibrating modes, one can reconstruct the field distribution along the wire. Detailed descriptions of the measurement procedure and field reconstruction algorithm can be found in Ref. [1]. It should be noted that because of the resonance amplification of the wire motion, and the use of the driving current as a reference for lock-in wire motion detection, the VW method is very sensitive to small magnetic fields.

The Vibrating Wire technique has been used on several occasions. In Laboratory for Elementary Particle Physics (Cornell University) VW technique was applied for magnetic center finding and alignment of final focusing quadrupole magnets of the Cornell Electron Storage Ring, [2]; for accurate finding of solenoid magnetic axis [3]; for permanent magnet wiggler end transitions tuning and magnetic field measurement along the wiggling beam trajectory, [4]. In Stanford Linear Accelerator Center National Laboratory, the method was used for finding the magnetic axis of LCLS quadrupoles [5]. In National Synchrotron Radiation Research Center (Taiwan), VW setup was proposed to align Taiwan Photon Source quadrupole magnets placed on the girder [6]. Ref. [7] describes the use of the VW technique for precise alignment of an NSLS-II quadrupole and sextupole magnets at Brookhaven National Laboratory.

It should be noted that in the majority of the applications listed above, only a few harmonics of the wire vibration were used. The field reconstruction algorithm was not employed.

The present study was motivated by the need for the field error measurement in small gap/bore undulator magnets as well as by a request for independent, from Hall probe, techniques for field

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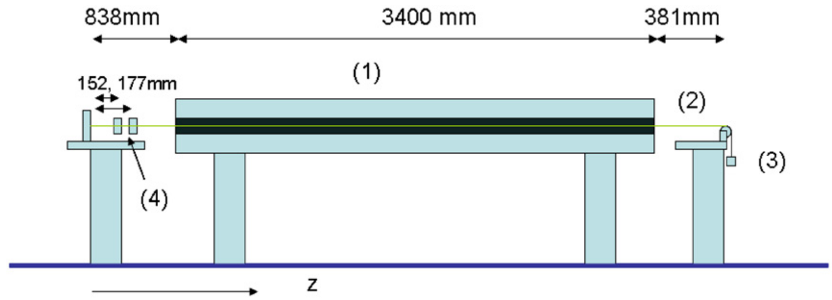

Fig. 1. VW setup. Here are (1)—LCLS undulator, (2)—4617 mm long 100 μm diameter copper–beryllium wire, (3)—tension mechanism, and (4)—wire position optical sensors.

measurement in elliptical undulators, where the planar Hall probe effect may significantly distort results. In this study, we took full advantage of the field reconstruction.

2. Setup

The setup is shown in Fig. 1. A copper–beryllium wire was stretched through the 3.4 m long LCLS undulator [8]. The undulator had 6.8 mm gap, 3 cm period, hybrid type magnetic structure with ~1.25 T peak field. The wire was extended by 838 and 381 mm beyond the magnet, and the ends were fixed on stands. Two LED-phototransistor assemblies (H21A1 from Newark Electronics) were employed as vertical and horizontal wire position sensors close to one end of the wire. The horizontal sensor was placed at $z=152$, vertical at $z=177$ mm. The tension mechanism was located on the opposite side.

A wave form generator Hewlett Packard 33129A controlled by IBM T42 laptop through GPIB interface, was used to drive AC current through the wire. In all measurements, the current amplitude did not exceed 100 mA. For the data acquisition, we used a DAQcard-6024E from National Instruments. A program based on "LabView" controlled the wave form generator, recorded the signal, and made initial processing. Subsequently, the data were analyzed with MatLab 7.1.

In the process of the measurement, the frequency of the AC current flowing through the wire was swept through the frequencies of the first 25 wire vibrating modes. Signals from vertical and horizontal wire position sensors were recorded and processed according to the recipe given in Ref. [1]. The standing wave amplitudes used for magnetic field profile reconstruction and defined there as parameters a_n were obtained through the resonance fit.

The first vibration mode resonance frequency of the wire was found to be around 30 Hz.

3. Experiments and results

The main goal for the experimental program was to explore the potential of the VW techniques, using the LSLC undulator as a test bench. Knowing the potential, one can develop the practical application. The first experiment was the test of the measurement repeatability.

3.1. Repeatability test

With an LCLS undulator (S/N 1) on the bench, we measured the magnetic field using 25 harmonics of the wire vibration. Figs. 2 and 3 depict data of three independent measurements. Measurements (1) and (2) were done subsequently within one hour; measurement (3) was done the next day. The measured amplitudes of the standing waves (parameters a_n, see Ref. [1]) up to 25 orders are shown in Fig. 2. Positive values mean the waves are in phase with driving current, negative ones indicate 180° phase. Plots in Fig. 3 present vertical and horizontal magnetic fields reconstructed from the wire vibration modes, following the algorithm developed in Ref. [1]. It should be noted that in Vibrating Wire field measurements, the tested field is intrinsically integrated over the shortest used half-wavelength. In the given measurements, the shortest half-wavelength was ~18 cm, which is approximately equal to 6 undulator periods. This integration zeroed the ideal field and left only the error field components.

According to this algorithm, the reconstructed field, as a function of distance, along the wire, Fig. 3, is the sum of the sinusoidal waves with amplitudes and phases presented in Fig. 2.

The data indicate that repeatability is quite satisfactory. An RMS of the difference between independent measurements is approximately three arbitrary units; i.e. ~1% of the signal maximum. Note, calibration described in the following section indicated that 3 a.u. correspond to approximately 0.1 Gauss field. That is $\sim 0.7 \times 10^{-5}$ of the undulator peak field.

3.2. Measurement of localized horizontal field variation

The next experiment was the measurement of a localized horizontal field change. The field component was created by a standard shim used for vertical beam trajectory correction. The shim was placed at location $z=231$ cm. Fig. 4 depicts the difference in the vibrating wire harmonics (left) and in reconstructed fields (right) between measurements before and after shim placement. The harmonics structure corresponding to "delta-like" function and well-defined peak in reconstructed field is clearly visible. A quadratic fit of the maximum, see insert, gives the location of the peak at $z=230.89$ cm, which is very close to the shim location (231 cm).

The symmetric ripple seen around the peak is due to the limited number of the harmonics used for reconstruction. This ripple can be eliminated by applying an appropriate filter.

3.3. Measurement of localized vertical field variation and signal calibration

The effect of a single By-shim, placed at $z=241$ cm, is shown in Fig. 5. The plots present the difference in the wire vibration harmonics and reconstructed field measured before and after the shim placement. A well-defined peak is present at $z=241.1$ cm, which is again very close to the actual shim position.

The peak area, i.e. integral of the reconstructed field over "z", is found to be 10,240 [a.u. cm]. From Hall probe measurement, we know this type of shims generates local field distortion with ~339 G cm integral. Comparing these numbers, one can find that 1 a.u. of the reconstructed field corresponds to 3.32e-2 G.

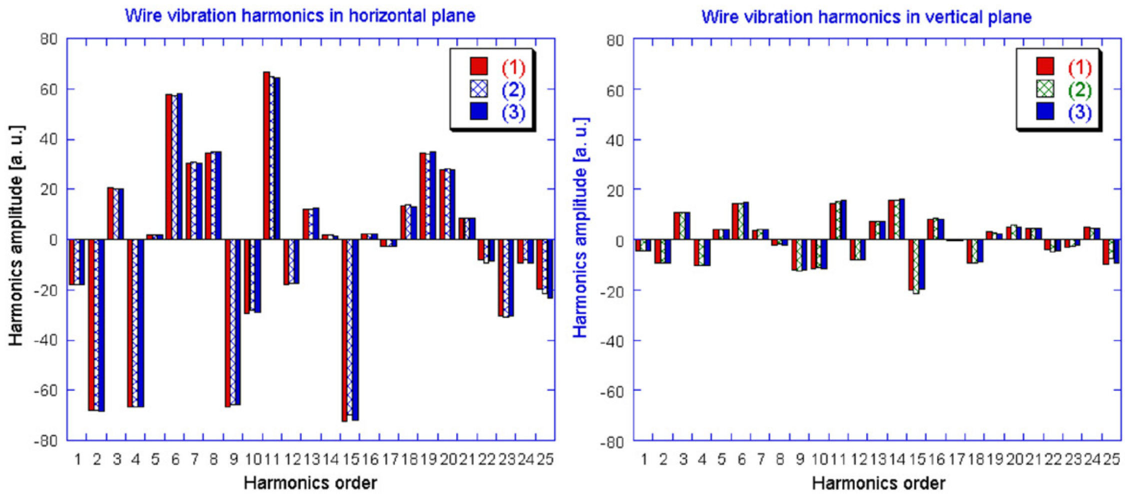

Fig. 2. Amplitudes of the wire vibrating modes (standing waves) in arbitrary units (a.u.) with phase in horizontal (left) and in vertical (right) planes.

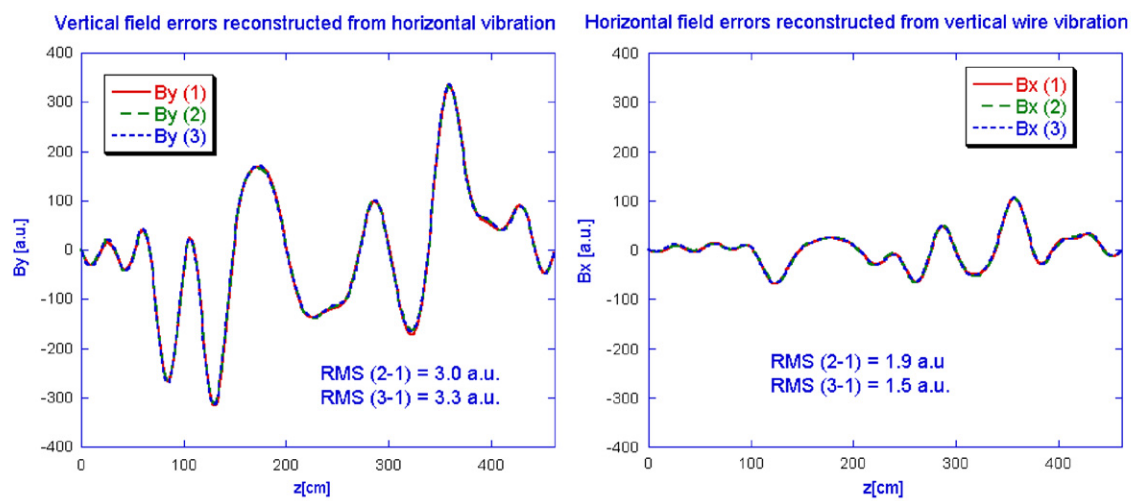

Fig. 3. Vertical (left) and horizontal (right) magnetic field reconstructed from the measured wire vibration modes. Three independent measurements are presented. The horizontal axis is the distance along the wire, vertical is a field component in arbitrary units.

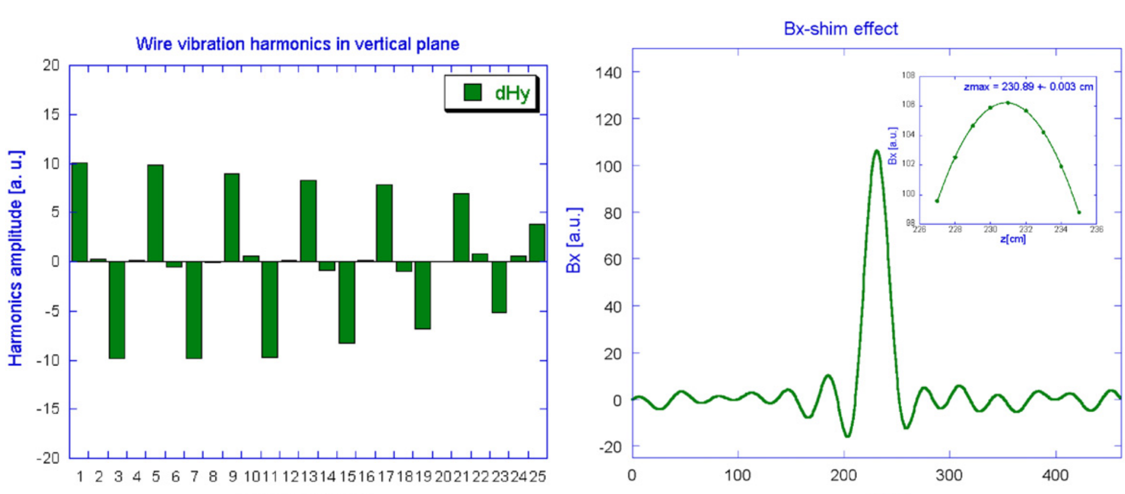

Fig. 4. Variation in the vertical vibrating harmonics (left) and in reconstructed field (right) caused by Bx-shim placed at $z=231$ cm. Quadratic fit of the peak maximum, see insertion, gives the peak location 230.89 cm.

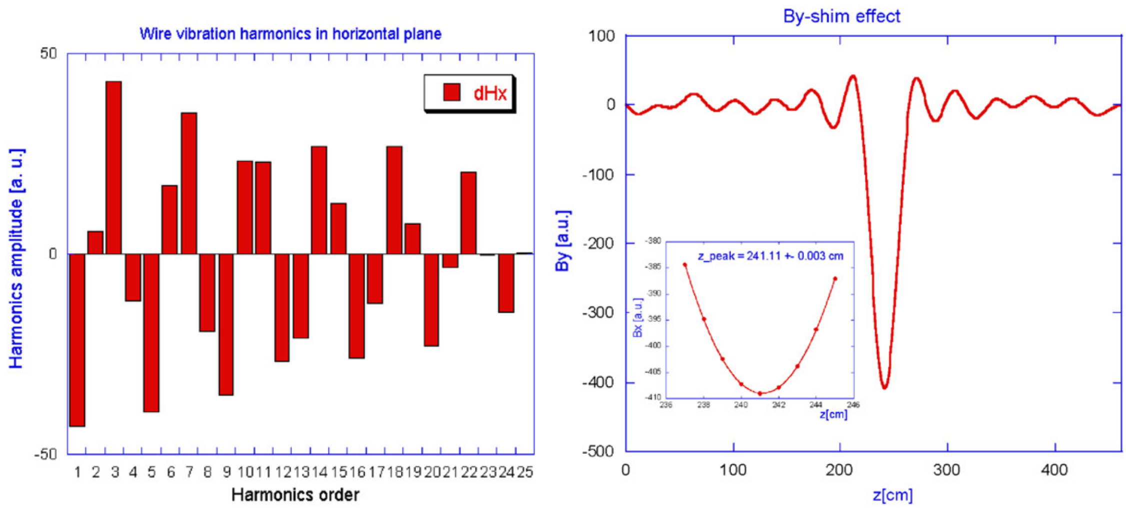

Fig. 5. Variation of the wire vibration harmonics (left) and reconstructed vertical field (right) caused by By-shim placed at $z=241$ cm. Quadratic fit of the top of the peak gives the peak location $z=241.11$ cm. The peak area (reconstructed field integral) is 10,240 [a.u. cm].

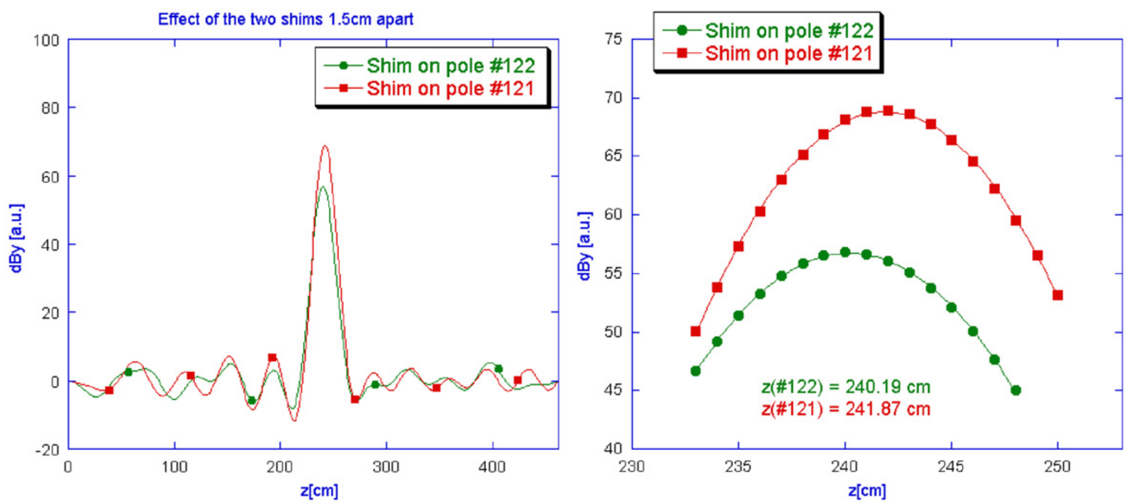

Fig. 6. Field created By-shims placed 1.5 cm apart. On left plot is a reconstructed field profile along the wire. Quadratic fit, see plot on the right, gives the difference between peak locations 1.7 cm. The expected distance is 1.5 cm.

3.4. Precision of the field distortion localization

In the process of the undulator magnetic field tuning, it is extremely important to apply the field correction, i.e., place the shim, at location where the field is distorted. To evaluate precision with which the Vibration Wire technique can predict the location of field distortion, we conducted series of experiments. In these experiments, we intentionally introduced field distortions By-shims placed at certain positions and used Vibration Wire technique to localize them.

In the first experiment, we measured field distortions created by two shims placed (one at a time) on two neighboring poles 1.5 cm apart. Data on the left plot in Fig. 6 show two reconstructed fields created by By-shims placed on poles #122 and #121.

The measurement indicates 1.7 cm distance between peaks, which is 2 mm longer than the expected 1.5 cm. In the second experiment, we measured vertical field distortions created by two shims placed on poles separated by 6 cm. Data are plotted in Fig. 7.

The distance between two peaks seen in measurement, 6.01 cm, is very close to the expected 6 cm.

Results of the measurement when two By-shims were placed on poles #225 and #42 are shown in Fig. 8. In this case, the distance between shims was $(225–42)\times1.5=274.5$ cm.

Accurate fit of the peak maximums shown on an inset gave 274.49 cm distance, while the expected is 274.5 cm.

Comparing the measured and expected distances between locations of the field distortion, we found the error RMS equals 0.9 mm. This number gives the method's precision for localizing of the field distortion.

3.5. Sensitivity test

Sensitivity to the *local* field change was tested in the following way. We varied the strength of the By-shim placed on pole #121 ($z\sim241$ cm) by turning the shim's screw which shunts magnetic field flux from the pole and measured amplitude of the 5-th mode of the wire vibration. The 5-th mode was chosen because it had maximum amplitude at shim location. In Fig. 8, the measured harmonic strength and residuals from the linear fit are plotted as a function of the screw position.

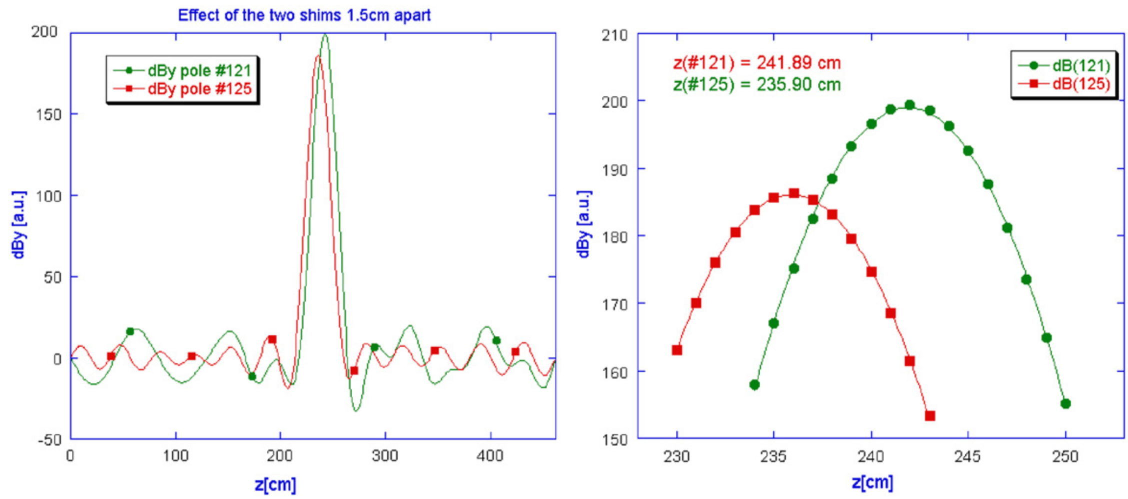

Fig. 7. Effect of two shims placed on poles #121 and #125 (6 cm apart), see left plot. The distance between two peaks seen in reconstructed field, see right plot, is 6.01 cm. The expected distance is 6.0 cm.

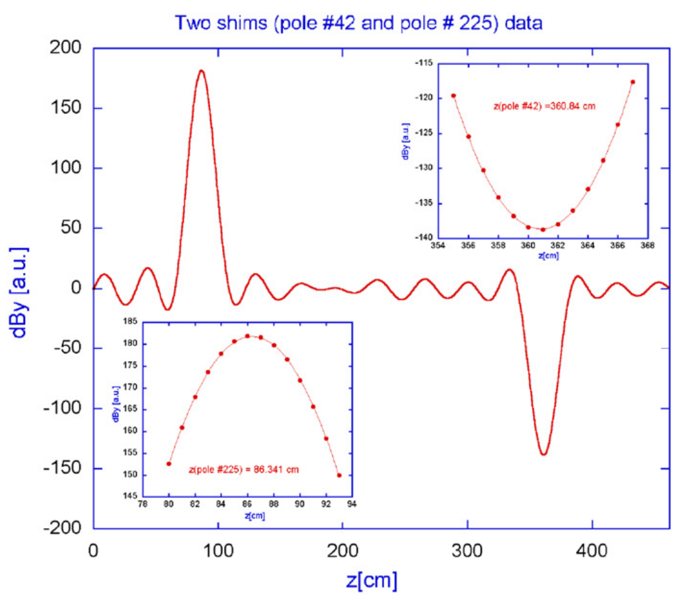

Fig. 8. Reconstructed field generated by two shims placed 274.5 cm apart on poles #42 and #225. Accurate fit, see inset, gives 274.49 cm distance between peaks, while the expected is 274.5 cm.

We estimated the measurement errors, which determine sensitivity, by using the residuals from the linear fit. The RMS of the residuals was calculated as 0.043 a.u. According to calibration, 339 G cm of the field integral from the shim placed on pole #122 results in 39.35 a.u. of the 5-th harmonic change, see left upper plot in Fig. 5. This implies that 1 a.u. of the harmonic's variation corresponds to 8.6 G cm of the field integral change. Consequently, 0.043 a.u. RMS of the harmonic strength measurement error translates to 0.37 G cm error in the field integral. The latter number can be considered as the method sensitivity to the local field change.

Sensitivity of the measurements of the field integrated over the entire magnet length was estimated from the data obtained for undulators S/N 1 and S/N 13. Integrating reconstructed fields presented in Section 3.1 (undulator S/N 1), we found the field integrals over all the magnet length $I_y=114.57\pm1.97$ G cm and $I_x=1.97\pm1.21$ G cm. The standard deviation $\sim$2 G cm can be considered as method sensitivity. Two data sets obtained for undulator S/N 13, see Section 3.6, gave the averaged field integrals $I_y=18.09$ G cm and $I_x=14.88$ G cm with differences $\Delta I_y=3.25$ G cm and $\Delta I_x=1.17$ G cm. These differences are in the range expected from the previous analysis.

Note that the sensitivity of the method to the local field change ($\sim$0.37 G cm) and sensitivity to the total field integral ($\sim$2 G cm) are quite different. This difference is due to the number of harmonics used for measurements. While for measurement of the local field change, we used only one harmonic, the total field integral is a sum of 25 practically independent single harmonic measurements. Because each measurement contributes some error, the final result uncertain is larger.

It should be mentioned that in both cases Vibrating Wire measurement sensitivity exceeds the sensitivity, which can be achieved in conventional Hall probe setup.

3.6. *Comparison with Hall probe measurement*

We compared magnetic field errors obtained with a Hall probe and with the Vibrating Wire technique. An LCLS undulator (S/N 13) was put on the stand and characterized with Vibrating Wire. In characterization, we used 25 harmonics of the wire vibration. The shortest half-wavelength equaled 18.5 cm or 6 (approximately) undulator periods. Plots in Fig. 9 depict the reconstructed field of the VW technique in comparison with the field measured with a Hall probe. The later was averaged over the shortest half-wavelength. Note that this averaging zeroed the ideal undulator field of $\sim$12,500 G amplitude, and left the field errors with amplitude $\sim1.7\times10^{-3}$ of the peak field. In the case of the vertical field (left plot), there are two regions at the undulator ends with bigger amplitudes. These regions represent end transitions, where the undulator field is not periodic. For the Vibrating Wire field reconstruction, we used the calibration obtained in the previous section. To give a sense of VW measurement repeatability on both plots (left and right), we depicted two independent sets of VW measurement data. At the given scale, they are indistinguishable.

Field error profiles obtained with the Hall probe and Vibrating Wire reveal similar structure and amplitudes. Both show approximately $\sim$15 G in the vertical field errors, and smaller, $\sim$3 G in the horizontal field errors.

Comparison between calculated 13.4 GeV LCLS beam trajectories based on measured fields by Hall probe and Vibrating Wire

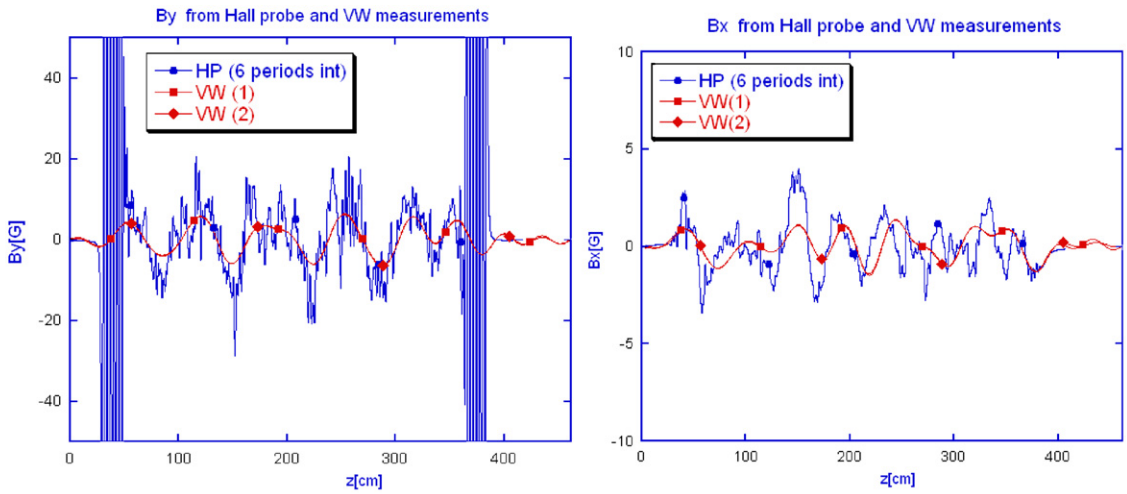

Fig. 9. Comparison between undulator field errors measured with Hall probe and Vibrating Wire. To obtain field errors from Hall Probe measurements, the field was averaged over six undulator periods.

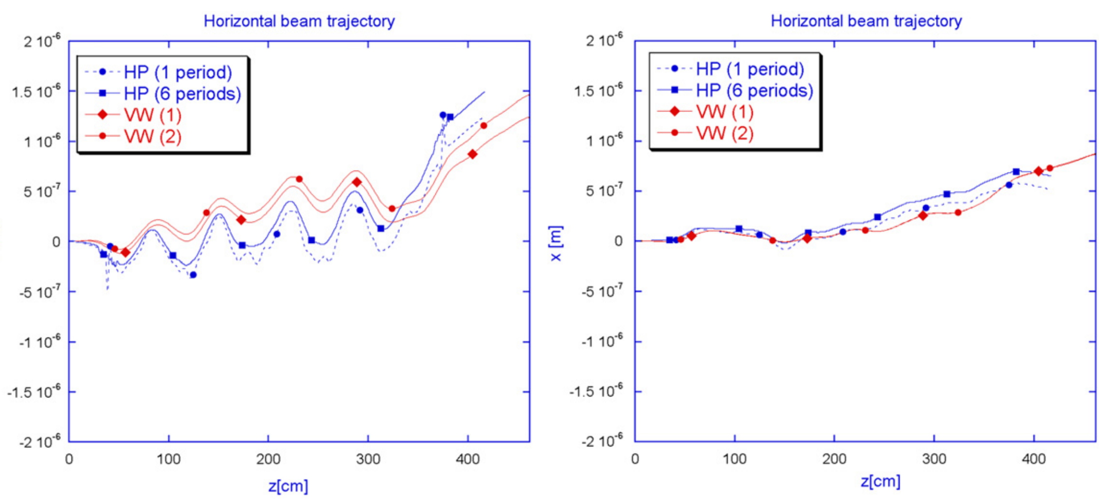

Fig. 10. Beam trajectories in horizontal (left) and vertical (right) planes calculated for Hall probe and Vibrating Wire measured field. Plots marked as " HP (1 period)" and "HP(6 periods)" represent trajectories calculated for Hall probe measured field averaged over one and six undulator periods. Plots labeled as "VW (1)" and "VW (2)" represent two independent VW measurements.

techniques is given in Fig. 10. The calculated trajectories from the two techniques show good agreement.

To explore the effect of the Hall probe field averaging, we calculated trajectories for the field averaged over 1 and 6 undulator periods, see plots marked as "HP (1 period)" and "HP(6 periods)". As one can see in Fig. 10, the difference between them is not significant. This validates calculating beam trajectories using the undulator field, which is averaged (or integrated) over multiple undulator periods. Note that the Vibrating Wire technique performs this integration intrinsically.

4. Discussion and conclusion

Using LCLS undulators as a test bench, we explored the potential of the Vibrating Wire technique for undulator field error measurement. The technique demonstrated:

(a) 0.37 G cm sensitivity for the measurement of localized magnetic field integral change and 2 G cm for field integrals over the total magnet length;
(b) ~1 mm space resolution for locating the magnetic field distortion;
(c) satisfactory repeatability

Beam trajectories calculated based on Hall probe and Vibrating Wire field measurements are in good agreement.

The small size of the magnetic field sensitive element (stretched wire) and the setup simplicity of the Vibrating Wire field measurement technique enable the characterization of magnets with small apertures and limited access to the tested field region. In addition, because the VW method automatically integrates the field over the length of the standing wave, the signal is sensitive to the field errors, but not to the main field. This results in very high sensitivity, which is difficult to achieve in Hall probe measurements. Also, this technique is free from effects analogous to the planar Hall Effect. The latter feature might be critical in the case of elliptical undulator tuning.

It should be noted that while the VW technique is more suitable for evaluation of the beam trajectory, it cannot be used for the measurement of undulator parameter "K," the variation of which along the magnet causes optical phase shake and compromises undulator magnet performance. Thus, the VW technique cannot completely replace the Hall probe measurement technique, and should be considered as a supplement.

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