LCLS-TN-24-1

A Single Stretched Wire System For Low Level Field Integral Measurements

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Abstract

A system has been developed to perform field integral measurements using a single stretched moving wire. The system was developed for enclosed bore undulators where very limited space is available for the measurements. The field integrals in undulators are ideally small, so the voltages generated by the moving wire are small. Techniques were developed for measuring the low level signals. This note describes the techniques and it then presents measurement results.

1 Introduction[1]

Two undulators are being built at SLAC which require magnetic measurements in an enclosed bore of small diameter. For these undulators, both point measurements with a Hall probe and integrated field measurements will be required. In this note we will concentrate on the integrated field measurements. Low level field integrals in undulators are typically measured with a multi-turn coil to increase signal strength. With a small diameter enclosed bore, there is no space for a multi-turn coil, so a single stretched moving wire will be used instead. The signal from a single wire moving in the low integrated field will be small. This leads to many challenges for making accurate measurements. In this note we discuss the techniques used to build the single stretched wire measurement system, and we show measurement results from the system.

The two undulators, Delta-II and a superconducting undulator (SCU), will require field integral measurements with the moving wire. The SCU, however, will also require quadrupole position and strength measurements with the moving wire. The quadrupole measurements will take place very near the quadrupole center. In all cases the field integrals will be small and the voltages from the stretched wire will be small. As an example of the expected signal, consider a field integral of 10 μTm. If the wire moves 0.5 mm, the flux change will be 5×10^{-9} Tm^2. If the wire motion takes 1 s, the voltage in the wire will be 5 nV. Accurately measuring such low level signals is the problem that must be overcome, and is the subject of this note.

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[1] Work supported in part by the DOE Contract DE-AC02-76SF00515. This work was performed in support of the LCLS project at SLAC.

For the existing LCLS undulators at SLAC, measurements similar in concept have been done for many years using a coil with many turns. A technical note was written to describe the principle of the measurements and the results of testing the multi-turn coil measurement system.[2] For the upcoming enclosed bore undulator measurements, the system described in this note was developed and early tests were performed.[3] After these initial tests, further developments were made and this note describes the updated single stretched wire measurement system.

2 Measurement Requirements

The LCLS-II undulator requirements come from a Physics Requirements Document.[4] The requirements related to the field integral measurements are briefly summarized below:

1. The first field integrals for both the SXR and HXR undulators must be below 40 μTm. This applies to both the Delta-II undulator and the SCU. The measurements must be accurate to a fraction of this value. We take the the accuracy requirement for the undulator field integral measurements to be below 4 μTm.

2. The SCU quadrupole center must be on the beam axis to better than 300 μm in order for beam based alignment to converge. The quadrupole is aligned warm and it moves as the SCU goes under vacuum and cools down. The amount of motion must be measured and then corrected for during the warm alignment. In order to do this, the quadrupole center position must be measured during testing both warm and cold and the difference determined. We wish the error on the change of the quadrupole center position to be a small fraction of 300 μm. We take the accuracy requirement for the measured change in quadrupole center position to be below 30 μm.

3. The SCU quadrupole integrated gradient must be known to 3×10^{-3}. The present SCU iron dominated quadrupoles are calibrated warm, and the change in the calibration from warm to cold must be measured. To do this, the single stretched wire system will be used to measure the integrated gradient before and after cooldown. In order to know the integrated gradient within tolerance when the quadrupole is cold, we wish to measure the change in integrated gradient warm to cold to better than 3%. An example helps to motivate this requirement. Assume the warm calibration has no significant error and the integrated gradient is 1 T = 10000 G. If the change in integrated gradient warm to cold is 1%, or 100 G, and we know the 100 G change to 3%, or 3 G, then the error on the cold integrated gradient is 3 G / 10000 G, or 3×10^{-4}. This is a factor of 10 below the tolerance on knowing the cold integrated gradient. Systematic errors in the warm and cold measurements drop out in the warm to cold difference. Thus if the change in integrated gradient is not too large, as expected, then measuring the warm to cold change in the integrated gradient at the

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[2] Z. Wolf, Y. Levashov, "Undulator Long Coil Measurement System Tests", LCLS-TN-07-03, April, 2007.

[3] M. Munawar, "Preparations For Superconducting Undulator Magnetic Measurements", LCLS-TN-23-8, September, 2023.

[4] H.-D. Nuhn et al., "Undulator System", LCLS-II Physics Requirements Document LCLSII-3.2-PR-0038-R3, June, 2017.

few percent level is sufficient to meet the 3×10^{-3} accuracy requirement on the cold integrated gradient.

3 Stretched Wire System Overview

Figure 1 shows an overview of the stretched wire setup during tests of the SCU quadrupole measurements. The quadrupole is on movers and its position is read out by Keyence LK-G82 laser displacement sensors as shown in figure 2. The movers and sensors allow precision moves of the quadrupole to compare to changes in the position measurements by the stretched wire system. The wire is 3.0 m long to account for the length of the SCU cryostat. The wire is positioned at each end by Newport GTS150 horizontal stages and GTS70V vertical stages. The stages are controlled by two Newport ESP302-2N controllers. One end of the wire has pins which position the wire, and a ratchet mechanism on a spool to tighten the wire. This wire end is shown in figure 3. The other end of the wire is positioned with pins and has a spool with a torsion spring underneath. This end is shown in figure 4. The stretched wire is inside a 5.0 mm OD, 4.5 mm ID stainless steel tube which simulates the guide tube for the Hall probe measurements. The stationary return wire is insulated and tied to the outside of the guide tube. When measuring inside a cryostat, the return wire must be inside the guide tube and a device to keep the return wire stretched in the bottom of the guide tube is under development. This should further reduce the noise and improve the measurements. The return wire must be in close proximity to the moving

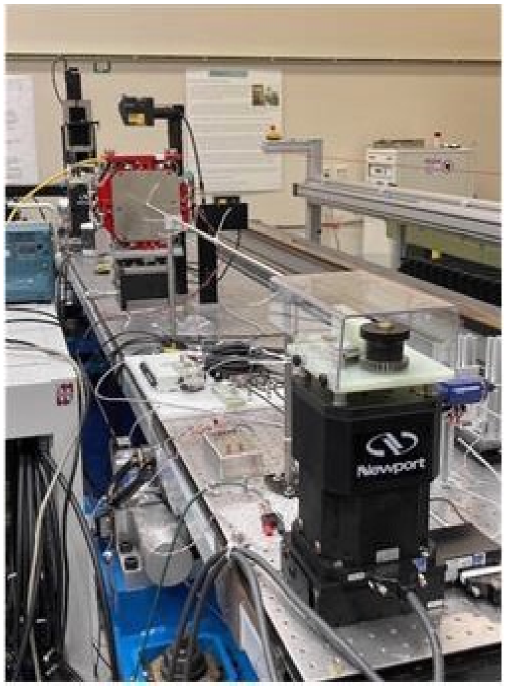


Figure 1: Overview of the stretched wire system.

Figure 2: The quadrupole is on movers and its position is read out by Keyence sensors.

wire in order to minimize the loop area, which minimizes 60 Hz pickup. The moving stretched wire and stationary return wire form a circuit with no electrical contact to any other components.

The ends of the stretched wire circuit are connected to a preamplifier as shown in figure 5. The preamplifier is an EM Electronics model A10 DC Nanovolt Amplifier. A 1% 10 kOhm resistor is attached to the preamplifier which sets the gain at $10,000$. A 1 μF capacitor is in parallel with the 10 kOhm resistor which limits the bandwidth to 16 Hz. The output of the preamplifier goes to an HP3458A voltmeter. The 3458 has an integration time of 2 power line cycles. With this integration time, the input noise is 0.1 ppm of the 100 mV full scale range, or 10 nV. One can see that without the preamplifier, the sub 10 nV signal from the wire could not be measured accurately. With the nanovolt preamplifier, the signal from the wire is increased to around 100 μV, well above the noise level of the voltmeter.

There is one common ground for the preamplifier circuit. The common ground is at the 0 V supply of the preamplifier. The stretched wire circuit is connected to this point. The girder, stages, electronics rack, etc. are connected to this point in order to avoid capacitive pickup. The preamplifier output signal which goes to the voltmeter uses this point as the reference voltage.

A typical signal from the wire moving 0.5 mm centered 1.0 mm from the center of the quadrupole is shown in the upper plot of figure 6. Voltage samples are taken before the wire moves in order to make sure the wire motion is captured and to establish the noise level and offset error at the beginning of the samples. The wire motion causes the voltage

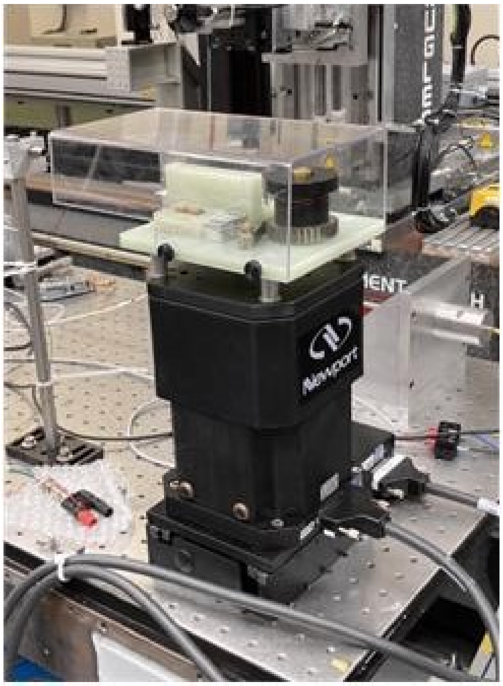


Figure 3: Wire end with a ratchet to tighten the wire.

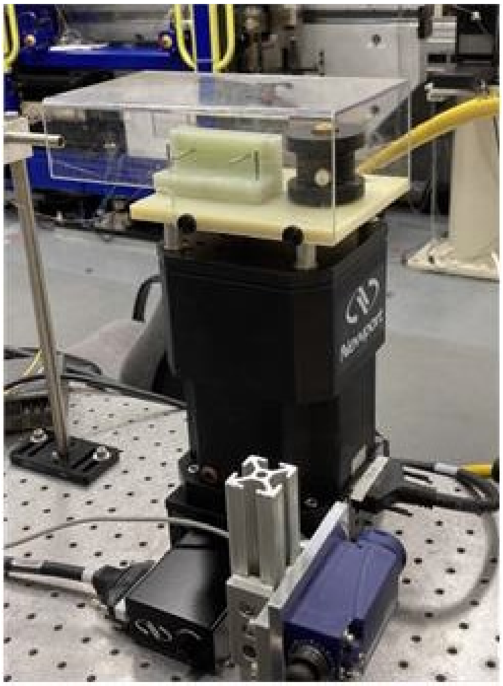


Figure 4: Wire end with a spool and torsion spring.

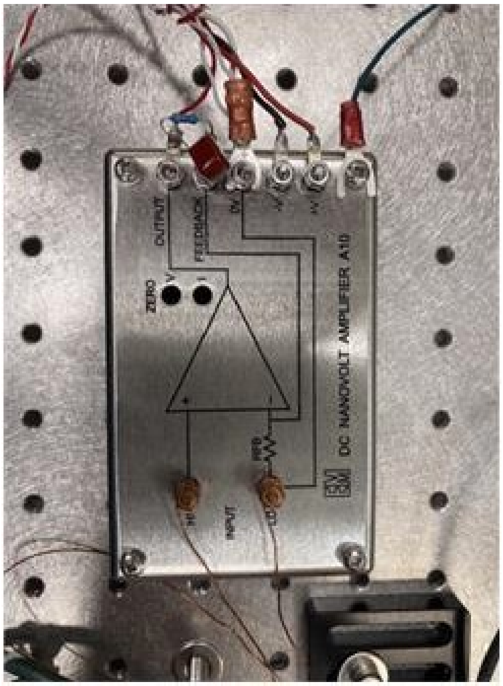


Figure 5: Preamplifier with a gain of 10,000.

increase from 1.25 to 2.00 sec. Samples are taken after the wire moves in order to capture the voltage from any oscillations of the wire so that the flux change from two fixed wire positions can be determined. The samples after the wire motion also indicate the offset error at later times in the sampling. The offset error changes with time so offsets before and after the wire motion must be determined independently.

The integrated gradient of the quadrupole is 4.2 T with a current of 6 A. One millimeter in X from the quadrupole center, the field integral I1Y $\left(I1Y = \int B_y dz\right)$ is expected to be 4.2×10^{-3} Tm. When the wire moves 0.5 mm for the measurement, the flux change is 2.1×10^{-6} Tm^2. The flux change is equal to the time integral of the voltage from the wire. Dividing the integrated voltage in the lower plot by the preamplifier gain, one gets about 1.9 μVS. The measured 1.9 μVS = 1.9 μTm^2 agrees with the expected flux change of 2.1 μTm^2. The wire moves over a time interval of about 0.75 sec, so we expect the average voltage to be about 2.8 μV. If ones divides the measured voltage in the upper plot by the preamplifier gain of 10000, one gets an average voltage of about 3 μV, which is consistent with expectations.

The previous example had a relatively large signal since the wire was 1 mm from the quadrupole center. Consider the situation near the quadrupole center. The signal from the wire near the quadrupole center is shown in figure 7. Notice that the voltage from the wire changes sign at the quadrupole center and the integrated voltage at the end of the wire motion is approximately zero. The noise in the voltage measurement is visible now with the low signal. The noise causes a problem with the offset voltage correction, which we now describe.

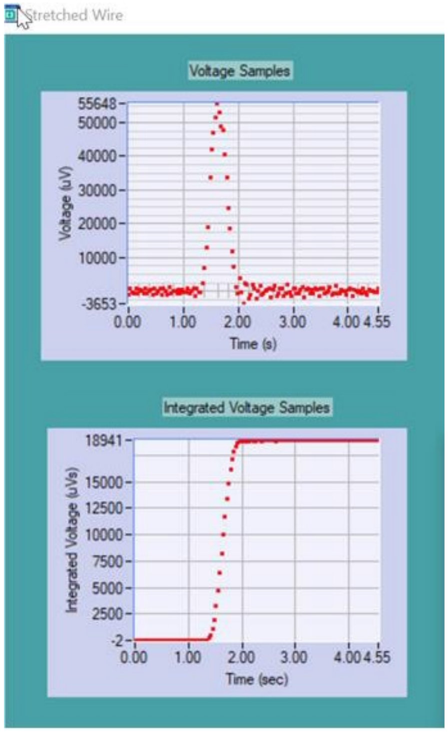


Figure 6: Voltage and integrated voltage from the wire moving 0.5 mm centered about a point 1 mm in X from the quadrupole center.

In figure 7, the wire is stationary for the first 1.25 sec, then the wire moves for about 0.75 sec, afterward the wire is stationary for the last 2.5 sec. When the wire is stationary, the voltage induced in the wire is zero, and any voltage measured is from offsets in the preamplifier and the voltmeter, and from any thermal emfs. We average the voltage samples for the first second, and then average the voltage samples for the last second, and make a linear fit through these two average values and subtract the fit from all the voltage samples for the first offset correction. The offset changes with time and that is why the linear fit is used instead of an average value. This procedure has a drawback in that noise in the measurements causes the two average voltage values to have errors. The fit subtracted from all the voltage samples then has errors which cause the slope of the integrated voltage before the wire motion and after to be different than zero. This is evident in the lower plot of the integrated voltage in figure 7. If one uses the final values of the integrated voltage plot to determine the integrated voltage, the slope of the curve when the wire is not moving can cause significant errors.

In order to mitigate the offset error problem, a second offset correction is performed. This second correction is illustrated in figure 8. The horizontal axis is time in seconds. The vertical axis is integrated voltage in microvolt-seconds. The integrated voltage for the first second before the wire moves is fit to a line (red line from 0 to 1 sec in the figure). Then the integrated voltage for the last two seconds after the wire has moved is fit with a

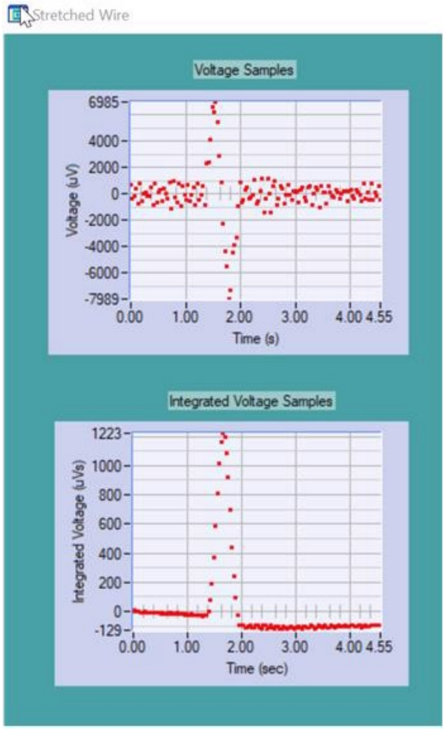


Figure 7: Voltage and integrated voltage from the wire moving near the quadrupole center.

line (red line from 2.5 sec to 4.5 sec in the figure). With no offset voltage, the fitted lines would be horizontal. The offset voltage is integrated causing the fitted lines to have a slope. The value of the fitted line immediately before the wire starts moving gives the integrated voltage at the start of the wire motion. The value of the fitted line immediately after the wire stops moving gives the integrated voltage after the wire moves. The difference gives the integrated voltage due to the wire motion. There is still an offset error during the wire motion, so the difference is taken in the center of the wire motion as indicated by the two red dots in the figure. This correction greatly improved the accuracy of the measurements. One can see from the figure that if instead, the integrated voltage at the end of the samples is used, there is a large error due to the slope of the integrated voltage samples after the wire motion has stopped.

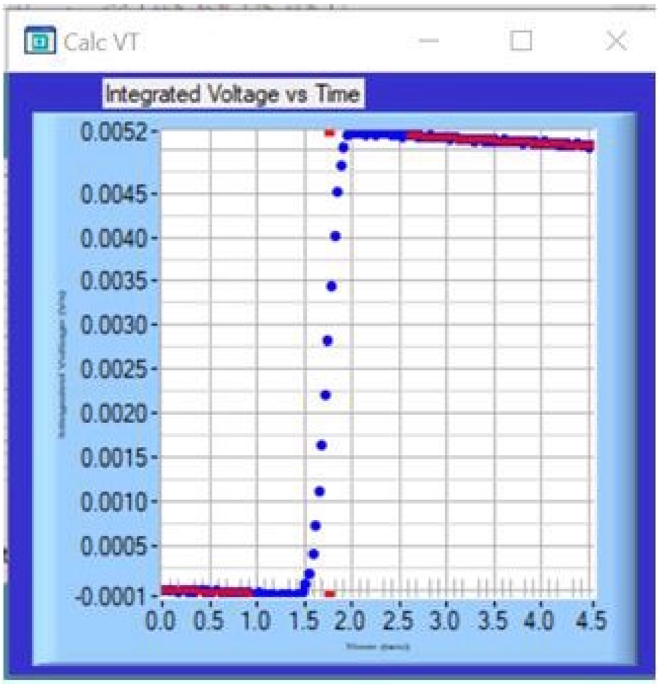


Figure 8: A second offset error correction is illustrated in this figure.

4 Measurement Results

Measurements were made at several positions near the quadrupole midplanes and the integrated gradient and quadrupole center position were determined. The quadrupole was then moved +100 μm in X and +200 μm in Y and the measurements were repeated. In our right handed coordinate system, X is horizontal, Y is vertical, and Z is in the beam direction. Figure 9 is a plot of the I1X vs Y measurements before the quadrupole was moved. In this notation, I1X is the first integral of B_x and I1Y is the first integral of B_y. Figure 10 is a plot of the I1X vs Y measurements after the quadrupole was moved +100 μm in X and +200 μm in Y. The text in the figures shows the integrated gradient and the magnetic center position which come from the slope and intercept, respectively, of the line fit to the points in each figure. The errors on the integrated gradient and magnetic center position are calculated from the errors on the measured individual points. From the text in the figures, note that the integrated gradient measurements are the same to 3×10^{-4} and the Y position of the measured magnetic center has changed by +197 μm. From the figure, the calculated error on the magnetic center positions is below 1 μm. The 3 μm difference between the movement of the quadrupole and the change in the magnetic center position from the stretched wire has a contribution from the Keyence sensors, however, the agreement is good enough that we do not pursue the error analysis.

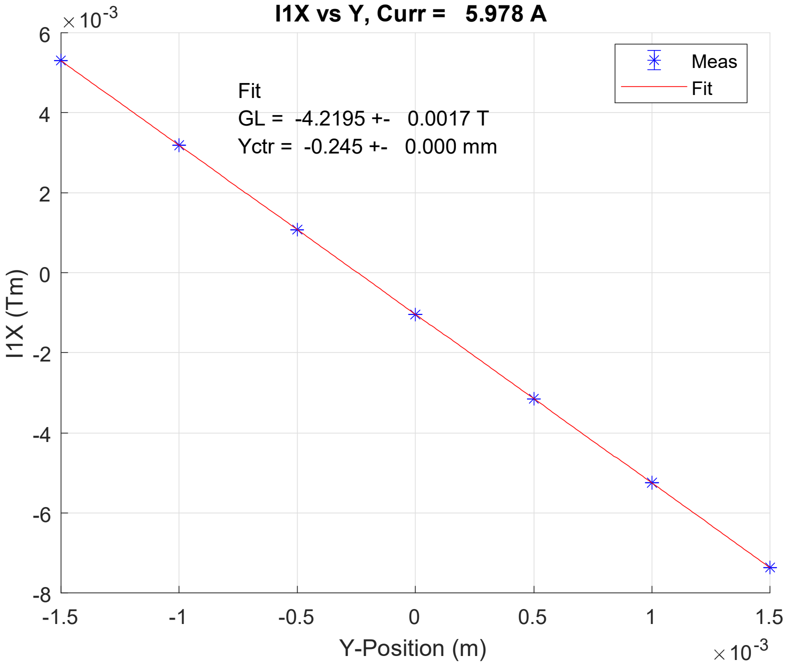


Figure 9: I1X vs Y before the quadrupole was moved.

The integrated field measurements for the data in figure 9 are shown in a table in figure 11. For each measurement, the wire was moved in the +Y direction centered about the X0, Y0 position indicated in the figure. The voltage samples were taken. The first voltage

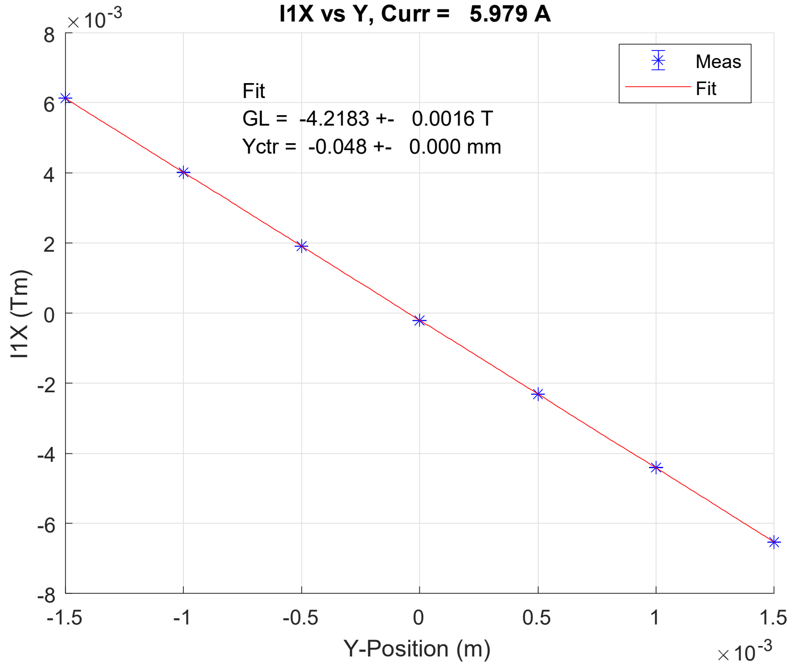
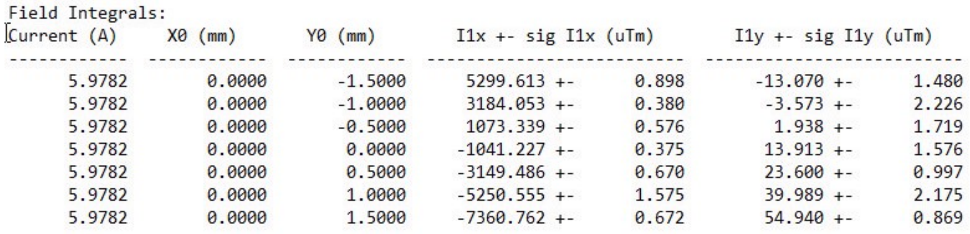


Figure 10: I1X vs Y after the quadrupole was moved +100 μm in X and +200 μm in Y.

offset correction was applied. Then the integrated voltage was calculated. The second offset correction was then applied to the integrated voltage. The value of the integrated voltage after corrections was then determined. Next, the wire was moved in the -Y direction and the calculations were repeated. The two integrated voltages were subtracted (since the signs are different) and divided by 2. This average integrated voltage was divided by the preamplifier gain and divided by the 0.5 mm that the wire was moved in order to get the integrated field strength I1X. A similar measurement was made by moving the wire horizontally to get I1Y. The process was repeated 4 times for each I1X and I1Y value. If required, one outlier ($> 1.5\sigma$) was removed from the four integrated field measurements for I1X and I1Y. The averages and standard deviations were determined and put into the table. One can see that the integrated field measurements are typically repeatable to better



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Field Integrals:
Current (A)     X0 (mm)      Y0 (mm)       I1x +- sig I1x (uTm)       I1y +- sig I1y (uTm)
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      5.9782        0.0000       -1.5000     5299.613 +-       0.898     -13.070 +-       1.480
      5.9782        0.0000       -1.0000     3184.053 +-       0.380      -3.573 +-       2.226
      5.9782        0.0000       -0.5000     1073.339 +-       0.576       1.938 +-       1.719
      5.9782        0.0000        0.0000    -1041.227 +-       0.375      13.913 +-       1.576
      5.9782        0.0000        0.5000    -3149.486 +-       0.670      23.600 +-       0.997
      5.9782        0.0000        1.0000    -5250.555 +-       1.575      39.989 +-       2.175
      5.9782        0.0000        1.5000    -7360.762 +-       0.672      54.940 +-       0.869
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Figure 11: Integrated field measurements taken before the quadrupole was moved.

than 2 μTm.

Measurements along the horizontal midplane were also made. Figure 12 shows I1Y vs X on the horizontal midplane before the quadrupole was moved +100 μm in X and +200 μm in Y. Figure 13 shows the I1Y vs X measurements after the quadrupole was moved.

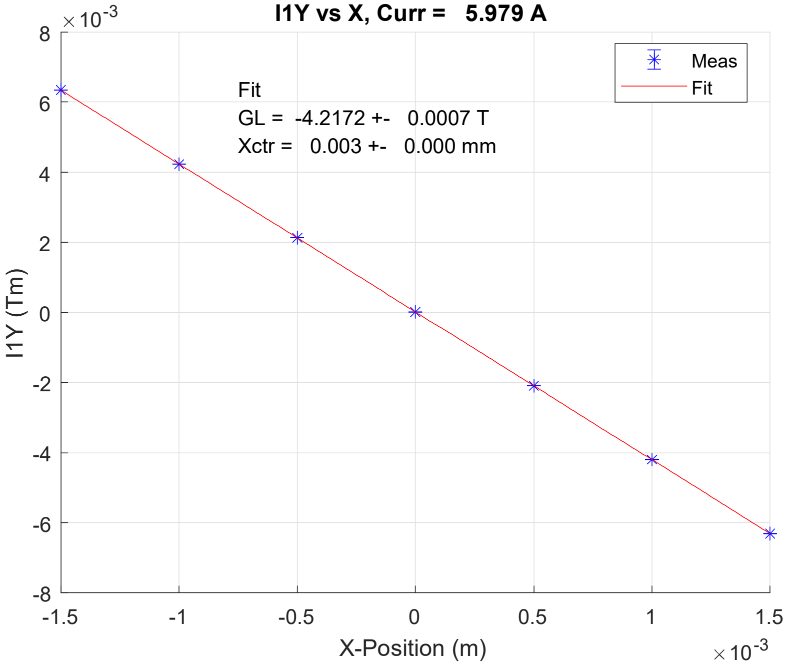


Figure 12: I1Y vs X before the quadrupole was moved.

The measured quadrupole center position moved by 102 μm as indicated by the text in the figures. The calculated error on each magnetic center position (as calculated from the errors on the points in the plot) is below 1 μm. The measured integrated gradient was repeatable to 7×10^{-5}. Note that the integrated gradient is not being measured accurately at this level since the gain of the preamplifier has not been calibrated to this level. The measurements are repeatable indicating the stability of the system, so changes in the integrated gradient are expected to be accurately measured at the 1% level of the gain accuracy of the preamplifier. The change in integrated gradient warm to cold is expected to be a small fraction of the integrated gradient. A 1% gain error on the small change will yield a cold integrated gradient with a small error. The magnetic center position is not affected by the preamplifier gain accuracy since we are finding the point where the integrated field is zero.

As a final measurement result, the quadrupole was turned off and the integrated field measurements were done at the quadrupole center where the remnant field is expected to be small. Results from these measurements are shown in a table in figure 14. These measurements are indicative of the small field integrals in an undulator. Note that the measurements are repeatable to better than 2 μTm. For comparison, in 2015 the Delta undulator was measured with a single stretched wire but without a nanovolt preamplifier.

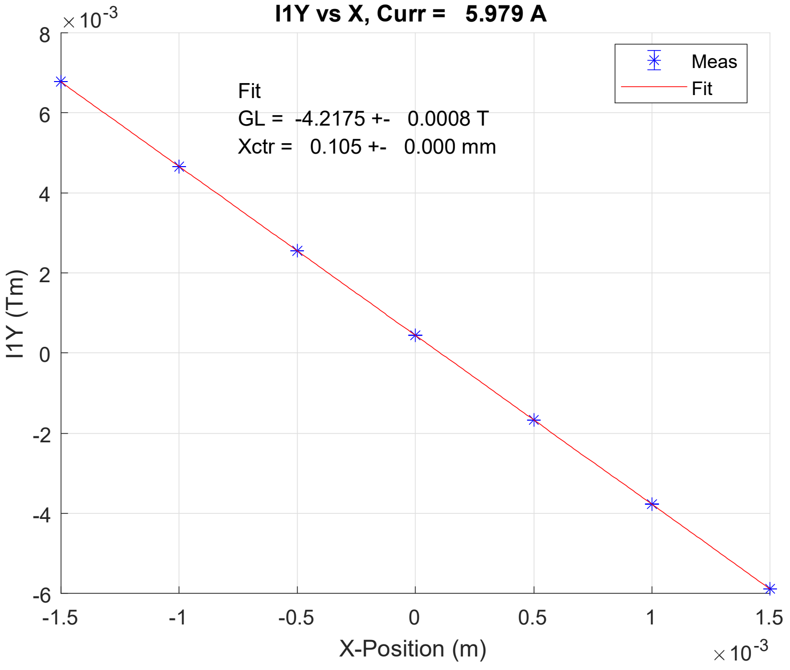
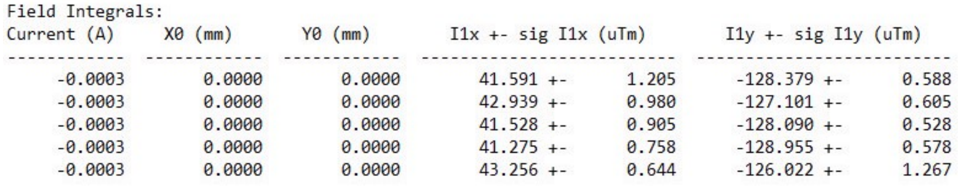


Figure 13: I1Y vs X measurements after the quadrupole was moved.



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Field Integrals:
Current (A)      X0 (mm)       Y0 (mm)         I1x +- sig I1x (uTm)         I1y +- sig I1y (uTm)
------------   ------------  ------------   -------------------------   -------------------------
     -0.0003        0.0000        0.0000        41.591 +-         1.205        -128.379 +-         0.588
     -0.0003        0.0000        0.0000        42.939 +-         0.980        -127.101 +-         0.605
     -0.0003        0.0000        0.0000        41.528 +-         0.905        -128.090 +-         0.528
     -0.0003        0.0000        0.0000        41.275 +-         0.758        -128.955 +-         0.578
     -0.0003        0.0000        0.0000        43.256 +-         0.644        -126.022 +-         1.267
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Figure 14: Background field measurements with the quadrupole turned off.

The repeatability of the first integral measurements was up to 16 μTm. The preamplifier and improved offset correction have reduce this to 2 μTm.

The Earth's field at the location of the stretched wire was previously measured in a similar setup to be $B_x = +0.24$ G and $B_y = -0.50$ G. The wire is 3.00 m long. Integrating the Earth's field over the length of the wire gives $I1X = +72$ μTm and $I1Y = -150$ μTm. The measured field integrals are in line with these values, as expected since the length of the wire is much longer than the length of the unpowered quadrupole so the signal should be dominated by the Earth's field.

The accuracy of the measurements is determined by the 1% accuracy of the preamplifier gain. A precise calibration of the preamplifier gain is not required for undulator field integral measurements because the field integrals are small, and 1% accuracy on a small field integral meets our 4 μTm accuracy requirement. Of course, calibration of the preamplifier can be performed when needed.

5 Conclusion

A single stretched wire system was developed for measurements in enclosed bore undulators with very limited space for the measurements. The system measured low level field integrals to typically better than 2 μTm, which is below the 4 μTm requirement. Quadrupole center motion was accurate at the 3 μm level, well below the 30 μm requirement. The SCU quadrupole strength was measured repeatably to 3×10^{-4} of the quadrupole strength. Changes in the quadrupole strength have an additional 1% uncertainty of the change due to the gain of the preamplifier. For a 1% strength change, this amounts to 1×10^{-4} of the quadrupole strength. These uncertainties are well below the 3×10^{-3} requirement.